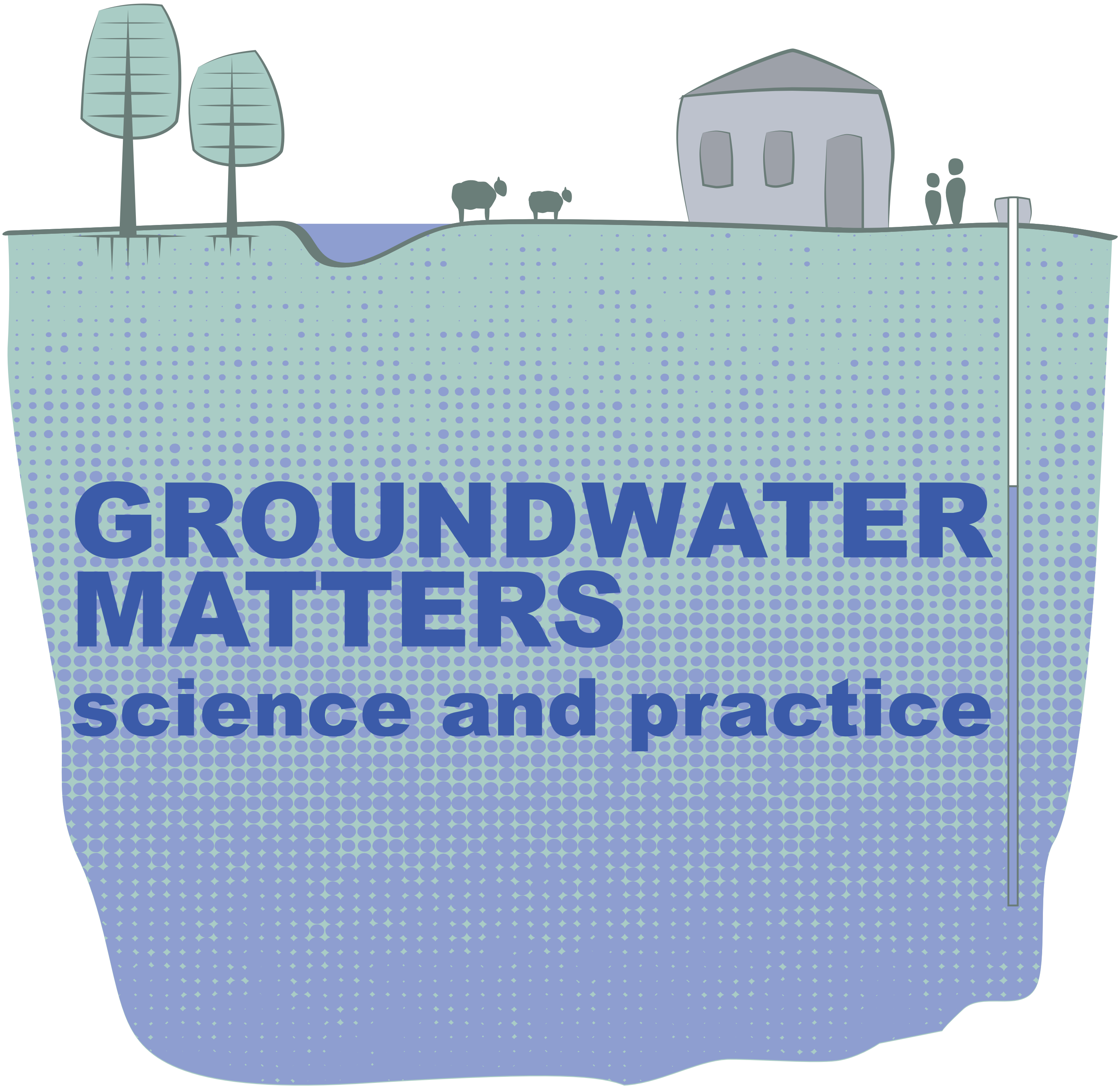

GROUNDWATER MATTERS science and practice

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS - Irish Group

Proceedings of the 38th Annual Groundwater Conference

Tullamore, Co. Offaly, Ireland

24th and 25th April 2018

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(IRISH GROUP)

Presents

Groundwater Matters: science and practice

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Tullamore Court Hotel
Tullamore
Co. Offaly

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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 in 2018 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

2018 Conference

This year's conference theme is *Groundwater matters: science and practice* – the title shall reflect our appreciation for scientific research on the one side, and professional "hands-on" expertise on the other side. Both of these aspects are relevant per se and for each other: scientific research with an open-minded attitude towards objectivity is one crucial element to further develop methods, which again may become our tools for daily practice to improve nothing less than the livelihood of our society.

The conference will be opened by Henning Moe, the president of the Irish Group of the IAH, and Minister of State Seán Kyne, TD.

The keynotes of this year's conference will be addressed by Dr Geoff Parkin (Newcastle University, UK) and Dr John McCray (Colorado School of Mines, USA). John McCray will present a method to improve the water quality of streams targeting the hyporheic zone. By using subsurface modules to modify the hydraulic conductivity to drive hyporheic exchange into the streambed and to control residence times, a water quality enhancement can be achieved.

Geoff Parkin will present the potential of engagement of communities and members of the public in environmental sciences to support monitoring: two case studies from Ethiopia and Northern England will be presented that highlight crucial issues to be resolved fur successful hydrosciences.

Over the two days, there will be 22 speakers presenting their research, methods, results, and challenges in five thematic sessions dedicated to a) groundwater flooding, b) groundwater flow controls, c) the Early Career Hydrogeologists Network (ECHN), d) impacts of landuse pressures on groundwater, and e) borehole operations with a focus on pumping efficiency and treatment needs.

In addition, there will be poster presentations by four early career hydrogeologists with the opportunity to engage and discuss. Following on, a wine reception will be provided sponsored by City Analysts, before the social gathering at Hugh Lynch's Bar.

This year, the committee of the IAH (Irish group) decided to offer the opportunity of a site visit on day two in order to witness and discuss science and practice. The site visit will be provided by Malcolm Doak (Irish Water) who will introduce attendees to the Tullamore Wellfield (north) at Ardan, 3.5 km north of the conference venue. Scope of the site visit is the assessment carried out for a potential increase of abstraction from the wellfield for the local water supply using CCTV, geophysical logging, and pumping tests. The site visit will be focussing on the two Ardan boreholes, the trial well drilled in 2017, and plans for a new production well to be drilled in May 2018. Due to limitation on site, maximum capacity of the site visit is 2 x 20 attendees. A shuttle bus will be provided between the conference venue and the site.

The committee of the IAH-Irish Group wishes to express their sincerest gratitude to all in attendance at this year's conference as well as over the last years: speakers and presenters, exhibitors, sponsors, and all delegates. Thanks to your trust, contributions, and commitment we are delighted to share the two days of the 38th IAH-Irish Group conference together.

Philip Schuler
IAH Conference Secretary

2018 IAH (Irish Group) Committee:

2018 Conference Sub-Committee:

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

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The proceedings for the 38th Annual Groundwater Conference 2018 will also be made available digitally on the IAH-Irish Group website within the next six months.

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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:

CDM Smith

STREAM BIOENERGY

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‘Groundwater Matters: science and practice’

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co. Offaly: Tuesday 24th & Wednesday 25th April 2018

Programme Day 1, Tuesday 24th April

08:30 - 09:30 *Conference Registration; Tea, Coffee, & Exhibits*

INTRODUCTION

09:30 – 09:40 Welcome and Introduction
Henning Moe – *President IAH Irish Group*

09:40 – 10:00 Opening Address by Seán Kyne TD is Minister of State at the Department of Rural and Community Development and the Department of Communications, Climate Action and Environment with responsibility for Natural Resources, Community Affairs, and Digital Development.

SESSION 1: KEYNOTE

10:00 – 10:30 ‘The Citizen Hydroscientist – benefits and challenges for hydrogeology’ – Geoff Parkin (Newcastle University)

10:30 – 10:45 Q & A

10:45 – 11:15 *Refreshments*

SESSION 2: GROUNDWATER FLOODING

11:15 – 11:35 ‘Satellite Flood Mapping: new approaches for monitoring and mapping groundwater flooding in Ireland’ – Ted McCormack (Geological Survey of Ireland (GSI))

11:35 – 11:55 ‘Modelling Groundwater Flooding: A unique challenge requiring a novel solution: a case study of South’ – Patrick Morrissey (University of Dublin Trinity College)

11:55 – 12:15 ‘Water Tracing: Lifting the lid in the Neale, the Mayo Deel and the Rathcroghan uplands’ – Coran Kelly (GSI & Tobin Consulting Engineers)

12:15 – 12:35 ‘A habitats & EIA Directive perspective on hydrological/hydrogeological assessment – are there any simple answers?’ – Patrick Roberts and Michael Watson (McCarthy Keville O’Sullivan Ltd.)

12:35 – 12:50 Q & A

12:50 – 14:00 *Buffet lunch in Tullamore Court Hotel*

SESSION 3: GROUNDWATER FLOW CONTROLS

14:00 – 14:20 ‘Waulsortian Limestone: Geology and Hydrogeology’ – John Murray (National University of Ireland Galway (NUIG) & iCRAG)

14:20 – 14:40 ‘Structural Controls on Groundwater Flow – From field studies through to 3D modelling’ – John Walsh (University College Dublin (UCD))

14:40 – 15:00 ‘Quantitative analysis of Cenozoic faults and fractures and their impact on groundwater flow in Irish bedrock aquifers’ – J.P. Moore (UCD)

15:00 – 15:20 ‘Geophysical Investigation of Structural Groundwater Pathways’ – Yvonne O’Connell (Apex Geoservices)

15:20 – 15:35 Q & A

15:35 – 16:00 *Refreshments*

SESSION 4: EARLY CAREER HYDROGEOLOGISTS NETWORK

16:00 – 16:15 ‘FloodRisk2WellWater: a socio-hydro(geol)logical approach to combining science and practice for mitigating flood-trigger groundwater contamination’ – Luisa Andrade (UCD)

16:15 – 16:30 ‘Chemical analysis of groundwater focusing on potential arsenic contamination of drinking water supply boreholes in Chikwawa, Malawi’ – Laura McGrath (ARUP)

16:30 – 16:45 ‘Agro-chemicals in Irish Groundwaters: Preliminary findings of anthelmintic drug occurrence in Irish karst and fractured aquifers’ – Damien Mooney (iCRAG, Trinity College Dublin, Teasgasc)

16:45 – 17:00 ‘Karst “Open Heart Surgery” time series analysis methods and visualisation’ – Lea Duran

17.00 – 17:15 Q & A

17:15 *Poster Presentations & Wine Reception sponsored by City Analysts*

19:00 *Social event at Hugh Lynch’s Bar including a light evening meal, sponsored by IAH (Irish Group).*

‘Groundwater Matters: science and practice’

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co. Offaly: Tuesday 24th & Wednesday 25th April 2018

Programme Day 2, Wednesday 25th April

08:30 – 09:00 *Tea, Coffee & Exhibits*

SESSION 5: KEYNOTE

09:00 – 09:30 ‘Engineered streambeds for water quality enhancement in urban streams’ – John McCray (Colorado School of Mines)

09:30 – 09:45 Q & A

SESSION 6: IMPACTS OF LANDUSE PRESSURES ON GROUNDWATER (I)

09:45 – 10:05 ‘The remediation of the east tip on Haulbowline Island’– Cormac Ó Súilleabháin (Cork County Council)

10:05 – 10:25 ‘Planning and development within a karst dominated landscape in County Monaghan: Case studies and experiences’ – John Paul McEntee (Monaghan County Council)

10:25 – 10:45 ‘Groundwater nitrate attenuation versus dissolved gas production: A hierarchy of scale’ – Eoin McAleer (RPS)

10:45 – 10:55 Q & A

10:55 – 11:20 *Refreshments*

SESSION 7: IMPACTS OF LANDUSE PRESSURES ON GROUNDWATER (II)

11:20 – 11:40 ‘Pesticides and metabolites in groundwater’ – Sarah-Louise McManus (TCD)

11:40 – 12:00 ‘Groundwater as a source and pathway for antibiotic-resistant infection in the Republic of Ireland’ – Jean O’Dwyer (University College Cork (UCC))

12:00 – 12:20 ‘Cryptosporidium in Irish waters: risk, prevalence and intervention’ – Julie-Anne Naughton (Dublin Institute of Technology (DIT))

12:20 – 12:30 Q & A

SESSION 8: BOREHOLE OPERATIONS – PUMPING EFFICIENCY AND TREATMENT NEEDS

12:30 – 12:50 ‘Effective and efficient pump systems’ – John Calder (Dura Pump UK)

12:50 – 13:10 ‘A proposed classification of water supply boreholes in Ireland based on treatment requirements’ – David Ball (Independent Hydrogeologist)

13:10 – 13:20 Q & A

13:20 Conference closing address: Philip Schuler (*Conference Secretary* – IAH Irish Group)

13:25 *Buffet lunch in Tullamore Court Hotel*

SITE VISIT

14:30 – 16:30 The Tullamore Wellfield (North) Ardan Wellfield – Field guide and notes to a groundwater community of practice – Malcolm Doak (Irish Water)

16:30 End of Site Visit

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SESSION I

THE CITIZEN HYDROSCIENTIST – BENEFITS AND CHALLENGES FOR HYDROGEOLOGY

Geoff Parkin
School of Engineering, Newcastle University

ABSTRACT

Engagement of members of the public in environmental sciences has significant potential to provide multiple benefits to communities and formal organisations. There are both institutional drivers for public engagement, and impetus at the community level particularly from events such as flooding, but also from a general interest and desire for good management of local environments including groundwater. At the heart of most environmental management is collection of data, and there are a range of approaches that can be used within the umbrella term of citizen science to support appropriate monitoring. Recent advances in mobile technology combined with use of the internet, and current developments towards low-cost monitoring, are leading to greatly increased potential for such approaches.
Two case study examples are introduced, one in Ethiopia related to development of small-scale irrigation from groundwater in shallow aquifers, the second in northern England considering catchment management with a specific focus on flooding. In both cases there has been close engagement with communities to design and implement monitoring using local observers, and results have been used in computer modelling to support catchment management. These studies have revealed some of the significant issues that need to be resolved for implementation of successful and sustainable citizen science monitoring programme in the hydrosciences.

INTRODUCTION

There is a long tradition of non-professional engagement in scientific inquiry in environmental sciences. Some fields have large cohorts of enthusiast amateurs who collect large datasets regardless of its possible wider use. A prime example is bird watching, with the RSPB being formed in 1889, at a time in the Victorian era when there was wide interest in scientific developments, and which has developed into the largest nature conservation charity in the UK, and one of nearly 6,000 voluntary organisations in the UK in 2014/15 related to the environment (https://data.ncvo.org.uk). While there are many enthusiastic amateur geologists, in common with most other sciences the barriers to contributing to new discoveries or understanding are fairly high due to the need for radvanced techniques and use of expensive equipment, although some dedicated enthusiasts can contribute to the field (Withington and Slater, 2017).

In recent years, there has been a step change in the possibilities for direct public engagement in scientific activities, through the combination of more ubiquitous access to mobile technologies, the internet, and low-cost monitoring technologies. This indicates the possibility of moving towards a more heterogeneous approach to environmental monitoring, with different types of observers contributing and sharing data (Buytaert *et al.*, 2016). Different approaches to the types and levels of engagement of public participants in scientific studies has led to much discussion in the literature of the terminology being used, some of the main terms being:

- **Citizen science**: Overall term for the process in which members of the public engage in activities with professional scientists
- **Crowd-sourced**: Lowest level of engagement – no or little active participation, eg social-media harvesting

- **Community-based**: High level of engagement including problem definition and design of monitoring approaches
- **Participatory action research (PAR)**: Involvement of the researcher with people in data collection, reflection, and action with the purpose of enacting change
- **Volunteered geographical information (VGI)**: Building and dissemination of geographical information by individuals
- **Co-production of knowledge**: Methods involving technical experts and people/society both contributing to producing new knowledge and understanding

There are some examples of research using citizen science approaches for directly geology-related applications, for example a study used volunteers to help provide more spatial coverage of data related to volcanic eruption early warning signals in addition to the few sites with costly equipment for continuously-monitored information (Williams-Jones *et al.*, 2008). However, much of the rapid recent developments are in hydrosciences, driven (top-down) by the need for public engagement through legislation or frameworks such as Integrated Water Resources Management (IWRM), Catchment-Based Approach (CaBA), or (bottom-up) the need for better information for local water management, with a notable impetus being to improve household or community-level flood protection and resilience.

This paper presents some considerations of the potential benefits and constraints for increased public engagement in hydroscience monitoring, from the perspectives of both communities and professional organisations. These will be fully illustrated with detailed results from the two example case studies in the associated conference presentation.

WHY DO WE NEED MORE DATA IN HYDROGEOLOGY?

TYPES OF DATA: STATIC AND DYNAMIC

There has been a commendable shift towards making nationally-funded data collection publicly available through open-source programmes, with both the Irish Geological Survey (IGS) and British Geological Survey (BGS) making significant additions to the published information on their websites in recent years. Most publicly available groundwater information, however, is generally related to static mapping, for example geological maps at different scales as digital images and spatial GIS datasets.

As groundwater is a component of the hydrological cycle, an integrated approach to monitoring and modelling is required in support of groundwater management (Peach, 2015), so more time-series monitoring data is required for climate, surface hydrology, and groundwater, both for flows and levels, and for water quality. In particular, it is relatively uncommon to have open access to time-series of groundwater levels, although these are important for understanding resilience of resources, particularly in relation to vulnerability to climatic variability and change (Bovolo *et al.*, 2009). Groundwater recharge is controlled by both evapotranspiration, a function of temperature, and the amount and intensity of rainfall; these are all likely to be affected under future climates, so knowledge of the relationship between these climatic variables and groundwater level responses as well as river flows is important, and requires monitored time-series of relevant data. Although there is increasing use of temporal information from satellite-based remote sensing, these also require local time-series information as ground truthing.

LOCAL UNDERSTANDING – THE IMPORTANCE OF PLACE

Although every location on the planet is, of course, unique, the general goal of science is to look for patterns of behaviour, and for underlying process understanding, to help explain observed behaviour. For catchment and groundwater management, such understanding can then, in principle, be used to help manage the environment better, addressing issues such as water resources management (including drought management), water quality, and flooding (including groundwater flooding). The balance between uniqueness of place (Beven, 2000) and underlying patterns of explanatory behaviour has been a continuing recent discussion topic in the hydrology literature. Pfister *et al.* (2017), for example, argue that although geology provides a first-order control on catchment response, the search for a consistent catchment classification system that would enable regionalisation of process understanding remains elusive.

Local aquifer behaviour can be particularly significant in karst aquifers, where conduit connectivity and fracture zones control groundwater and contaminant movement, response times are often short, and buffering capacity small in comparison to porous aquifers. O'Connor *et al*. (2016) outline the "Groundwater 3D" (GW3D) project which aims to improve local hydrogeological understanding, including improving understanding of stakeholder needs; this is aimed primarily at mapping, rather than monitoring time-series of local hydrological responses.

PROCESS UNDERSTANDING – HOW MUCH DATA ARE NEEDED?

Although environmental scientists always look for more data, monitored over long periods of time, with high spatial and temporal density, the reality is that information is always limited in space and time, so design of effective monitoring networks requires understanding of the purpose of data collection, and the relation between the monitoring regime and the hydrological regime.

Monitoring of long-term datasets may include automatic data loggers, which provide near-continuous data but are relatively expensive to maintain, or manual methods. Manual observations are often designed to be carried out on a regular basis, e.g. daily rainfall or river levels, or weekly/monthly groundwater levels or chemical sampling. These may introduce biases into results, for example chemical loads in rivers may be disproportionately higher or lower during floods than under normal flows, and less frequent groundwater monitoring may miss notable recharge events. Flood events are, of course, critical to understand and characterise, especially larger infrequent events for risk assessment, where flow behaviour may differ significantly than under normal hydrological conditions. Floods are also very place-specific, and local understanding of response mechanisms, as well as detailed spatial rainfall, may be needed (this is illustrated in the UK example case study). Monitoring is therefore required both on regular intervals, but also on an event basis.

POTENTIAL ROLES FOR A CITIZEN HYDROSCIENTIST

FORMAL AND INFORMAL ORGANISATIONS AND MONITORING NETWORKS

The above arguments point towards the potential benefit of heterogeneous networks of monitoring data, which may include a basic framework of long-term regular monitoring with high-frequency data where possible, supplemented by data supported by citizen scientists, which may include a higher spatial density network of low-cost monitored sites, and episodic monitoring, both project-based to characterise behaviour at a particular location, and event-based monitoring.

The basic frameworks for environmental monitoring networks are normally the responsibility of government departments (or national organisations supported by central government funding), who are responsible for network design, instrument maintenance, and data download, storage, security and quality control. However, there has been a general worldwide decline in such networks, particularly notable in some regions such as Africa (Walker *et al*., 2016). The potential for more widespread use of citizen science monitoring data requires similar approaches, which may be achieved through partnerships between community-level observers and formal organisations. In many cases, such partnerships already exist in some form, for example where unpaid volunteer amateur observers are supported by formal organisations to support data collection. Figure 1 shows some outputs from the Weather Observations Website (WOW), which is run by the UK Meteorological Office. This was originally designed to allow daily rainfall observers to upload observations efficiently, but has recently been extended to cover other types of data.

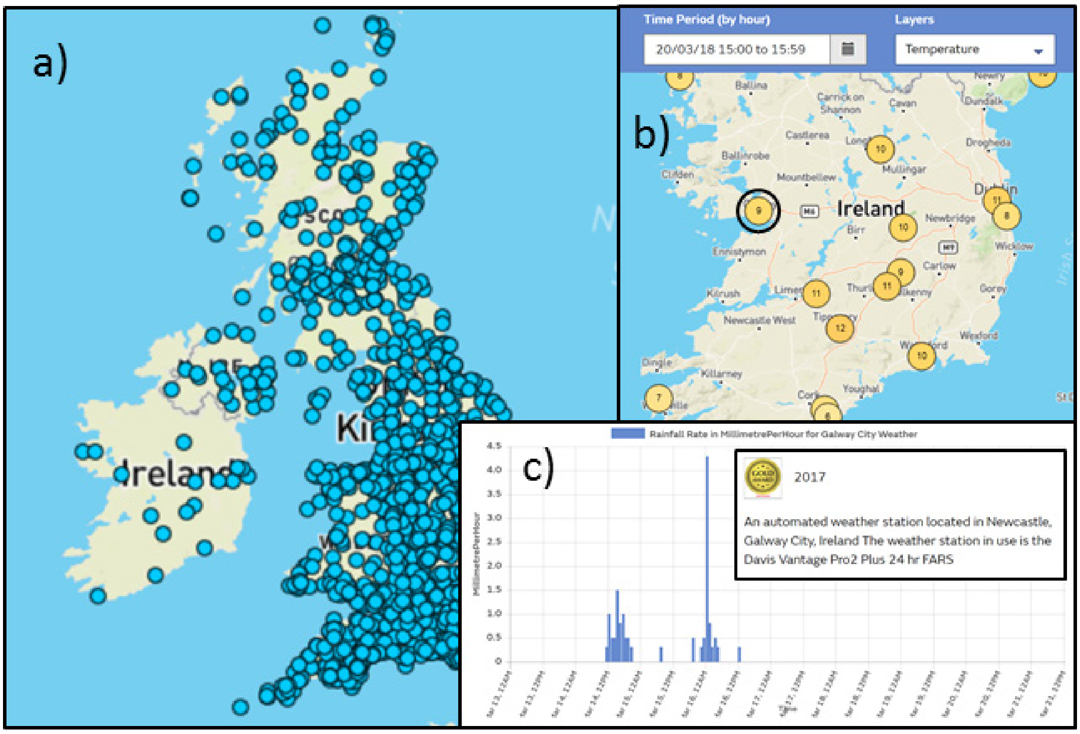

Figure 1: WOW (Weather Observations Website, https://wow.metoffice.gov.uk), a) Registered sites in UK and Ireland, b) snapshot of temperatures in Ireland, c) example of historical rainfall rate data from automated weather station in Galway

BENEFITS FOR THE CITIZEN HYDROSCIENTIST

Daly (2017) notes that “Public/community engagement on water management has been largely unsuccessful to-date”. Direct involvement in monitoring may provide a mechanism for better engagement. Although observers may need to invest substantial time and money, there are many reasons why different community members may wish to become involved in these activities. Re (2017) presented a social science approach to assess farmer’s perceptions of environmental issues, and willingness to be involved in groundwater monitoring networks.

A key issue is motivation, especially for long-term monitoring. Although pure scientific interest or self-interest through improving local environments (e.g. for flood resilience) may be important, often some level of external support or validation may be involved. Figure 1 shows, for example, an award system that is used on the WOW platform to recognise consistency of observations over time. Other rewards may be financial, often indirectly given, for example through maintenance support for locally-purchased and owned equipment. A further possibility may be through micro-payments for data supplied, which could also help in the issue of data ownership, as this could be linked to transfer of ownership or licensing to a central organisation.

Data sharing is a key aspect of delivery of wider benefits; the potential shift towards a heterogeneous data model opens up wider possibilities of data use. Figure 2 illustrates how flood-related data management and access could move from the existing approach of “expert-driven” control, past a stage (where we are now) of expert use of community-sourced data, towards a more open system of real-time data sharing. This would require co-ordination between environmental management organisations, and further development of toolkits to support community use and interpretation of data (e.g. Barron, 2017).

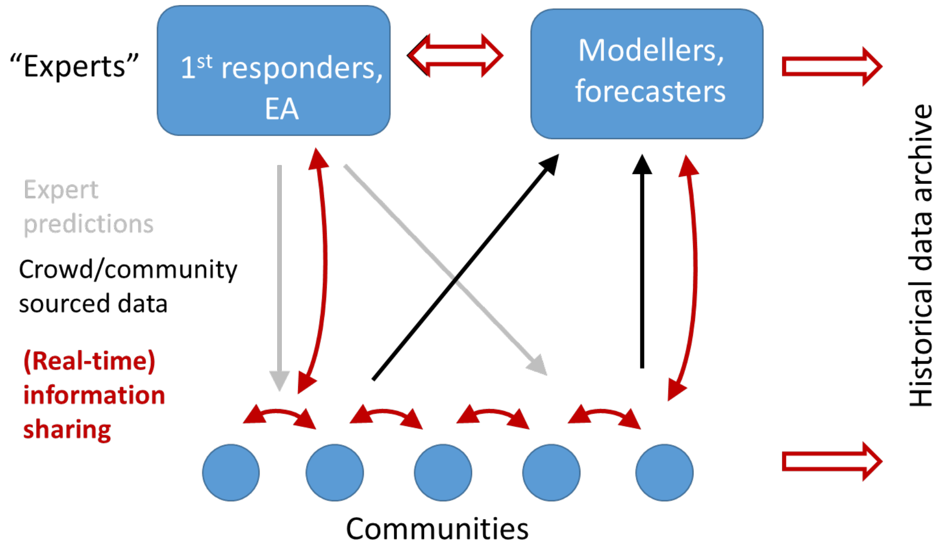

Figure 2: Schematic of information sharing between actors for flood-related monitoring

CASE STUDIES

GROUNDWATER IN AFRICA: DANGILA WOREDA, ETHIOPIA

The first case study is based on a programme of research in Ethiopia into the development of small-scale irrigation from groundwater from shallow aquifers. The primary study area is located close to Bahir Dar in the headwaters of the Abay catchment (Blue Nile) in the Ethiopian highlands close to Lake Tana. The shallow aquifers comprise weathered regolith and Cenozoic basalts overlain by alluvium in seasonally-flooded valleys (Figure 3). The research is built around the concept of community observers providing local information on rainfall, river levels and flows, and groundwater levels, to support modelling studies leading to mapping of groundwater potential, and understanding of resilience of shallow groundwater supplies under climate variability and land management. A key first step of assessment of the data quality of community-monitored observations is reported in Walker *et al.* (2016).

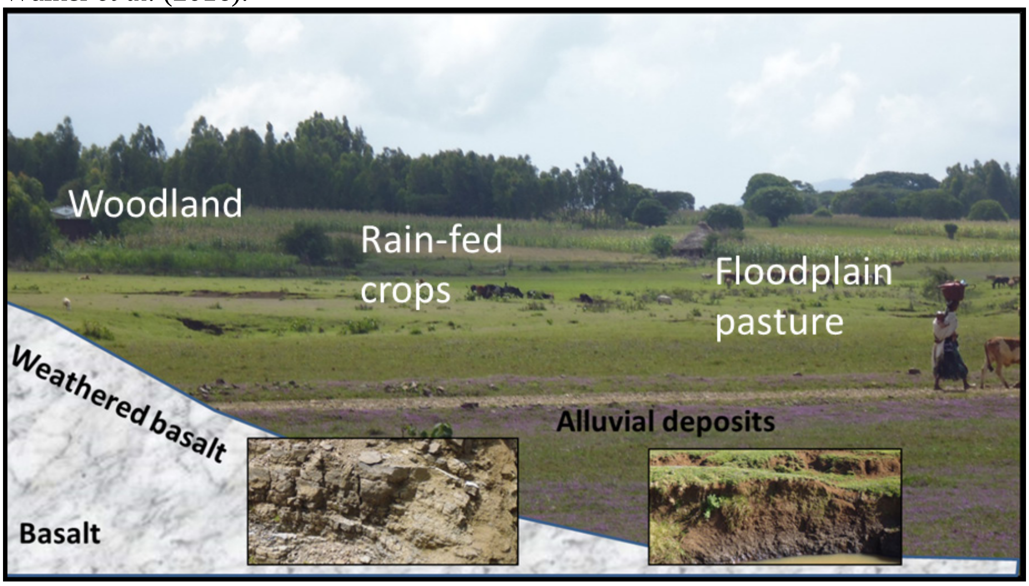

Figure 3: Shallow aquifer resources at Dangila woreda, Ethiopia

CATCHMENT MANAGEMENT IN THE UK: HALTWHISTLE BURN, NORTHUMBERLAND

The second case study focusses on community-based catchment management at a small tributary of the River Tyne catchment in the UK. Details of this study can be found at http://research.ncl.ac.uk/haltwhistleburn. Although wider issues of catchment management were addressed (see general review written for use by local communities, which has had over 8,000 downloads; Starkey and Parkin, 2015), the main concern of the community was on flood protection. A range of types of monitoring of different complexities were developed, with toolkits including simple monitoring guidance cards, and their utility for different types of community members assessed. In this case, the community-based rainfall monitoring captured a localised convective storm event that was not recorded by the formal monitoring network, and the benefit of having this additional localised information was demonstrated through a spatial modelling study (Starkey *et al.*, 2017). Natural flood management (NFM) interventions have subsequently been designed and built in the catchment.

CHALLENGES AND FUTURE PROSPECTS FOR CITIZEN HYDROGEOLOGISTS

There are relatively few examples of citizen science studies related to groundwater or hydrogeology, compared to those related to weather or catchment hydrology. Some short-term studies explore the potential for community involvement in groundwater monitoring. For example, Manda and Allen (2016) ran a 10-week project at a coastal community in the USA in which members of the public monitored groundwater levels in the context of coastal flood risk. The study assessed the data quality which was found to be good in comparison to data loggers, and how participants benefitted through improved understanding of environmental issues. Longer term monitoring is more challenging to establish and maintain, although some examples are emerging of more sustained data collection (e.g. Little *et al*., 2016).

There are current potential opportunities to achieve multiple benefits in wider engagement of the general public in hydrology and hydrogeology. The benefits include improved understanding of a community's local environment, helping them to contribute to a range of aspects of land and water management, as well as building a wider base of information to contribute to wider science understanding, for example of the impacts of land use changes such as natural flood management, and climate change.

To realise this potential, a number of issues must be addressed. A summary of key issues is given in Table 1. Many of these are inter-related; for example, one of the key requirements to ensure continued motivation is to feedback information from the monitoring to the observers on a regular basis, to provide data and interpretations that are relevant and useful to the local community, but also simply to let the observers know that their data are useful and being used. While some of these issues are being addressed separately in some projects, an integrated strategy would ensure that a shift towards a more shared approach to monitoring and understanding our environment can be achieved, providing routes towards empowering local communities in environmental decision-making.

ACKNOWLEDGEMENTS

This paper is supported by research from a number of colleagues and PhD students, partner organisations including International Water Management Institute (IWMI), Tyne Rivers Trust and others, as well as local community members without which the work would not have been possible. The author is particularly grateful for the support of John Gowing, Eleanor Starkey, David Walker, Alemseged Haile, and members of public at Dangila woreda, Ethiopia and Haltwhistle, UK.

Table 1: Summary of key issues – a framework for successful citizen hydroscience

	Issue	Potential benefits	Steps to realise benefits
Community perspectives	Motivation	Maintain long-term sustainable monitoring with high quality data	Identify motivation of different community members; ensure data collection fits with interests, capabilities, and time available for different groups
	Cost	Low or minimal costs to observers of equipment and time enables more data to be collected efficiently	Develop and make available improved low-cost technology; implement appropriate funding sources or payment mechanisms
	Education	Improved understanding of environmental processes by communities, leading to better management	Provide appropriate information through knowledge translators, and easy-to-use guidance documents on monitoring protocols
	Information	Regular feedback supports motivation and understanding, leading to improved environmental management	Provide regular (real-time if possible) access to data, open access to interpretations, using clear visualisations
Data considerations	Data quality	High quality data is required for wider science applications; lower quality may be suitable for local understanding	Implement standard data quality control protocols, both by observers themselves if possible, and by professionals or trained intermediaries
	Duration and frequency	Short-term projects or event monitoring supports local understanding; long-term monitoring supports wider science development	Clear statement of objectives of monitoring, and protocols; monitoring designed to achieve specific objectives
	Storage, access and ownership	Open access supports full use of data for multiple purposes	Central online open-access storage of data, maintained and funded by an established organisation; clear arrangements for ownership, e.g. through open source licensing
	Interpretation and use	Indigenous interpretations by communities support local understanding; professional interpretation and modelling puts information into wider context	Develop user-friendly toolkits to help communities to interpret their data; use appropriate methods for integration of different types of data and levels of uncertainty in models

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SESSION II

SATELLITE FLOOD MAPPING: NEW APPROACHES FOR MONITORING AND MAPPING GROUNDWATER FLOODING IN IRELAND

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ABSTRACT

Mapping how floodwaters develop and recede accurately is critical for effective flood risk management. However, unprecedented groundwater flood events in recent years have highlighted the need for improved mapping methodologies for this complex geohazard. Little or no hydrometric data of groundwater flooding was collected during the recent flood events. In response to this, Geological Survey Ireland initiated the GWFlood programme to address the data shortfall, particularly in relation to flooding at turloughs. GSI, in collaboration with University of Dublin Trinity College, is using traditional field measurement methods to observe turlough flooding and is also developing advanced remote sensing methods to observe flood events both future and past.

While a monitoring network of over 60 temporary sites was established over the winter of 2016/2017 to rapidly increase hydrometric data in-take (a selection of which will be permanent telemetric status), there remains a significant amount of un-monitored groundwater flood hazard sites. For these sites, Earth Observation data from the Sentinel satellite programme (European Space Agency) is being used to generate high-resolution flood extent mapping and also provide near real-time flood monitoring. This EO mapping is being carried out at a catchment scale and will contribute to the revised national groundwater flood map being developed by GSI for the OPW as part of the second implementation cycle of the EU Floods Directive. Furthermore, time series of Synthetic Aperture Radar (SAR) images are being combined with high resolution topography to construct hydrographs for priority sites affected by groundwater flooding. These new data will improve the fundamental hydrological understanding of groundwater flooding in Ireland, enabling key stakeholders to develop appropriate flood mitigation measures and allow for informed flood assessments to be made in future.

INTRODUCTION

The winter of 2015/2016 saw unprecedented levels of rainfall across the Republic of Ireland. Over 600mm of rainfall fell across the island of Ireland between December and February, representing 190% of the long-term average and making it the wettest winter on record in a rainfall time series stretching back to 1850 (McCarthy et al., 2016; Noone et al., 2016). The sustained heavy rainfall caused exceptional and widespread flooding, with rivers across the country bursting their banks and registering some of the highest levels on record. Winter 2015/2016 also saw the most extensive groundwater flooding ever recorded on the karstic limestone plains in the west of Ireland (Figure 1).

Groundwater flooding events in Ireland are primarily associated with the limestone areas of the western lowlands, which extend from the River Fergus in Co. Clare in the south upwards to the areas east of Lough Mask and Corrib in Co. Galway and southern Co. Mayo. The prevalence of groundwater flooding in the western counties is fundamentally linked to bedrock geology. Groundwater flow systems in these areas are characterised by high spatial heterogeneity, low storage, high diffusivity, and extensive interactions between ground and surface waters, which leaves them susceptible to groundwater flooding (Naughton et al., 2017). During intense or prolonged rainfall, the solutionally-enlarged flow paths are unable to drain recharge and available sub-surface storage rapidly reaches capacity. Consequently, surface flooding occurs in low-lying topographic depressions known as turloughs, which represent the principal form of extensive, recurrent groundwater flooding in Ireland (Mott MacDonald, 2010; Naughton et al., 2012). There are over 400 recorded examples of turloughs across the country, with the majority located in the limestone lowlands in counties Roscommon, Galway, Mayo and Clare. Due to the record breaking rainfall in the winters of 2009 and 2015, turlough flooding impacted on dozens of homes, as well as causing widespread and extended disruption to transport networks across the region.

Unlike fluvial flooding (or fluvially derived groundwater flooding due to seepage through permeable deposit riverbanks), where the flood is typically caused by high intensity rainfall, groundwater flooding in turloughs is primarily driven by cumulative rainfall over a prolonged period. It is this accumulation of water over a period of weeks or months that determines flood severity and duration. Furthermore, the long-term hydrometric data required for traditional flood frequency analysis does not exist for groundwater flooding, impeding the calculation of flood risk (combination of likelihood of an event and the damage caused by the event) as required in flood defence scheme assessments.

Figure 1: Groundwater flooding, 2016, South Galway.

GEOLOGICAL SURVEY IRELAND GROUNDWATER FLOOD PROJECT

In response to the unprecedented flood events of 2009 and 2015, the Geological Survey has initiated a new programme, GWFlood, to investigate flooding specifically related to groundwater and turloughs. The phenomenon of groundwater flooding can pose a significant flood hazard for many rural communities and its increased frequency in recent years highlights the clear need for further research into the issue of groundwater flood prediction and risk assessment in karst regions. Geological Survey Ireland, in collaboration with Trinity College Dublin has developed a monitoring, mapping and modelling programme to address the knowledge gap regarding these complex karst systems. This programme is enabling the OPW and local authorities to develop flood mitigation strategies for groundwater flooding and allow for better informed decisions regarding future groundwater flood risk management. The study is providing the requisite data to address this knowledge gap by establishing a permanent monitoring network, as well as developing analytical tools to help address issues surrounding groundwater flood mapping and flood frequency estimation.

FLOOD MONITORING NETWORK

Hydrometric data is a crucial component to understanding the dynamics of surface and groundwater flow systems. Information such as stage and discharge are recorded at gauging stations across the country in rivers, lakes, boreholes and coastlines, providing data vital to local authorities and planning agencies for effective flood risk management. However, consistent long-term hydrometric data do not exist for groundwater flooding applications. A primary objective of this project is thus to establish a monitoring network to provide key baseline data for flood risk and habitat management applications. While some turlough systems posing a flood risk, such as the Gort Lowlands, are relatively well understood, there is limited hydrogeological knowledge on most Irish karst groundwater flow systems.

The project commenced in September 2016 and to date over 60 exploratory monitoring stations have been installed in counties Galway, Clare, Mayo, Roscommon and Longford (Figure 2). Data from these sites are helping to develop a preliminary understanding of the hydrodynamics and flooding potential of turlough systems across key catchments, and inform the site selection process for the permanent monitoring network. A subset of 20 sites representative of the spectrum of groundwater flooding conditions in Ireland is being established as permanent telemetered stations providing real-time information on groundwater flood conditions. The installation of pilot permanent monitoring stations commenced during summer 2017 and the remaining sites will be installed throughout the summers of 2018 and 2019.

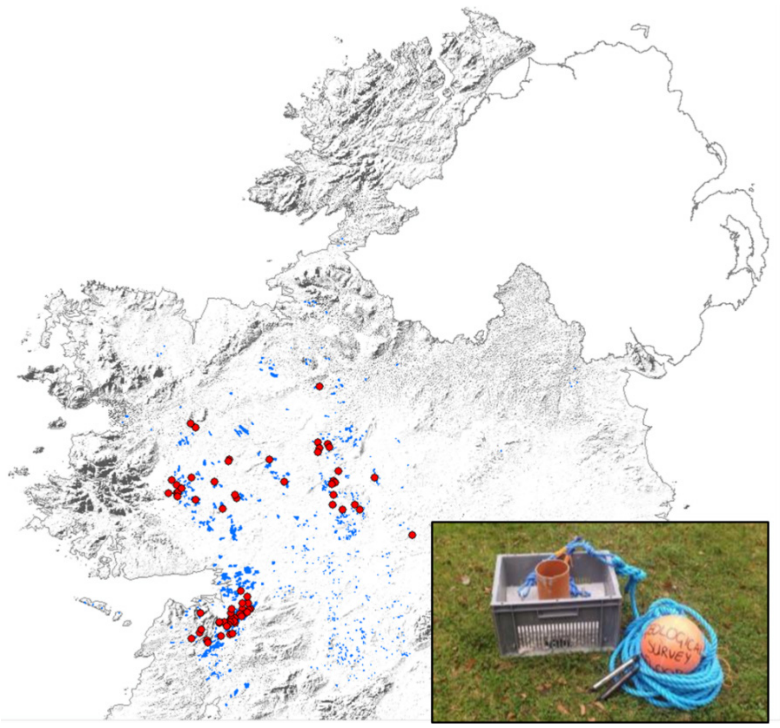


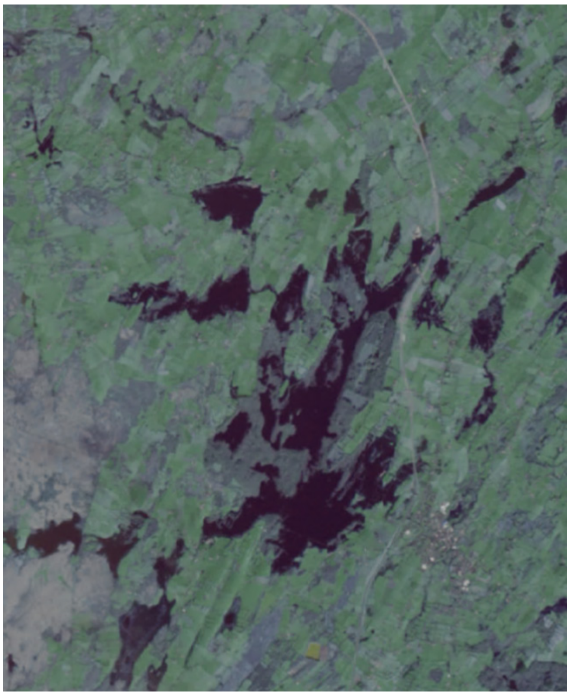
Figure 2: GWFlood Turlough Monitoring Network (red) overlaid on groundwater flood hazard sites (blue) (Mott MacDonald, 2010). Inset: exploratory network monitoring equipment.

FLOOD MONITORING AND MAPPING USING EARTH OBSERVATION DATA

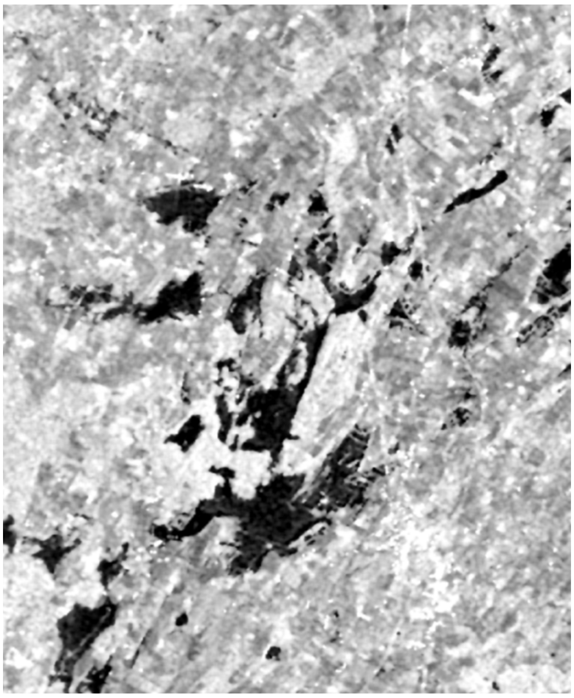
While traditional monitoring is an effective tool at priority sites, the distributed nature of groundwater flooding in karst lowlands hampers any systematic monitoring efforts. Floods tend to occur in isolated basins across the landscape and so would require an impractical amount of field monitoring to provide a complete picture. Earth Observation and Geographical Information System approaches offer significant advantages in this respect. Passive satellite imagery, such as the USGS Landsat or ESA Sentinel-2 programmes, can be used to image and delineate floods at a catchment scale (Figure 3). In the case of Landsat, a long historical archive of images also allows the observation of past flood conditions and provides some data with which to validate hydrological models. However, an obvious limitation of satellite systems which require a clear view of the earth's surface is the issue of cloud cover. When cloud cover is extensive, as is often the case during winter floods, no useful data can be collected. Under these conditions active systems, such as synthetic aperture radar (SAR), are extremely useful as they are not impacted by cloud cover (or time of day).

SAR systems, such as those used by ESA Sentinel-1 satellites, emit radar pulses and record the return signal at the satellite. This strength of this signal, or backscatter, is largely dependent on surface roughness and geometry. Flat surfaces such as water operate as specular reflectors resulting in minimal backscatter signal returning to the satellite. Interpretation of SAR images involves a degree of ambiguity due to factors such as speckle effects and dielectric properties but overall SAR systems offer a powerful tool for water delineation.

An additional benefit of SAR is the frequency of image capture; the ESA Sentinel-1 satellites achieve a global coverage cycle every six days. Within this time period the satellites orbits over Ireland multiple times with large overlapping image swathes. As such, a new image of any location in Ireland is typically available at least every 2-3 days. While this revisit time may be inadequate for observing flash floods, which can appear and dissipate within hours, it is suitable for monitoring groundwater flooding which occurs at a much slower rate. Groundwater floods typically appear and recede over a timescale of weeks to months. Thus the considerable catalogue of Sentinel-1 imagery available has allows the tracking of groundwater flood development through time, increasing our understanding of this complex flood form at scale which would otherwise not have been possible by conventional means.



(A): Landsat-8 imagery of flooding near Gort, February 2016.



(B) Sentinel-1 SAR imagery of flooding near Gort, February 2016.

Figure 3: Landsat-8 and Sentinel-1 comparison imagery of flooding near Gort Town, February 2016.

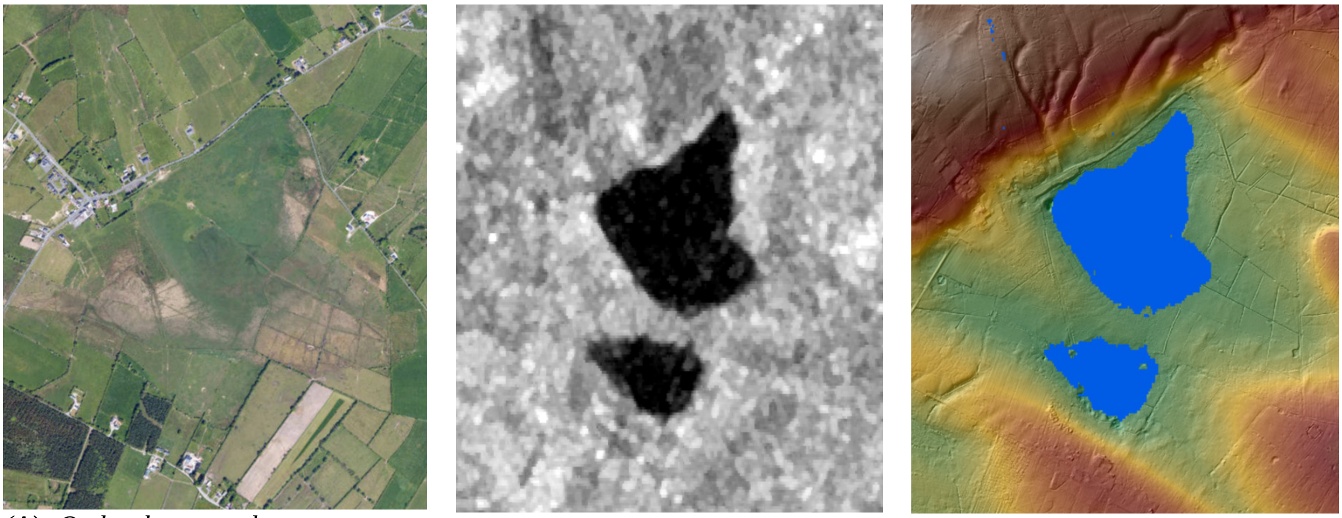
Numerous studies have demonstrated the efficacy of delineating water bodies using SAR remotely-sensed data (Chini et al., 2017; Martinis et al., 2015; Matgen et al., 2011). Similar image processing techniques are being trialled and developed under the GWFlood project to optimise detection of groundwater flood extents from SAR data. By combining satellite derived flood extents with high resolution topographic mapping, it is possible to extract water level information from each satellite image. This methodology enhances the accuracy of once-off flood extent maps as well as enabling the generation of historic flood hydrographs for previously unmonitored sites. This flood mapping methodology consists of five broad stages as described below:

1. Data acquisition and pre-processing

Sentinel 1 Ground Range Detected (GRD) data is downloaded in batch via API from ESA Copernicus Open Access Hub and run through a series of pre-processing steps. These steps include slice assembly, border noise removal, thermal noise removal, radiometric calibration, terrain correction, co-registration and speckle filtering. Once pre-processing is complete, the images are then exported into GIS software for flood delineation.

2. Flood delineation.

Several methodologies exist to delineate water from SAR imagery. These include visual interpretation (Brivio et al., 2002), histogram thresholding (Matgen et al., 2011), supervised classification (Pulvirenti et al., 2011), change detection (Rémi and Hervé, 2007) and various image texture algorithms (Schumann et al., 2010). In general, delineation accuracy is improved with increased complexity and greater user interaction (and thus a degree of unrepeatable ambiguity). The process under development for turlough water delineation however is intended to be near fully automated, and as such, the delineation method chosen will be as unsupervised as possible (with minimum errors). Currently, the most appropriate method under consideration is a combined process of histogram thresholding and change detection. The end result of this process is a classification for each pixel identifying whether the pixel represents flooded or non-flooded conditions (Figure 4).

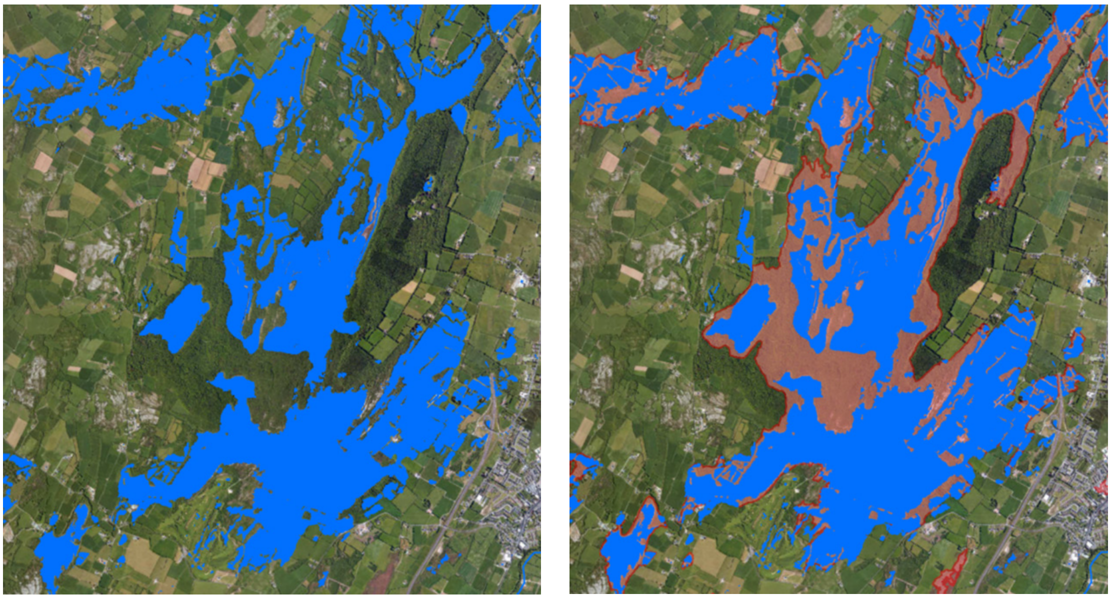


(A): Orthophotography *(B): SAR imagery, March 2017* *(B): Flood delineation, March 2017*

Figure 4: Imagery of Castleplunket Turlough Co. Roscommon showing orthophotography of it empty (A), pre-processed SAR imagery of it flooded (B) and a flood delineation overlaid on LiDAR data (C)

3. Image filtering & correction.

The interpretation of SAR imagery is subject to a level of ambiguity due to a number of inherent factors such as radar shadow on leeward hillsides or geometric distortion caused by trees/forestry. This ambiguity can often result in misclassification of which pixels are flooded and which ones are not (i.e. false negative and false positive results). For instance, Figure 5 demonstrates the underestimation of flood extent surrounding Coole Turlough (Co. Galway) in January 2016 due to false negative pixels. In order to avoid source of error such as this, images are filtered to remove areas likely to cause such false results before further processing.



(A): SAR delineated flood only (forestry obscures some flooding). *(B): SAR delineation and actual flood extent.*

Figure 5: Comparison of SAR delineated flood extent vs. actual flood extent, Coole Turlough, Co. Galway, January 2016.

4. Application of topography

After filtering out likely errors, the delineated flood extent is cross referenced with a high resolution digital topography map (DTM) to provide contextual information. This methodology benefits from the fact that turlough flooding typically occurs in enclosed, isolated basins. As a result, and unlike river flooding scenarios, the water surface is usually flat. In theory, this means that every pixel along the flood boundary should have the same elevation on the DTM. However due to a range of factors (particularly DTM resolution) the elevation values of pixels along the land-flood interface is inconsistent. As such, statistical analysis is preformed to establish the most probable land-flood interface elevation value. When this probable flood elevation value is calculated, the flood boundary can subsequently be remapped based on the given elevation value's contour produced from the DTM.

5. Map and hydrograph generation

With the pre-processing, delineation, filtering and DTM application stages complete, a flood map for a given time is generated. For sites with suitable size and topography characteristics the process can be repeated for every satellite orbit which enables the generation of dynamic flood mapping and hydrographs. Preliminary results of this hydrograph generation process are promising; however, the delineated flood levels tend to be underestimated at higher elevations (Figure 6) and work is on-going to minimise this error and automate the delineation methodology. This is being accomplished using the data records from the monitoring network which enables the delineation method to be calibrated and validated. Once the calibrated SAR generated hydrometric records are available, they will be used in the development of hydrological models to enable probabilistic groundwater flood mapping.

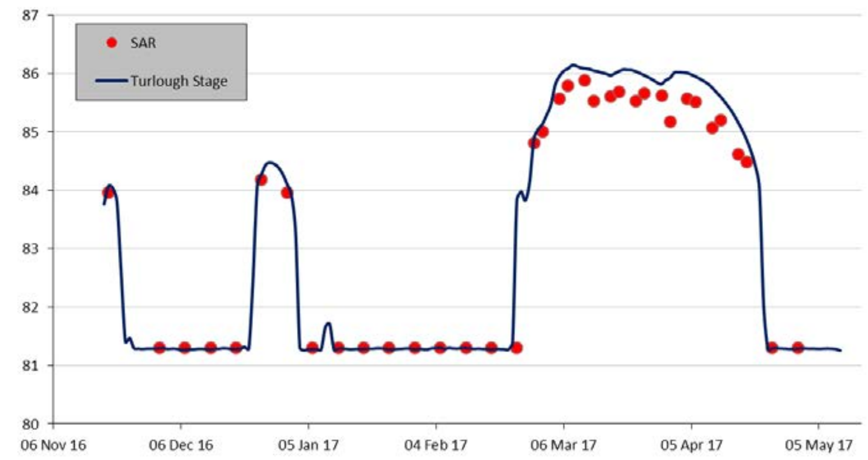


Figure 6: Comparison of directly observed water levels vs. SAR generated water levels at Castleplunket turlough, Co. Roscommon.

SUMMARY

The increased frequency, damage and disruption caused by turlough flood events in recent years has highlighted the clear need for further research of groundwater flooding and increased monitoring efforts. Remedying this lack of current monitoring poses significant technical challenges as groundwater flooding tends to occurs in isolated basins across the landscape. The large number and wide distribution of these basins makes them impractical to systematically monitor using traditional field instrumentation. While priority sites are being monitored using traditional methods, the availability of Copernicus EO data represents a practical and cost-effective alternative for the un-monitored locations. Critical flood data can now be gathered at a scale that was previously thought unachievable, and provided to relevant regional authorities and local communities in a timely manner. By developing this mapping methodology, the GSI GWFlood programme will provide the necessary high-quality data, mapping and analysis techniques required to inform future planning decisions, and so help to ensure the sustainability of vulnerable rural communities affected by groundwater flooding as well as the turlough habitats themselves.

ACKNOWLEDGEMENTS

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MODELLING GROUNDWATER FLOODING. A UNIQUE CHALLENGE REQUIRING A NOVEL SOLUTION: A CASE STUDY OF SOUTH GALWAY.

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ABSTRACT

Groundwater flooding poses a significant risk in the lowland karst limestone regions of western Ireland. Extensive and damaging flood events which have occurred in recent years have highlighted the need to improve our ability to understand and quantify the frequency and mechanisms by which this flooding occurs. The timing and mechanisms by which groundwater flooding occur differ vastly from typical fluvial flooding and floods of similar magnitude can occur following very different antecedent rainfall conditions. Determining the frequency and likely reoccurrence of such flooding is therefore complex. Trinity College Dublin is investigating new and novel approaches to modelling groundwater flooding which occurs in turloughs or temporary lakes with a few to improving our overall understanding of how these systems operate. This will provide essential technical knowledge to relevant stakeholders and decision makers, enabling them to make scientifically-informed decisions regarding groundwater flood mitigation and prevention.

INTRODUCTION

Groundwater flooding events in Ireland predominantly occur within the lowland limestone areas of the west of the country. This flooding is inherently linked to the underlying bedrock geology. Extensive interactions between ground and surface waters are predominant with sinking and rising rivers/streams common with surface water features absent completely in many areas. The dominant drainage path for many catchments is via bedrock through the karstified limestone bedrock, however during intense or prolonged rainfall the fractures or conduits within the limestone are unable to drain recharge and with storage within the bedrock limited, the result is surcharging of groundwater above the surface. This flood water is usually contained within low-lying topographic depressions known as turloughs, which represent the principal form of extensive, recurrent groundwater flooding in Ireland (Naughton et al., 2017).

The dramatic nature of the flooding associated with these turloughs has led to considerable groundwater flooding events in recent years beyond their established upper seasonal boundaries following exceptional rainfall events, causing considerable damage and disruption. An extreme groundwater flooding event took place in the study catchment during the winter of 2015/2016; this represented the most extensive groundwater flooding ever recorded. A number of homes and farmyards were flooded with extensive damage caused by floodwaters. The nature of groundwater flooding gives rise to lands being inundated for extended periods of time in the order of many months and during the 2015/2016 flood, many homes and farms were cut off for extended periods of time due to roads becoming impassable – see Figure 1 below. Large areas of farmland were flooded impacting on agricultural activity and causing livestock welfare concerns. Whilst the study catchment contains numerous turloughs (temporary lakes) which ordinarily flood on an annual basis due to winter rainfall and groundwater levels, these turloughs exceeded their established maximum bounds and overflowed their natural basins in dramatic fashion often joining together to form enormous swathes of inundated lands covering many square kilometres.

Figure 1 – Flooding of roads and agricultural land with homes threatened are common in the lowlands of south Galway (Image Source: Galway Co. Co. & OPW)

Following the flooding evens of 2015/2016, the Geological Survey and the University of Dublin Trinity College collaborated on a new project to investigate flooding specifically related to groundwater and turloughs. This project, titled GWFlood, is monitoring, mapping and modelling groundwater floods to address the obvious knowledge gap which existed. Trinity College is studying one particular catchment in significant detail. The study catchment covers an area of approximately 500 km^2 in south Co. Galway and receives allogenic recharge through runoff from adjacent mountains and autogenic recharge from rainfall over the catchment. The entire catchment drains to a number of intertidal springs at Kinvara Bay via the karst limestone bedrock. During periods of sustained rainfall, the underground karst conduit system surcharges through a system of estavelles and floods low lying basins causing ephemeral lakes known as turloughs. These turloughs provide additional storage of groundwater not available within the limestone bedrock and thus act as a form of naturally occurring management mechanism for groundwater flooding. The catchment is unique as the natural flow system has not been heavily altered by land reclamation or arterial drainage schemes and has therefore been relatively unimpacted by human activities. The associated seasonal inundation cycle has led to the development of unique ecology within the normal upper and lower bounds of flooding providing a habitat for many floral and faunal species of national and international importance; many of these areas are therefore protected within the European Natura Network.

GROUNDWATER FLOODING – A UNIQUE CHALLENGE

Whilst one of the key objectives of this project is to model groundwater flooding – with TCD specifically focused on the turloughs of south Galway; the inherent difficulty in understanding and quantifying the conditions which give rise to extreme groundwater flood events must first be addressed. Areas flooded during an extreme groundwater flooding event stay inundated far longer and are spatially far more extensive when compared with typical fluvial flooding. There are four extreme groundwater flooding events recorded within the past 30 years in south Galway. These flood events occurred in the winters of 1989/1990, 1993/1994, 2009/2010 and 2015/2016. Cumulative rainfall and daily rainfall intensity plots for the preceding 365 days prior to each of the groundwater flood events are shown in Figure 2 below. It can be seen that whilst the cumulative rainfall quantities occurring prior to each event are comparable, ranging between 1,950mm – 2,195mm, the pattern in which this occurred visibly differs leading to a broad range of rainfall intensities in the preceding months. For example, the flooding which occurred between February and March of 1990 took place under the backdrop of what was described as being the wettest February on record (Met Eireann, 1992) with 3.6 times the normal rainfall for the month of February observed. The lands inundated with water extended to over 15.7km^2 and remained inundated for over two months between the end of January and early April 1990 (GSI, 1992). During this period the maximum water level at Blackrock turlough near Gort in Co. Galway was reported as being 30.45mOD (OPW, 1994). In comparison the flooding which subsequently occurred in 1994 was preceded by very different antecedent conditions. It is reported that between December 1993 and March 1994, 293mm more rain fell compared to all records for the same period. During this flood event the maximum level recorded at Blackrock turlough near Gort in Co. Galway was reported as being 28.26mOD (OPW, 1994), however the period of inundation of lands was far longer extending over 5 months from January to May 1994. The lands inundated during this flood event were estimated to be over 13.22km^2.

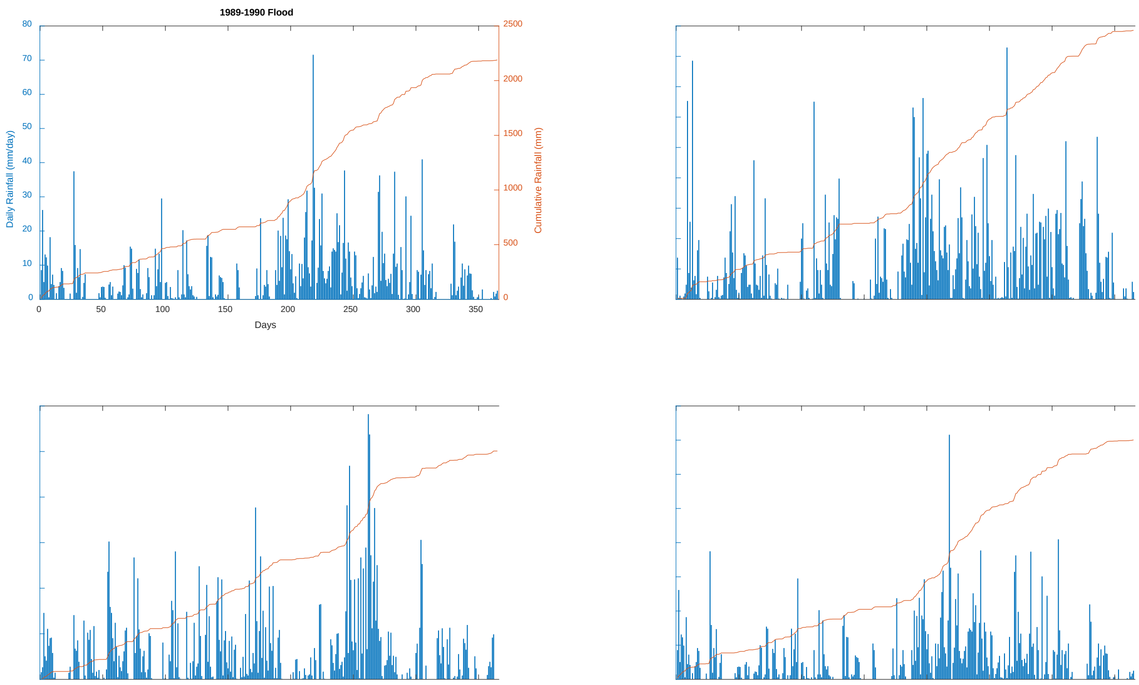

Figure 2 - Plot of daily rainfall intensity and cumulative rainfall totals for the previous 4 major flooding events in the south Galway lowlands

The complexity of the nature of groundwater flooding is demonstrated with a comparison of the flooding which occurred in February 1990 with the rainfall profile for the same period in 2014. It was reported that the extensive flooding which occurred in 1990 was due to the “exceptionally heavy rainfall which occurred in the months of January and February 1990” (GSI, 1992). As stated above, the 287mm of rainfall which occurred at Derrybrien rainfall station was the wettest February on record and combined with the total for January resulted in 454mm cumulative rainfall. Total rainfall for the month of February in 2014 was 285mm, almost identical to the total for February 1990. In addition, the total cumulative rainfall for January and February 2014 was 540mm exceeding the total for the same period in 1990. However, the level and scale of flooding which occurred in February 1990 did not occur in February 2014. This demonstrates the complexity of the underlying karst system which ultimately determines the level of flooding which occurs.

A number of consecutive research projects undertaken in Trinity College Dublin, have involved the installation of pressure transducers to record turlough stage (water level) at a number of turloughs in south Co. Galway (Gill et al., 2013; McCormack et al., 2014). In order to further demonstrate the complexity in understanding and ultimately modelling/predicting groundwater flooding and flood frequency, a more detailed analysis and comparison of the two most recent extreme flooding events in south Galway is presented below. The data presented relate to Blackrock turlough which is located near Gort in south Co. Galway. The Owenshree River flows into a swallow hole at the base of Blackrock turlough which surcharges during high flow conditions creating an ephemeral lake. Figures 3 & 4 below present daily rainfall intensities, discharge data for the River Owenshree upstream of

Blackrock turlough, stage (water level) within the turlough and the flooded volume of the basin and surrounding lands.

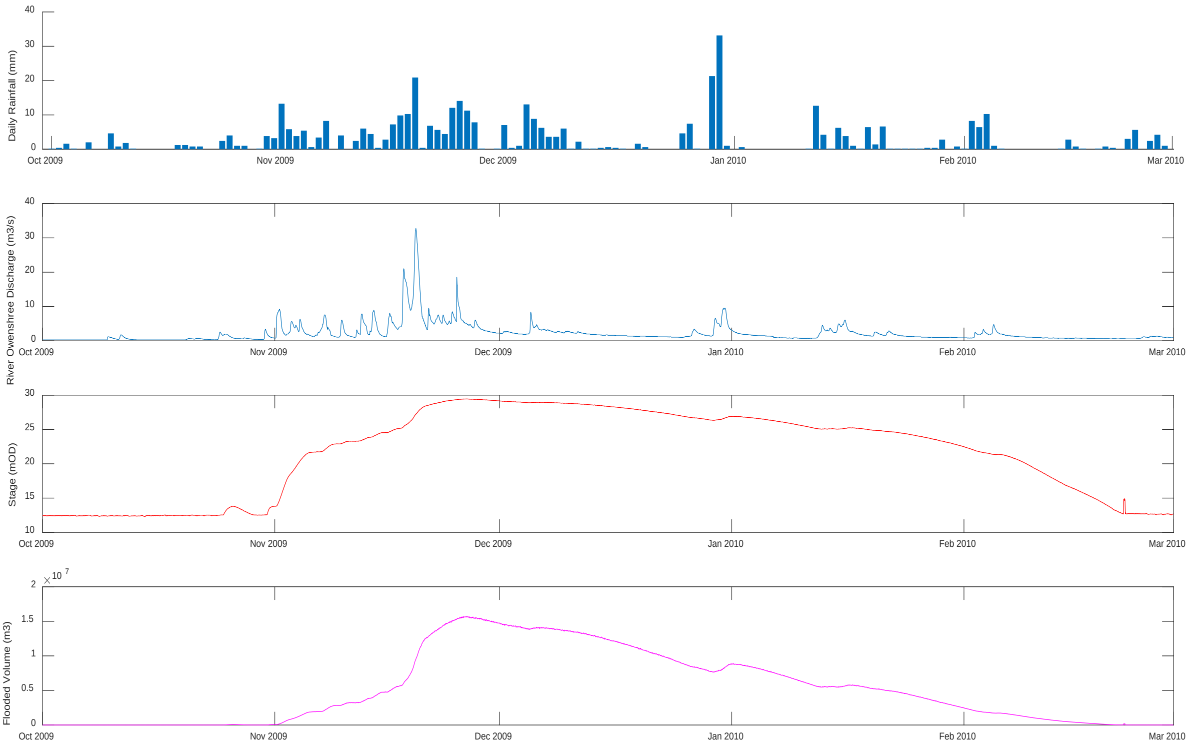

Figure 3 – Data relating to Blackrock Turlough during the 2009/10 flood event

Examining the period between October 1st 2009, when the water level in the turlough was 12.44mOD (essentially empty) and November 29th 2009 when the water level in the turlough reached its maximum level of 29.45mOD (an increase of 17.01m), the following statistics were observed:

- A total of 183mm of rainfall fall between 1st October 2009 and the 29th of November 2009.
- The flooding event in the turlough began on the 30th of October 2009 and it then took 30 days for the maximum water level to be reached.
- The turlough remained flooded for 85 days and did fully not empty until the 22nd of February 2010
- The water level was above 25mOD for a total of 63 days.
- Once the maximum water level was reached a further 223mm of rainfall occurred.
- The month of November 2009 was recorded as being the wettest November on record, but no single storm event with a return period of greater than 50 years (0.2% AEP) occurred.

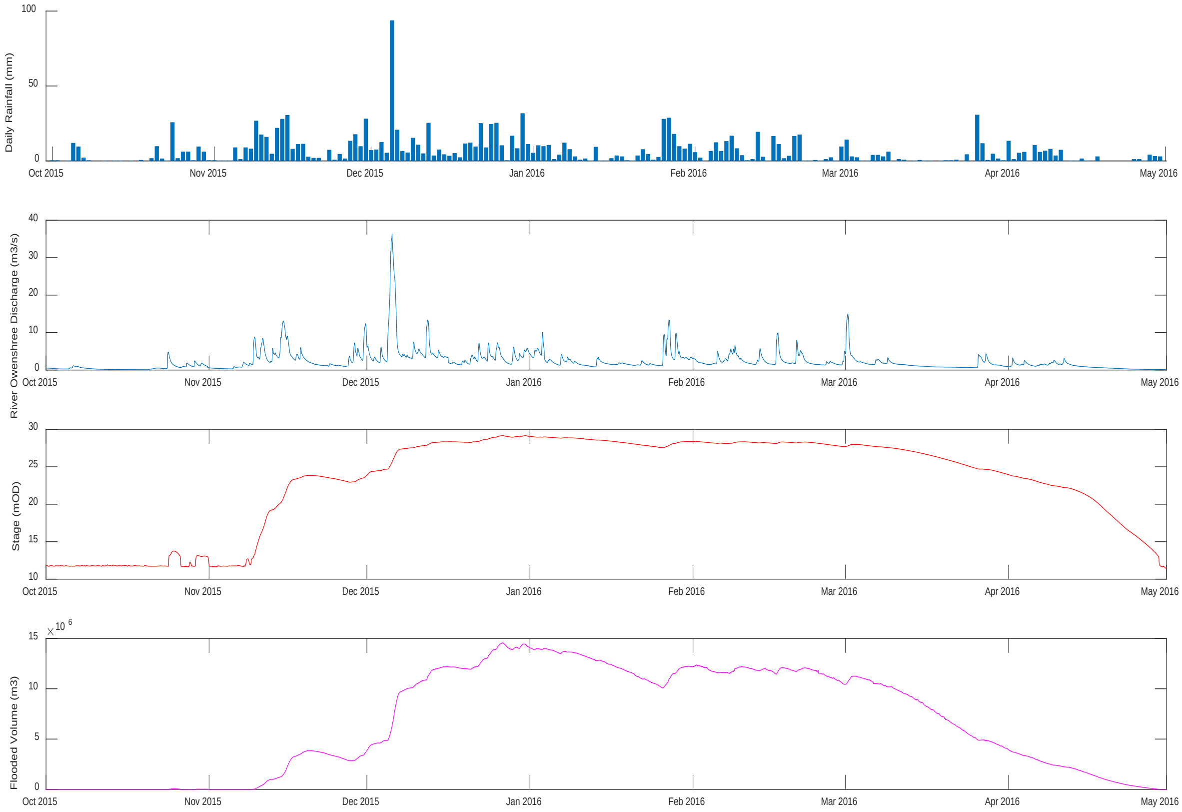

Figure 4 – Data relating to Blackrock Turlough during the 2015/16 flood event

Examining the period between October 1st 2015, when the water level in the turlough was 11.87mOD (essentially empty) and December 26th 2015 when the water level in the turlough reached its maximum level of 29.15mOD (an increase of 17.28m), the following statistics were observed:

- A total of 761mm of rainfall fall between 1st October 2015 and the 26th of December 2015.
- The flooding event in the turlough began on the 8th of November 2015 and it then took 48 days for the maximum water level to be reached.
- The turlough remained flooded for 125 days after the December 26th 2015 and did fully not empty until the 29th of April 2016
- The water level was above 25mOD for a total of 110 days.
- Once the maximum water level was reached a further 643mm of rainfall occurred.
- The month of December 2015 included Storm Desmond which brought 99mm of rainfall in a 48hour period (4th & 5th December 2015); Storm Eva which brought 25mm of rainfall in a 24hour period (23rd December 2015) and Storm Frank which brought a further 40mm of rainfall in a 48hour period (29th and 30th December 2015) (Met Éireann; 2016).
- Return periods for each of these individual storm events have been estimated at 100years+ for Storm Desmond, 3years for Storm Eva and 5years for Storm Frank however the 3 and 4 month rainfall accumulations within the November 2015 – February 2016 period have been estimated to have return periods of far in excess of 100 years (Baker et al., 2016).

Given that the two flood events which occurred in 2009 and 2015 resulted in similar flood levels but very different flood durations and happened following very different antecedent rainfall conditions – the process of determining the frequency and likely reoccurrence of such flooding is extremely complex

GROUNDWATER FLOOD MODELLING: A NOVEL APPROACH

A number of different deterministic (or global) modelling approaches have been attempted to simulate karst aquifers. Simple black box models containing no spatial information on the karst aquifer have had some success predicting spring discharge using a simple transfer function. More complex deterministic models have been utilised in modelling karst systems which attempt to account for the non-linearity and heterogeneity of the system inputs over time. Another approach is to build a distributive model which uses theoretical concepts such as simplified aquifer geometry and hydrodynamic flow equations to simulate the hydraulic behaviour of karst aquifers. Applying either modelling approach to groundwater flooding in Ireland is extremely difficult due to the lack of historical data available and lack of data relating to the nature and response of inputs to the system such as flow within the epikarst. Furthermore, in the case of the study catchment, the inability to measure the discharge rate from the system at the intertidal springs leads to further difficulty in validating the overall mass balance of any model. The diverse and dramatic range of responses to different antecedent rainfall demonstrated above further adds to the complexity of creating a reliable model. The lack of historical data by which to fit and validate a model is, however, the main challenge which presents itself. It is well reported that mathematical models which are created using small sample sets of data are in danger of overfitting (Hawkins, 2004). An overfit model is overly complicated and models random noise in your specific sample rather than reflecting the overall population. An overfit model will not likely fit new data due to the noise which is modelled within the original data. Figure 5 below demonstrates the difficulty in calibrating a mathematical model for turlough stage based a limited dataset.

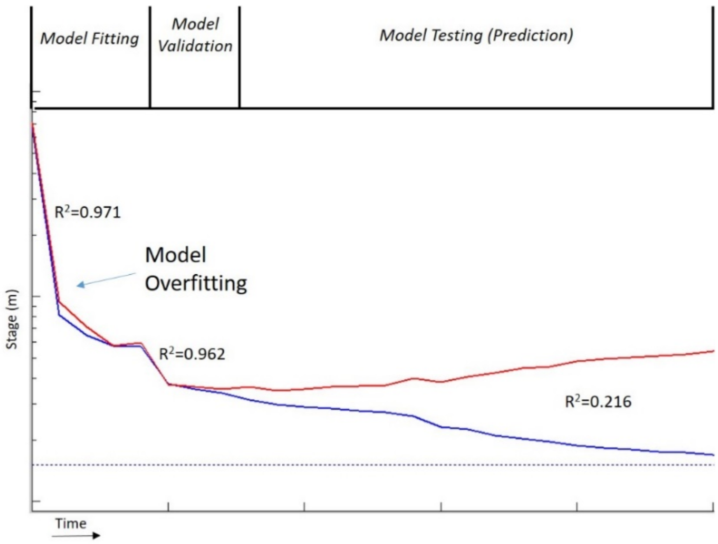

Figure 5 – Demonstration of overfitting in a mathematical whilst attempting to calibrate a model for turlough stage with a small dataset

A distributive model of the complex karst system within the Gort Lowlands has been developed at TCD (Gill et al., 2013; McCormack et al., 2014) over the past 10 years. This model uses a pipe network to simulate the groundwater-surface interactions within the karst conduit network and a series of interconnected turloughs. Karst conduits were represented as pipes with turloughs represented as ponds. The stage-volume relationship of the turloughs was determined from field surveys accurately measured using GPS surveying equipment and was input for each pond storage area. An example of the model setup is shown in Figure 6 below. The model was calibrated using historical stage data from a number of turloughs which was collected over an extended period. The model has been shown to accurately simulate stage within the turloughs which were included (Gill et al., 2013; McCormack et al., 2014). Key to the success of this approach was the conceptual model being built utilising data collected from physically measured data within the study catchment. Information on the location and connection of conduits in the karst limestone was represented within a conceptual pipe network model which is therefore a good representation of reality.

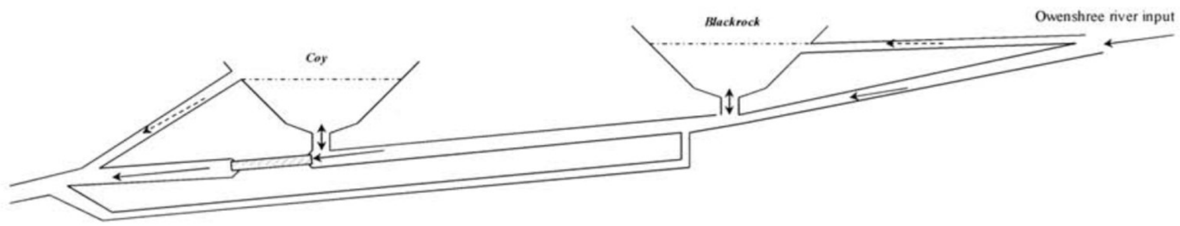

Figure 6 – Hydraulic configuration of the pipe within the model for Blackrock and Coy turloughs (Gill et al., 2013)

Currently the TCD research effort is modifying the 1D pipe network and adding links to a 2D mesh generated from high accuracy LiDAR data of the catchment allowing the flooding regime to be accurately simulated. The model is being calibrated using historical stage data from a number of turloughs with aerial photography taken during recent flood events also used to inform and define flood extents. Once the model is calibrated and validated, the next step will be to utilise the model for predictive purposes.

SUMMARY

Groundwater flooding poses a significant risk to property and agriculture causing widespread cost and disruption for long periods when it occurs. The more frequent and extreme flood events which have occurred in recent years have highlighted the need to improve our ability to understand and quantify the frequency and mechanisms by which this flooding occurs.

Understanding and indeed modelling groundwater flooding is a difficult and complex task which requires a novel solution. Trinity College Dublin is in the process of developing new and novel approaches to modelling groundwater flooding which occurs in turloughs with a few to providing essential data to inform decisions regarding groundwater flood mitigation and prevention.

ACKNOWLEDGEMENTS

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WATER TRACING: LIFTING THE LID IN THE NEALE, THE MAYO DEEL AND THE RATHCROGHAN UPLANDS

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ABSTRACT

This paper aims to highlight recent insights into three karst areas gained from water tracing studies used investigate their groundwater characteristics for different reasons. Karstified limestone regions in Ireland are important resources for water and flora and fauna. Owing to their inherent properties, karst areas provide many management challenges across large geographic areas that involve a range of different stakeholders. Some of the recurring challenges are around water provision and protection and flood management.

INTRODUCTION

In the west of Ireland, where karstified limestone is the predominant bedrock type, the hydro(geo)logy is complex and particularly so in the low-lying portions of the landscape. Due to the combination of a temperate climate and a low-lying glacio-karst terrain, there are numerous and ever-evolving groundwater-surface water interactions, which can be expressed on the surface as abundant turloughs, large karst springs and relatively few natural surface water courses present.

The underground routes are often unpredictable both in location and direction of flow; can cross surface water catchment divides; and, can rapidly convey groundwater over relatively long distances.

For the experienced hydrogeologist, the challenges of managing water resources in these karst terrains are increased due to their added complexity and unpredictability beyond that of non-karst environments (which are themselves not necessarily straightforward). However, these management challenges, which may be for determining optimal flood relief options, whether it is groundwater flooding or surface water flooding; land use management; drainage; water provision and treatment; drilling boreholes; defining protection zones; conducting risk assessments; enforcing regulation; and building roads, are the responsibility of engineers (water, civils), agricultural scientists, environmental scientists, catchment scientists, ecologists, etc. For these professionals, the ‘unseen’ nature of groundwater multiplied by the ‘schizophrenic’ behaviour of karst further amplifies those challenges.

The extent and scale of such investigations into the ‘study areas’ is typically large, seemingly disproportionately expensive, and can take considerable time, often beyond that initially planned for the investigation. Nonetheless, groundwater systems need to be understood in order to successfully optimise solutions, prevent or ameliorate issues, and, to protect and enhance the water and natural environment, including flora and fauna in turloughs and other Special Areas of Conservation. One such investigation method is water-tracing (also called dye-tracing). Nothing is fool-proof in karst areas, but water-tracing that continually gives results that improves understanding and directly feeds into management options.

This paper highlights recent insights and updates that water-tracing studies have provided into three karst areas in the west of Ireland: the Neale in south Mayo; Crossmolina, north Mayo; and the

Rathcroghan Uplands, Roscommon (Figure 1). Each of these areas required investigations into the karst systems for different reasons, which are outlined in the case studies.

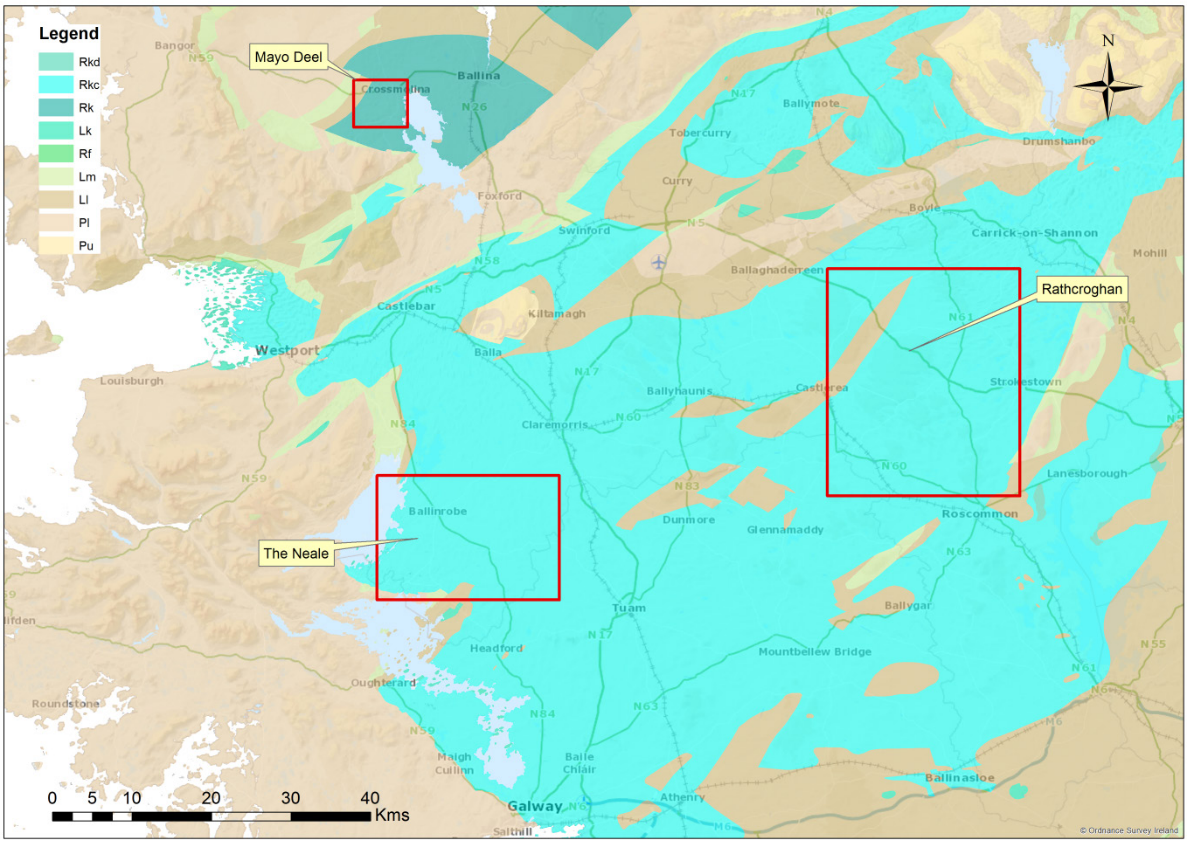

Figure 1. Regional map showing locations of the study areas referenced in this paper: The Neale, Crossmolina and the Rathcroghan Uplands. The bedrock aquifer map is shown and the red boxes reflect the study area dimensions.

THE NEALE (SOUTH MAYO)

Geological Survey Ireland conducted a water trace in the vicinity of the Neale earlier this year, through its "GW3D" and "GWFlood" projects, in order to inform the flood relief programme being carried out under the auspices of Mayo County Council. 'The Neale', a village between Cong, Ballinrobe and Kilmaine, and located close to Lough Mask and Lough Corrib, suffered unprecedented groundwater flooding in 2015/2016.

Much work (both investigative and drainage) has previously been undertaken in this general area. Publications by Coxon (1986) and Drew & Daly (1993) include *natural* hydrological feature maps (Figure 2). At first glance, the natural surface hydrological features do not suggest much hydrological connectivity across the area *i.e.* no rivers and a smattering of isolated lakes.

The regional drainage in this area has been significantly modified for land use (drainage), flood alleviation and navigation purposes. Most notable changes include the installation of the Cross River, which is routed *via* turloughs between Kilmaine and Cross; the Cong Canal, channelled from Lough Mask to Cong; the Bulkaun River which links springs near Ballinrobe to the Robe River; the Hollymount River connecting a series of turloughs to the Robe River; and, a channel from Carras Lough to the Black River in the eastern part of the area (Figure 3).

For various reasons, this karst region has been extensively studied by several authors[1] over the last 20/30 years and much of the understanding of the groundwater-surface water system has been revealed through water-tracing experiments and mapping and water level monitoring of c.30

[1] Include: Coxon, 1986; Drew and Daly, 1993; Kelly *et al*, 2014; Meehan and Kelly, 2011; Naughton *et al* 2012; Wilson *et al* 2013.

turloughs. The tracings reveal a great deal about the underground pathways and connections between swallow holes, both internal and external to the turloughs, and the main spring occurrences, and to the broad groundwater catchment divides.

From time to time, the turloughs exceed their 'normal' water level ranges and, as with other flood-prone areas, flood roads and disrupt community life and business. The Neale is an example of one of the worst situations where its environs have been completely isolated due to the surrounding flooded areas.

The positive tracings, including the traces from February 2018, are superimposed on the map in Figure 4. They show groundwater flow patterns converging on the main spring clusters, indicating largely discrete groundwater domains discharging to Lough Mask and Lough Corrib (Figure 4).

The tracings from February 2018 indicate peak travel times in the order of 80 m/hr to 110 m/hr and the dye flushed through relatively quickly, demonstrating the rapid responsiveness, or 'flashiness' of the system, and that conduit flow is the dominant flow mechanism. These data fit with the established data from previous tracings.

These tracings show that the catchment to the Cross Springs extends further westwards than previously thought, and supports the view (P. Johnston, personal communication, 2013) that the turloughs around Neale are hydraulically connected to the Lough Corrib. The recent tracings provide further evidence to suggest that each spring cluster has its own contributing area, which was indicated by the established tracings, but with less confidence (Figure 5). It is useful to contrast the groundwater and surface water divides with the pre-arterial drainage map (Figure 5). Additional work is required to further refine the catchment boundaries to the lakes and the springs.

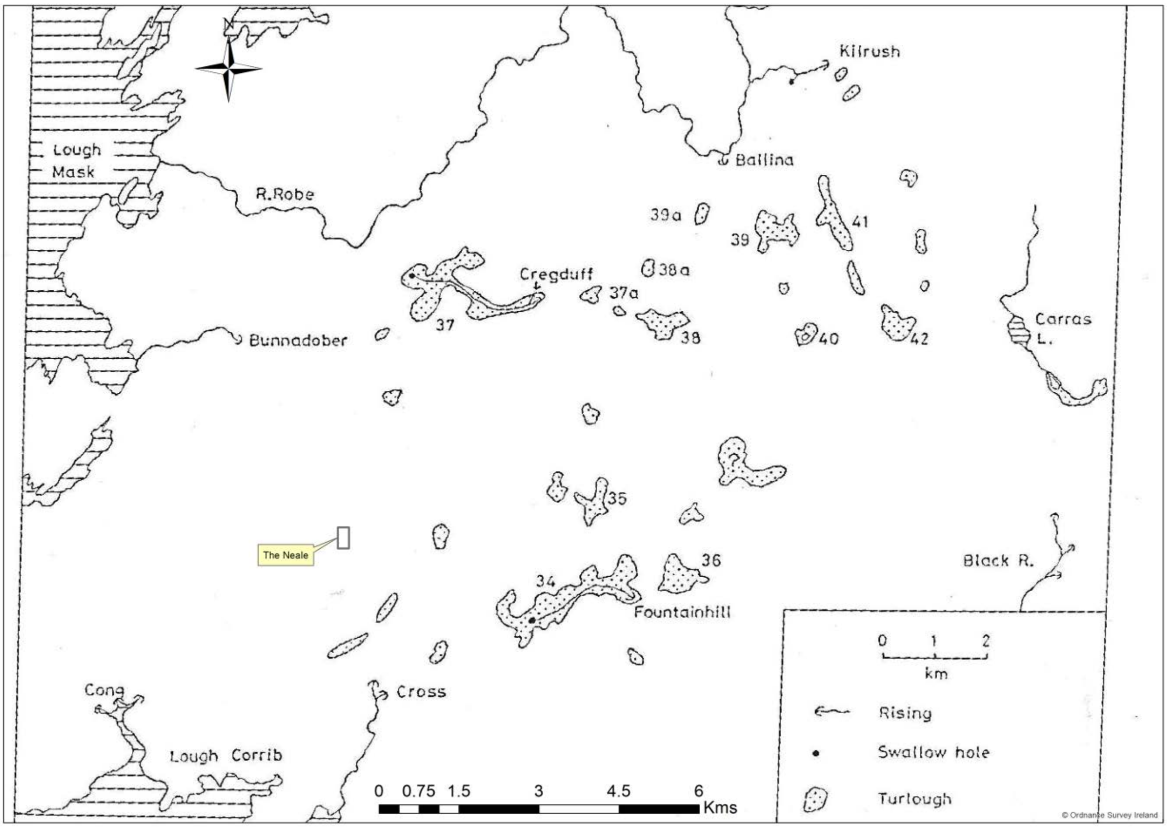

Figure 2 Pre-arterial drainage, early 19th century (after Coxon, 1986)

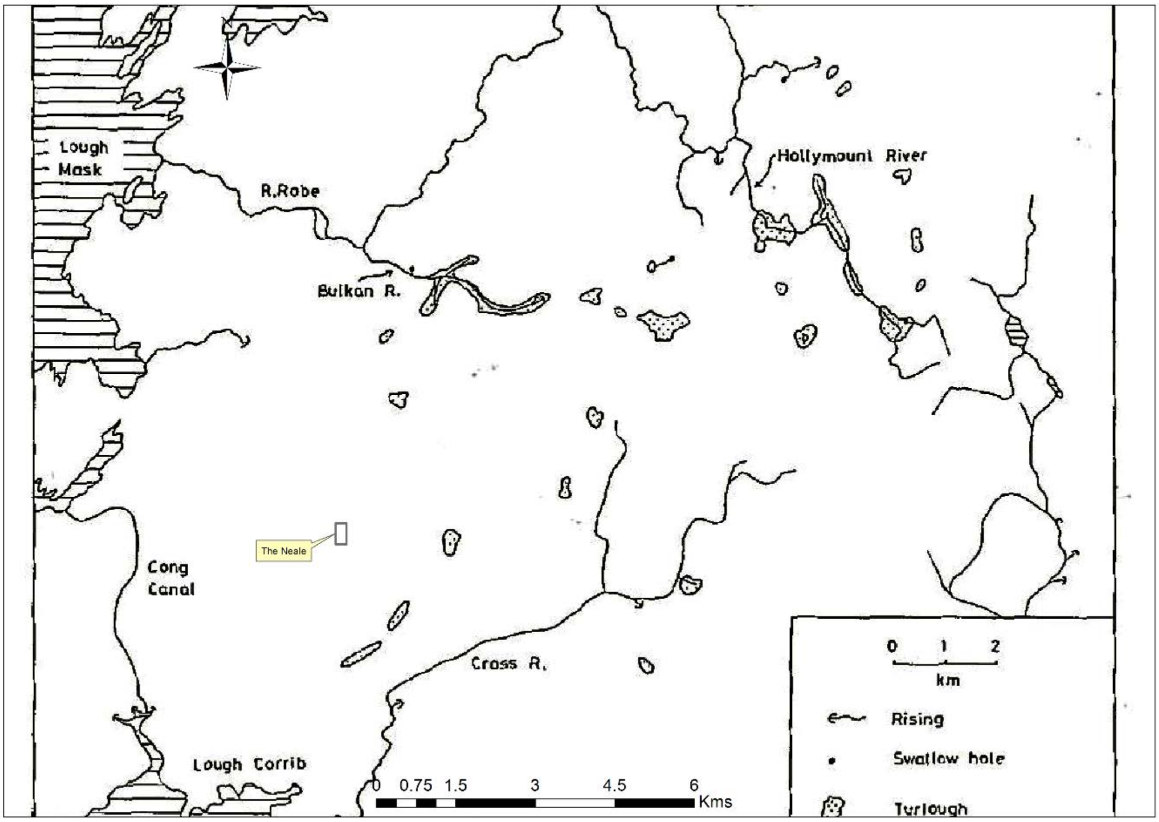

Figure 3 Post-arterial drainage, end 19th century (after Coxon, 1986).

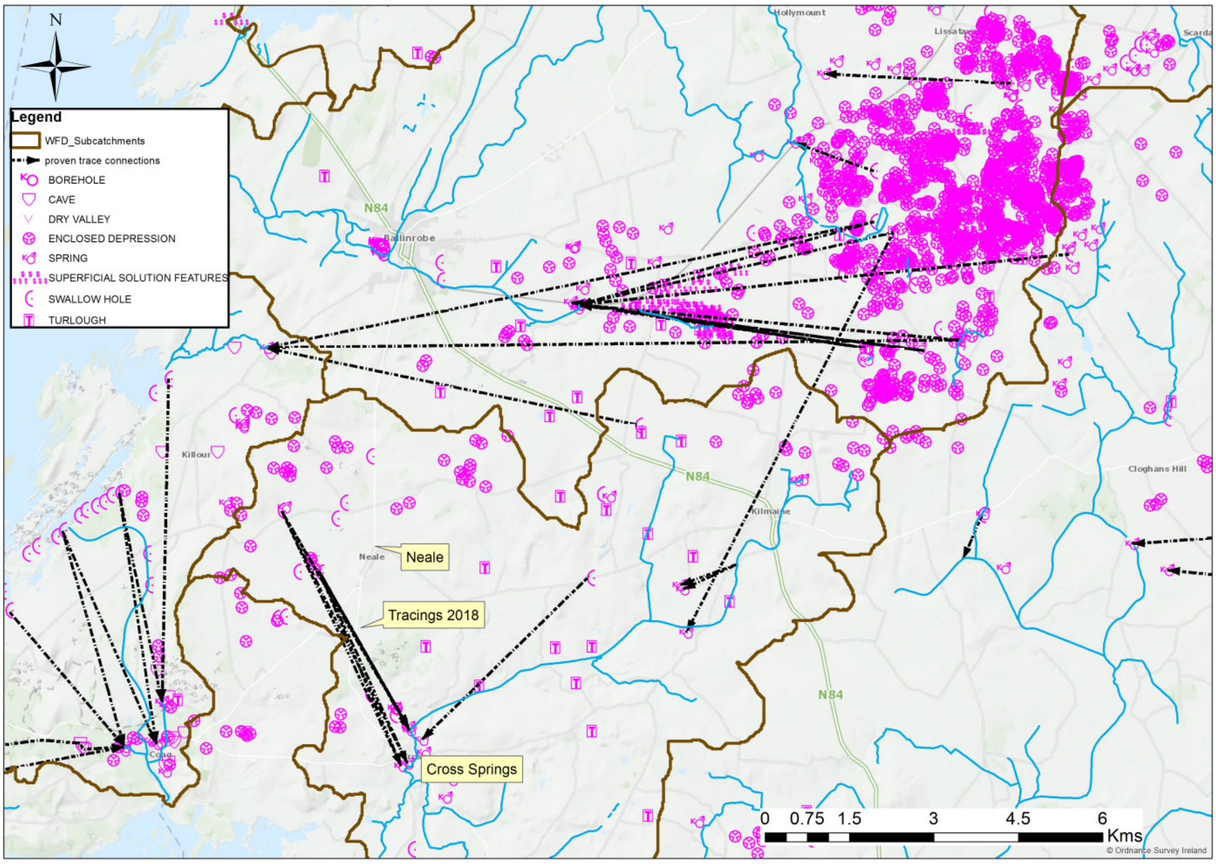

Figure 4 Established groundwater traces, surface water catchments and mapped karst features

THE MAYO DEEL, CROSSMOLINA

Crossmolina suffers from regular occurrences of fluvial flooding when the River Deel breaks its banks in the vicinity of the town. The river traverses a karstified limestone region, and investigations into the karstic aspects were required of the area. These were conducted and led by Dr. David Drew and included water tracing. The tracing results provide an insight into the characteristics of the karstified bedrock aquifer that were previously unknown.

There are several locations south of the town where river water sinks underground (Figure 5). After prolonged dry spells when the river flow is low, the entire river disappears underground. Regardless of the flow in the river, the losses underground are in the order of 800–1200 litres/sec (Drew and Duncan, 2017). The tracings show that the sinking water in the river re-emerges at two connected springs at Mullenmore, approximately 1.2 km and 2.3 km northeast of the losing river sections (Figure 5). The springs are also connected underground to the outlet of Lough Agawna, approximately 4.5 km to the southwest (Figure 5).

Repeat tracings, which are only in their infancy here in Ireland, were carried out using increased sampling definition, including the use of two portable automatic field fluorometer owned by Geological Survey Ireland. The higher resolution sampling improved the resultant data, and has provided insightful information on the aquifer characteristics. In the most basic trace, a simple 'positive' is reported without any breakthrough curve. The more sophisticated, automatically sampled tracings provided almost continuous data that enabled patterns to be observed that would otherwise be missed. This is illustrated in the graphs in Figures 6, 7, and 8, which represent tracings from November 2016 (simple), April 2017 and May 2017 (both higher resolution). It can be seen that the breakthrough curves from the higher resolution data show first arrival times, peak times, and subsidiary peaks in the April tracing, whereas the first arrival time is missed with the lower resolution tracing and there is no certainty on the peak concentration time. The high resolution data for both the April and May tracings had concurrent water level data available for the combined outflow, which further enabled dye recovery analyses. The recovery analysis for the May tracing is shown in Figure 8 and indicates almost 100% recovery.

As mentioned, the April tracings exhibit subsidiary peaks, whilst the May and November tracings exhibit no obvious secondary peak(s). The double peaked curves may relate to a number of factors: bifurcation; sorption/remobilisation; sediment infill; hydraulic jumps; geometry of the conduits; or dead-end passages. The April and November tracings are in locations with several adjacent swallow holes, with short distances and durations, which may suggest bifurcation and tributary in/out-flows along the main routes to the springs. The secondary peaks are observed in both springs for all three tracers. The conditions for the May tracing were drier with lower flows lower than in April, so it could it be that the main trunk routes further predominate the flow, and/or some routes are abandoned. The near 100% recovery for the May tracing may support this.

Overall, the tracings indicate a highly karstified, complex conduit dominated flow system, perhaps dominated by a few main trunk routes. Currently, the bedrock is defined as a *general* Regionally Important Karst Aquifer (Rk), not as yet categorised as either Rk^c (dominated by conduit flow) or Rk^d (dominated by diffuse flow) (Figure 1). The recent tracings demonstrate that, in the vicinity of Crossmolina at least, the groundwater system is complex and likely to be conduit dominated. This is emphasised in Figure 9, which compares a tracing from Crossmolina to one of the recent tracings from Cross. Other information on the springs themselves, as well as locally mapped dolines and collapse features, as well as ancillary information from geophysics and drilling, all support the tracing data, which indicates a conduit dominated aquifer.

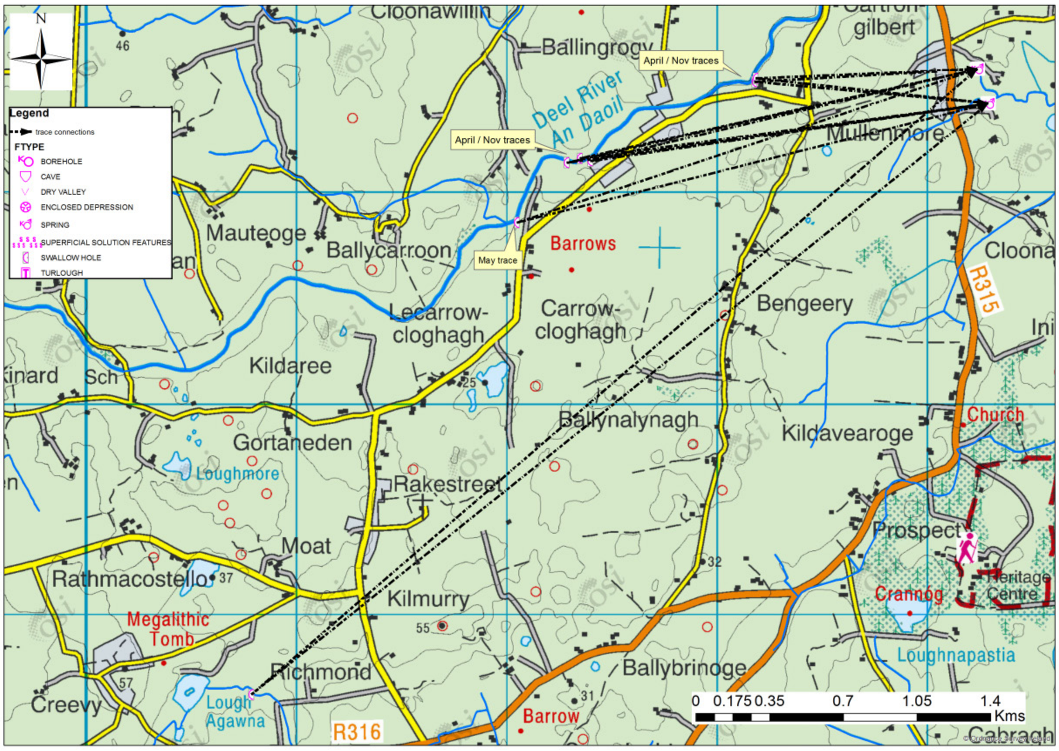

Figure 5 Map showing the bedrock aquifer, karst features and traces around Crossmolina

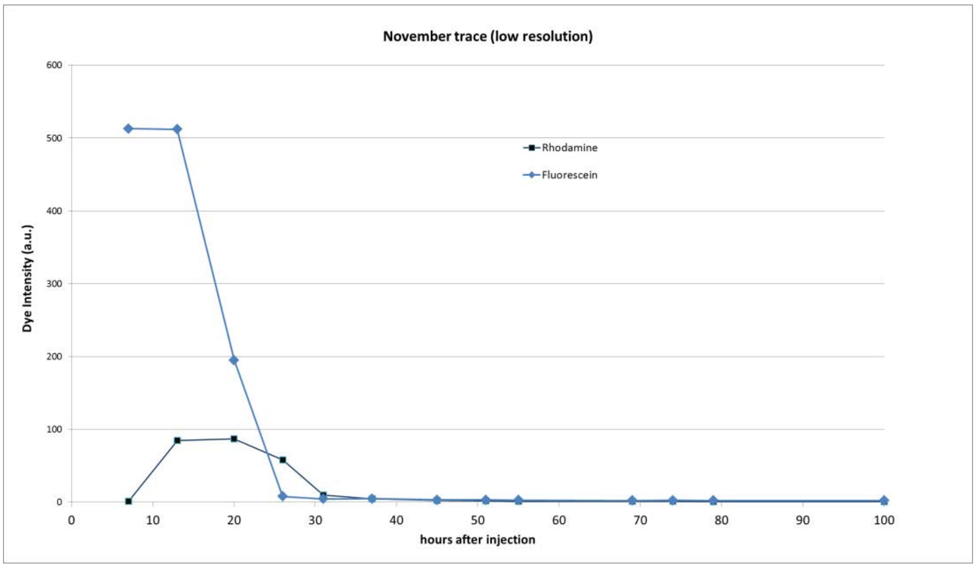

Figure 6 Breakthrough curve for the November trace 2016. There is uncertainty regarding the hydraulic parameters and there is no indication of subsidiary peaks.

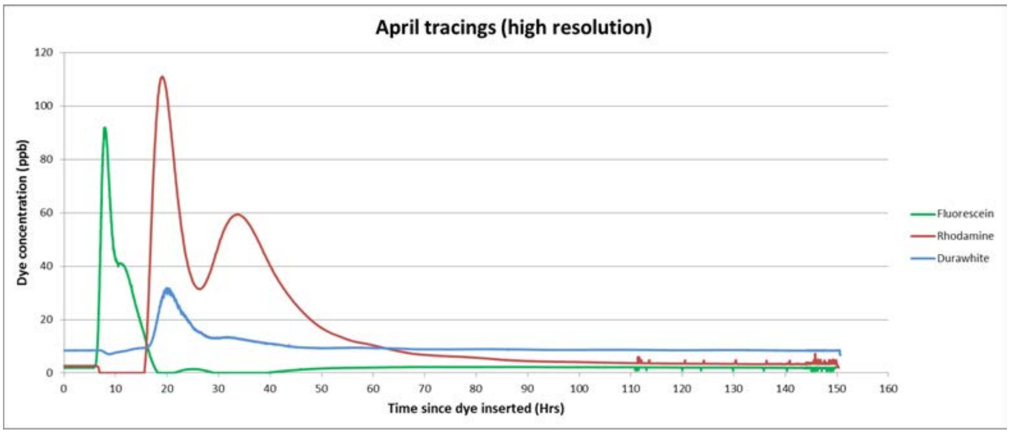

Figure 7 Breakthrough curves for the April Traces 2017 which provide information on the straight line velocities and on the conduit system.

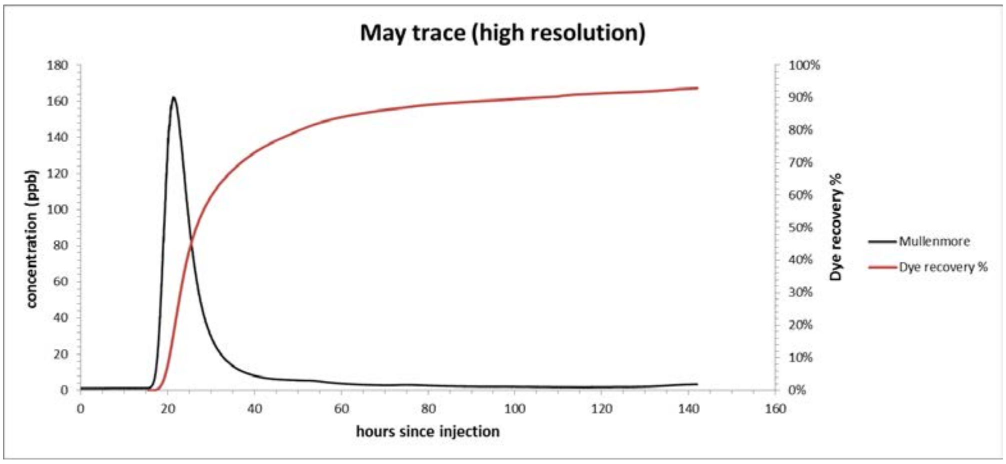

Figure 8 Breakthrough curve for the May trace 2017. In addition to the hydraulic parameters, the data give an insight into the mass recovery and reliability of the trace.

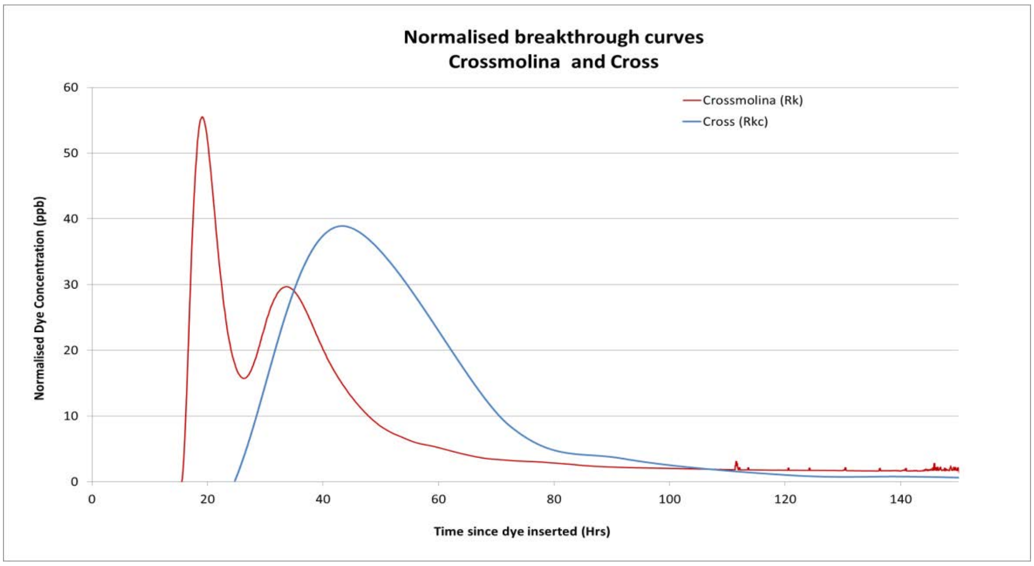

Figure 9 Comparison of breakthrough curves for Crossmolina (Rk) and Cross (Neale Rkc). The average straight line velocities are greater than 100m/hr in both cases.

RATHCROGHAN UPLANDS

The original purpose of the Rathcroghan Uplands study was to support zone of contribution delineation for the local Group Water Schemes – groundwater provides drinking water through the main springs that emerge from the perimeter of the uplands. Another key reason for improved hydrogeological understanding was that the N5 road was planned to cross the Uplands. Findings specific to the Rathcroghan Uplands study were presented at the 2017 IAH conference (Duncan and Kelly, 2017). Further to these works, disruptive groundwater-turlough flooding associated with excessive 2015/2016 winter rainfall was also found to be a problem in this area (amongst others), which also benefited from the water tracings conducted in 2015 and 2016.

It can be seen from Figure 10 that the scale of the study area is large, over 100 km^2, and the tracings demonstrate groundwater flow paths that are several kilometres in length. They are rapid, cross surface water catchment divides and several lower-order water courses. The jigsaw arrangement and pattern of the zones of contribution established for the springs demonstrate that in general the main springs each have their own groundwater catchments. Whilst some of the tracings are surprising, the general orientations appear to correlate with broad structural trends identified by Moore *et al* (2013) as being significant for groundwater flow. Further information on this topic is being presented at this year's conference, and is contained in these proceedings.

Most of the tracings were conducted over a two year period, and comprised sixteen attempted traces, fourteen of which gave a positive result. Whilst the results are impressive and provide an insight into the area, the investigations took a long time and considerable number of staff hours, over 150 person-days (not including the tracings prior to 2015). The tracings indicate the scale and extent of the area and the implications for groundwater protection and management. Since the publication of the findings at the 2017 conference (Duncan and Kelly, 2017) there has been progress to highlight this work and drive stakeholder engagement. This is a joint collaboration between Geological Survey Ireland, National Federation of Group Water Schemes (NFGWS), Local Authorities Water Community Office (LAWCO), and Roscommon County Council. The scientific, defensible tracing results are the cornerstone on which these communications are built. Not only are they generally interesting, they help people to visualise the 3D nature of groundwater flow and, critically, provide evidence in the face of possible contamination issues or disputes.

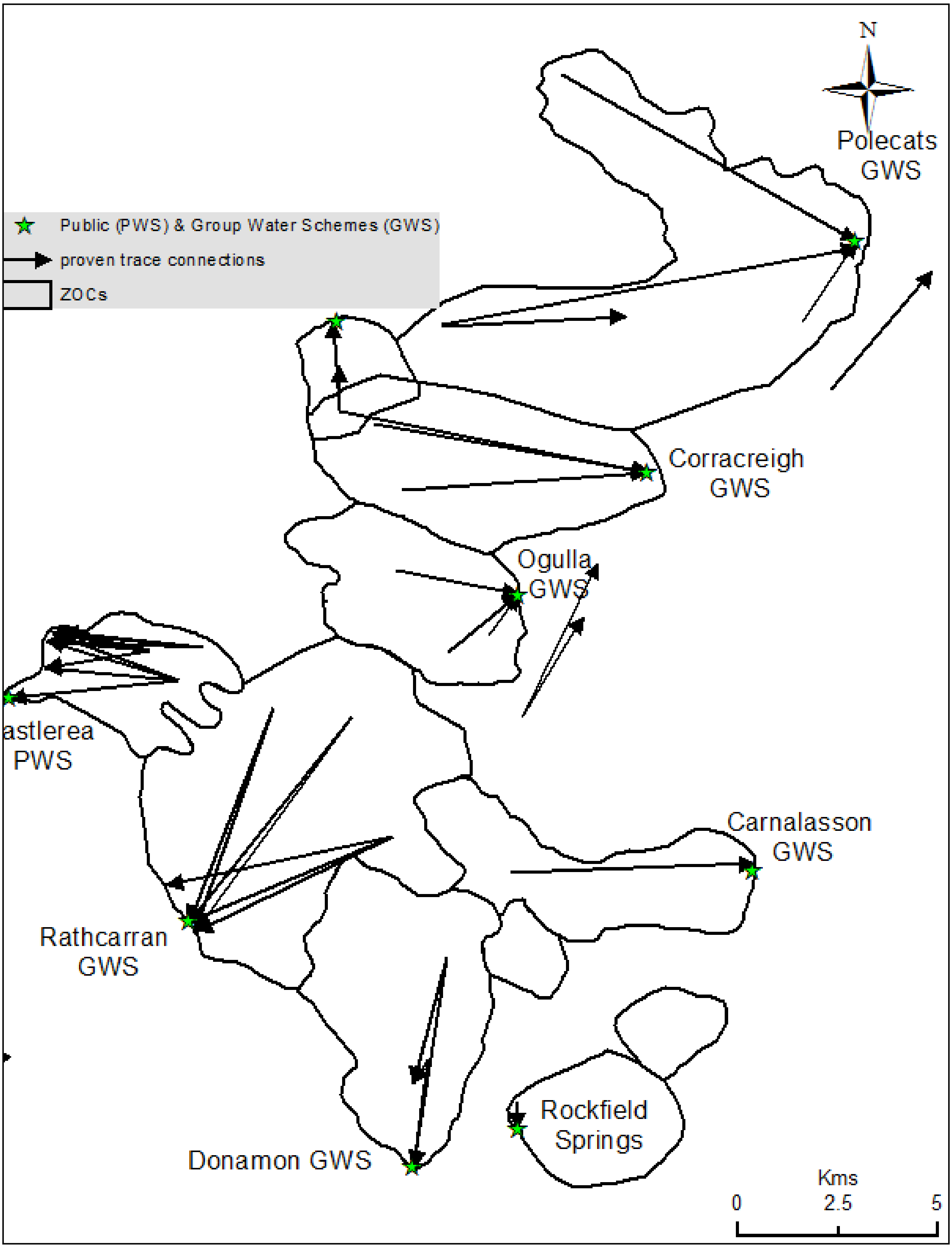

Figure 10 Rathcroghan Uplands: Water traces and established Zones of Contribution. The area is over 100km^2. After Duncan and Kelly, 2017.

OVERVIEW

The studies briefly outlined in this paper show how the tracings highlight specific findings for each area to aid management of differing issues. However, the tracings, together with the wealth of existing Irish karst investigations, and also by using high sampling resolution with automatic samplers, provide improved insights into karst areas generally, some of which are outlined as follows:

- The tracings show that investigations may involve large areas and may extend across several water catchments.

- The results continue to demonstrate that water tracing is a key technique in investigating karst areas to significantly enhance understanding, which supports management and, critically, yield *defensible* results. The investment (money and time) required is warranted and this is now becoming more recognised in other professions (e.g. engineers) and organisations (NFGWSs). Similarly further/repeat tracing is required in many cases to advance our understanding of certain regions as initial tracing may actually pose further questions. Overall, this progresses the cumulative knowledge on karst systems, both nationally and internationally.

- More sophisticated tracings using portable autosamplers greatly improve the resultant data and enable detailed analyses and interpretations into hydraulic and geometrical parameters of the karst system. Additionally, repeat tracings are necessary to decipher the complexity and temporal variability. This is not only important to understand how zones of contribution for drinking water supplies might expand and contract under different flow/seasonal conditions, but are fundamental to fully understanding (and properly planning for) karst-influenced flood events.

- Establishing protection areas for karst springs or boreholes that are abstracting a lot of water is difficult and water tracings provide critically important information. They provide a scientific basis for groundwater catchments to be delineated, which underpin risk assessments and drinking water safety plans - important for catchment management. They also assist in flood relief management and road design. To date, tracings provide the most definitive karst information for stakeholders.

- The tracings indicate the degree of karstification and aid aquifer classification, in particular, providing evidential support for Rk^c or Rk^d. Early work is being into comparing breakthrough curves from Rk^d aquifers and it is planned to progress this over the coming year. The use of high resolution data and automatic samplers in the study areas presented here have only scratched the surface of what can be done for aquifer classification.

- As the work in Crossmolina demonstrated, water tracing in relatively unexplored karst areas is an invaluable technique, in most circumstances. More sophisticated tracing methods enable a greater understanding into the groundwater systems of these areas. Even in areas that have had many tracings conducted, such as the Gort Lowlands, additional and higher resolution water tracing can enhance both conceptual site models and computer models. Although this may be considered ‘finessing’ the huge amount of work already undertaken in some of these areas, all three studies presented demonstrate how this ‘finessing’ can actually alter our conceptual understanding of system and therefore may be able to enhance successful management.

TRACING: THE KARST HYDROGEOLOGISTS’ PANACEA?

These, and hundreds of other Irish and international tracings, have improved our understanding of karst groundwater flow – and possible management options – exponentially when compared to other hydrogeological investigative techniques. However, there is always a risk that they may not work: dye may not be recovered. This may be due to groundwater flowing to discharge zones outside of the planned monitoring area, which has resulted in a few surprised phone calls about red or green springs/rivers/bays in the past. Alternatively, it may simply seem to vanish, which was the outcome of repeated tracer tests investigating zones of contribution for public water supplies in North Cork (Kelly, *et al*, 2010; 2012).

As collective experience increases, better understanding, planning and preparation can reduce some of the risks of a ‘negative result’. Even with this though, geology and hydrogeology can be immensely complicated. A negative result under today’s flow conditions might be positive under tomorrow’s conditions, next month’s or next year’s. Or perhaps the groundwater does not go to where it was thought to go, and monitoring needs be further afield next time. The bottom line is cost vs. the results. Certainly there are no doubts about the benefits, as demonstrated in the case studies here. It is also likely that with higher resolution monitoring and technological improvements we will find and recover more dye, more frequently, which will support the justification to others for the investment.

FURTHER WORK

Areas and topics for further work include:
The orientation of the tracings in the areas highlighted in this paper appears to correlate with the predominant geological structural trends that are known to be prone to karstification and promote groundwater flow. Further water tracings and analysis of the orientations would be useful to test and explore this correlation. Conversely, the water tracing may be useful to support and /or amend mapping of geological structures and boundaries.

The duration of tracings in the conduit dominated systems are typically very short, with quick straight line velocities. By contrast, the characteristics of water traces in Rk^d aquifers may be expected to be ‘slower’, comprise subdued responses, in conjunction with smaller spring discharges, less ‘flashy’ spring hydrographs, and overall better water quality. To date there are barely a handful of positive water traces with complete breakthrough curves in such aquifers. Whilst statistically limited, they indicate slower straight line velocities and longer tails. And there are quite a few failed tracings. Thus, further water tracing in Rk^d and Rk aquifers are required, a few of which are planned for later this year.

Whilst there are many karst areas where has been no water tracing conducted, repeat water traces are recommended. Repeat traces that have been carried out in Crossmolina, the Corrib/Mask area and elsewhere have been useful to test differing ‘flow’ states, variable aquifer responses, trace validity and equipment.

The more sophisticated tracings and resultant breakthrough curves being established will enable hydraulic and geometrical parameterisation which will improve the understanding into the karst systems in Ireland.

Further work is being carried out in County Clare and Leitrim under the iCRAG research programme and recent traces have also been carried out in County Fermanagh. Geological Survey Ireland plans other tracings this year that include Offaly, Laois and Kerry.

ACKNOWLEDGMENTS

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A HABITATS & EIA DIRECTIVE PERSPECTIVE ON HYDROLOGICAL/HYDROGEOLOGICAL ASSESSMENT – ARE THERE ANY SIMPLE ANSWERS?

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McCarthy Keville O'Sullivan Ltd.

NOTES

SESSION III

WAULSORTIAN LIMESTONE: GEOLOGY AND HYDROGEOLOGY

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ABSTRACT

Waulsortian limestone is extensively developed in Ireland, and it represents a phase of submarine bank development during the Tournaisian (Mississippian, Carboniferous). These carbonate buildups are rich in (now lithified) lime mud, contain a shelly marine fossil fauna and generally lack any sign of a rigid supporting framework. Complex cavity systems commonly developed and these were subsequently infilled with a variety of geopetal muds and sparry cements. As Waulsortian banks grew and developed they generated a complex topography on the seafloor. Lateral facies variation is common as a result: the centre, or core, of individual mounds is typically represented by massive, or poorly-bedded bank facies. This may pass laterally through flank facies (around the periphery of mounds) and into laterally equivalent off-bank facies, which is generally composed of interbedded argillaceous limestones, shales and cherts.

Hydrogeologically, the Waulsortian limestone has generally been considered unproductive, however, potential for groundwater flow does exist. The massive bank (or 'core') facies is not spatially or stratigraphically ubiquitous, and the laterally equivalent off-bank bedded facies might present better opportunities for promoting flow. The very fine-grained carbonate lithology is also relatively pure and, in the right circumstances, amenable to dissolution and karst development. It is also susceptible to Mg replacement and dolomitisation, which can further enhance permeability. Brittle faults and fractures are also extremely important in providing conduits and pathways for groundwater in the subsurface. Some of these deep-seated fault structures played a key role in the generation of many Pb/Zn deposits in the past, and now provide potential conduits for deep groundwater.

Waulsortian banks originally developed in a dynamic and heterogeneous environment on the seafloor and an appreciation, or awareness, for its capacity for lateral facies variation is essential when investigating it. An integrated and holistic approach is recommended to maximise understanding of this carbonate system, using all geological and hydrogeological information available.

1. INTRODUCTION

Waulsortian limestone is extensively developed across much of southern and central Ireland and is routinely encountered by mineral (principally base metal) exploration geologists, and also hydrogeologists working with aquifers developed in Carboniferous strata. The carbonate lithofacies is generally interpreted as representing a series of carbonate buildups produced by biological activity and accretion on the seafloor. In the past these buildups have been variously described as *'reefs'* and *'mud-mounds'*; however, the term 'Waulsortian banks' is presently preferred as these bioherms lack any form of rigid supporting framework (typical of more recent reef systems) and they have been shown not to always develop mound-like geometries.

Waulsortian banks developed across areas of the European seafloor in late Tournaisian times (Figure 1) and derive their name from the Belgian town of Waulsort, where they were first described. Similar limestones (in terms of carbonate lithofacies and stratigraphic age) are now known from a range of locations worldwide, including the western and southwestern United States, Ireland, Britain and France (Lees & Miller 1995). Waulsortian buildups essentially represent a phase of 'reef' recovery in the immediate aftermath of the late Devonian mass extinction (Wood 1999; see also Aretz & Chevalier 2007). For reasons that remain unclear, Ireland was a prime location for Waulsortian bank growth and development: it is are more extensively developed there (both geographically and also in terms of maximum lithostratigraphic thicknesses attained) than anywhere else in the world (see Murray 2010 for discussion). The purpose of this contribution is to provide a review of the geology of Waulsortian limestones, and consider this within a broader hydrogeological perspective.

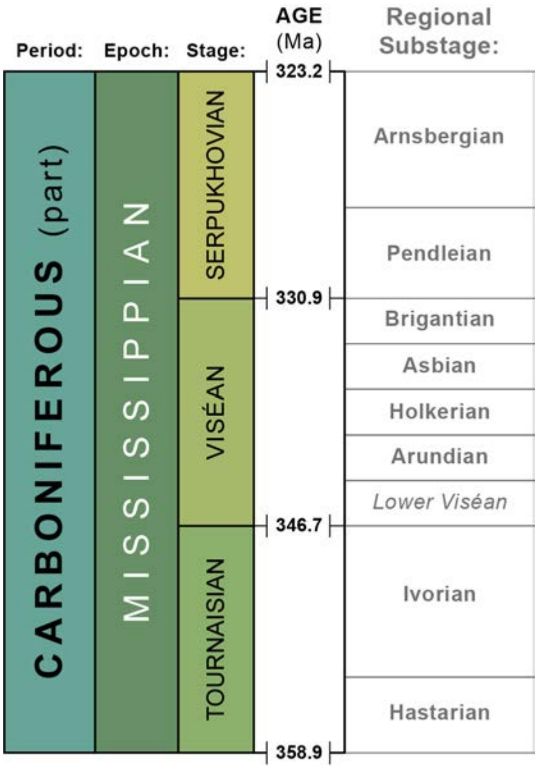

Figure 1: *ICS stratigraphic subdivision of the Mississippian (Carboniferous). The positions of regional stage and substage divisions are also shown. Colour coding used for internationally agreed subdivisions (on left) are those prescribed by the Commission for the Geological Map of the World, Paris France. Waulsortian limestone developed in Ireland primarily during the Ivorian substage of the Tournaisian and, in certain locations, it is known to have extended into the lower Viséan.*

2. GEOLOGY OF WAULSORTIAN LIMESTONE

2.1 LITHOLOGY AND CARBONATE COMPONENTS

Waulsortian limestone typically comprises pale-grey and very fine-grained (calcilutite-grade) carbonates, which display mudstone to wackestone depositional textures. The pale colouration reflects, to a certain extent, the relative purity of the carbonate matrix, which contains very little to no argillite and is essentially composed of lime mud. Lees & Miller (1995) provide the most comprehensive review of Waulsortian facies available at present and in their opinion the muddy matrix is *the* most important component of these buildups. Several generations of muds (termed 'polymuds') are usually evident and Lees & Miller (1995) speculate that much of it may have been produced in-situ on the surfaces of the banks by microbial communities. A range of fossil bioclasts is commonly preserved in Waulsortian bank facies, much in the form of skeletal debris. Crinoids and fenestrate bryozoans dominate volumetrically; however, brachiopods and molluscs are also frequently encountered macroscopic components (Figure 2). In some locations well-preserved and diverse benthic marine communities have been recorded (e.g. Hudson *et al.* 1966).

Discrete and conspicuous sparry calcite masses are often present in the matrix and may even be quite abundant (Figure 2). These features represent infilled primary or secondarily enlarged (through subsequent physical or chemical erosion) cavity systems, and they attest to the original biohermal nature of the carbonate buildup. The primary cavities formed in a variety of ways, but are broadly divided into those with skeletal support (sometimes termed shelter cavities – i.e. where a brachiopod shell or a flattened fenestrate bryozoan frond provided a roof for the void space) and those lacking any discernable form of support. The latter group are more difficult to understand in terms of their origin, and they include the very distinctive stromatactis structures – elongate cavities with flat bases and irregular, often digitate, roofs. The cavities are often floored by a geopetal infill of carbonate mud, and these features have, in some instances, facilitated reconstruction of the palaeo-horizontal and determination of original depositional dips.

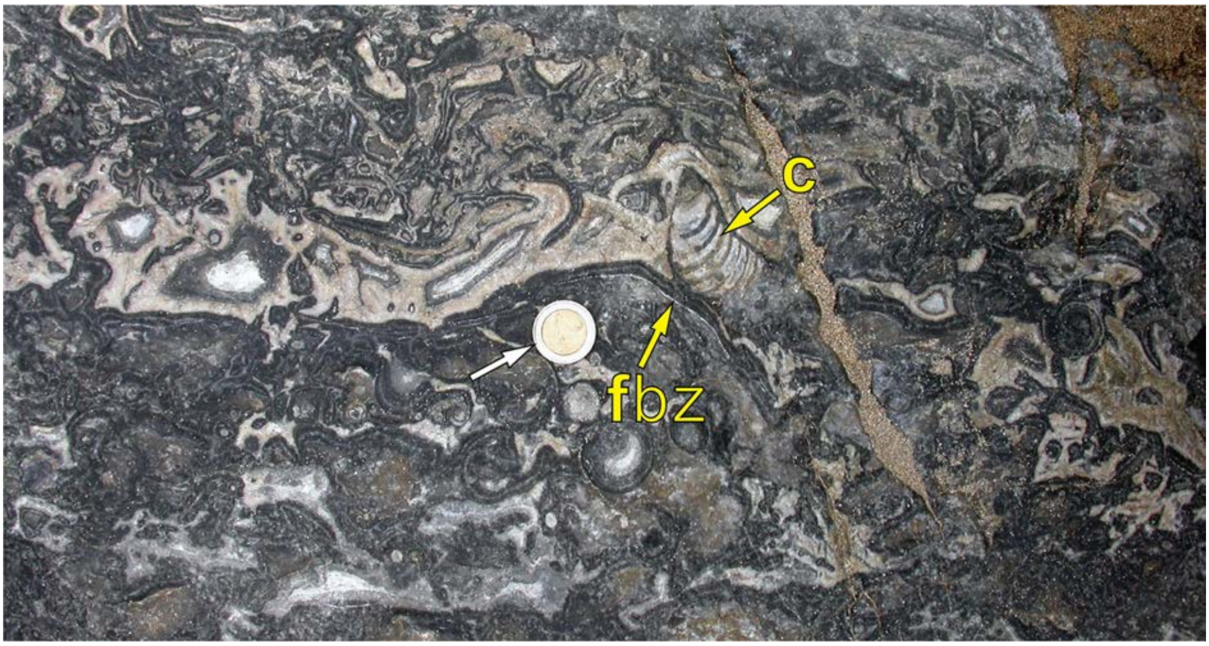

Figure 2: *Wave polished surface from Ballybunion beach in north County Kerry, showing complex cavity development in Waulsortian limestone facies. Several generations of carbonate mud (polymuds) are evident along with numerous bioclasts. Fenestrate bryozoan fronds are particularly common (one is arrowed fbz), and a chambered cephalopod shell is also present (arrowed c). Scale (white arrow) is a 2-euro coin.*

2.2 GEOMETRY AND BATHYMETRY OF BANKS

A characteristic feature of Waulsortian limestones is that they are often poorly bedded, or even massive in nature. This reflects the fact that they formed, largely in-situ, as carbonate buildups on the seafloor. Individual banks possess their own gross anatomy consisting of bank, flank and off-bank facies (Miller 1986; Figure 3), which often may not be apparent, or indeed possible to observe on the scale of an individual outcrop.

Devuyst & Lees (2001) examined the basal zone at four Irish Waulsortian localities, and identified a highly distinctive transition facies with ‘precursor’ muds, which they felt was microbial in origin. They also noted that despite considerable variation in palaeobathymetry and associated palaeoenvironmental conditions (light and energy) between the study sites, all locations went on to produce 'standard' Waulsortian banks, independent of any broader significant regional-scale environmental change.

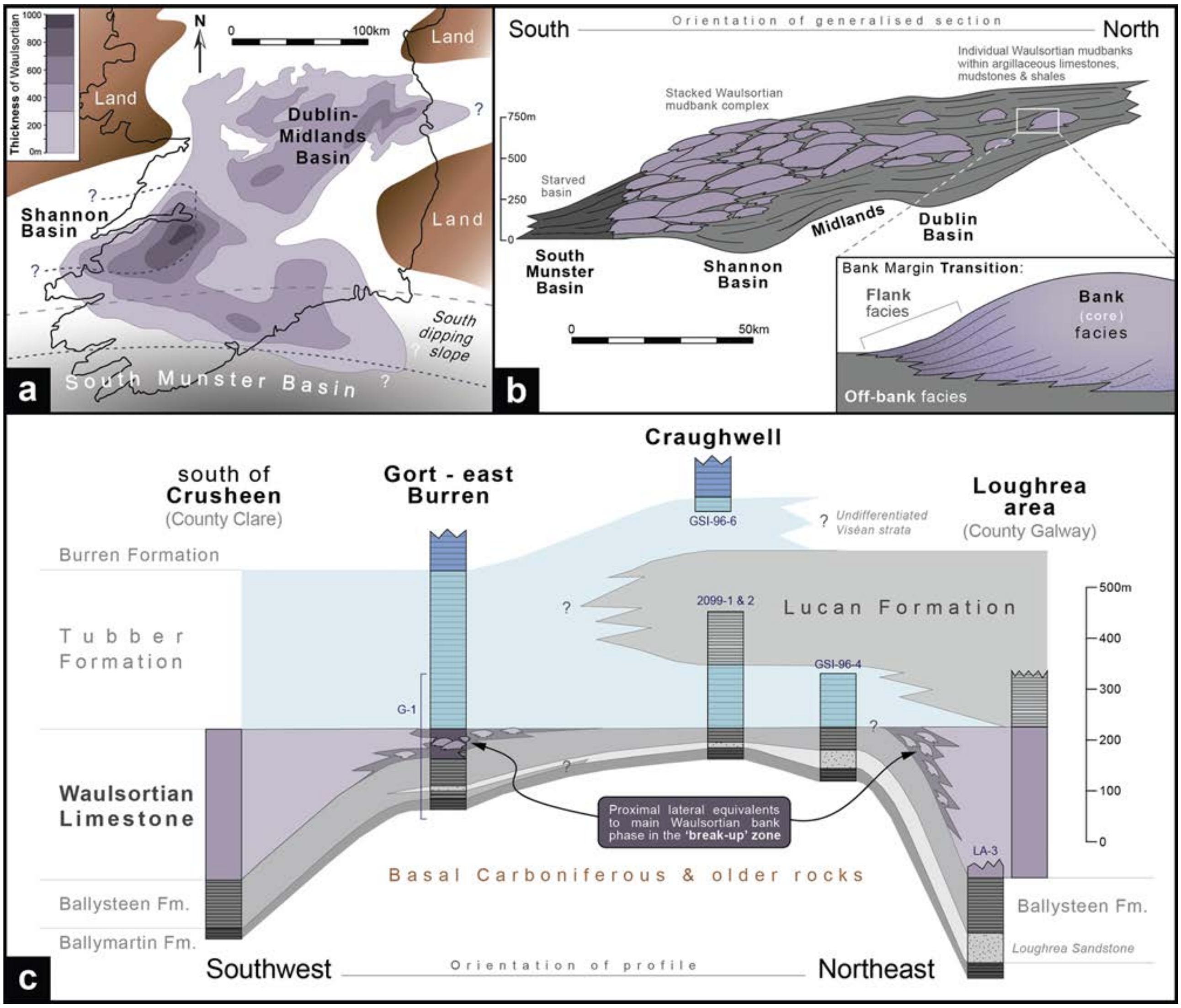

Figure 3: *Distribution and spatial variation of Waulsortian bank facies in Ireland.* ***(a)*** *Palaeogeographic sketch-map of south and central Ireland during the late Tournaisian. The lateral extent and thickness of Waulsortian facies is indicated: note thickest developments around the southeastern zone of the Shannon Basin. Redrawn and modified from Lees & Miller (1995).* ***(b)*** *Generalised south-north section through Ireland illustrating the distribution and thickness variation of Waulsortian limestone; redrawn from Hitzman (1995). Inset (lower right) shows facies distribution along the margin of an individual Waulsortian bank and is modified from Devuyst & Lees (2001). (c) Lithostratigraphic variation of Waulsortian limestones and enclosing units in north County Clare and south County Galway. The horizontal baseline for the section is taken at the base of the Tubber Limestone Formation, which very broadly coincides with the Tournaisian-Viséan boundary. Individual section labels in blue text (e.g. GSI-96-4 etc.) refer to boreholes. Redrawn from Pracht et al. (2004).*

Bank (or 'core') facies is typically more massive in appearance, although crude layering, generally in the form of alternating mud-rich and spar-rich bands, may be evident. This facies passes laterally (often quite rapidly) through flank facies around the immediate margins of the mounds and into equivalent off-bank facies, which is commonly darker, more argillaceous, shaley and cherty, and has generally thinner and more defined bedding developed (Figure 3b). Individual Waulsortian banks often coalesced and grew on top of each other to form aggregate mound complexes (Lees 1964, 1994). Quite considerable morphological variation is expressed by Waulsortian banks; they could be quite flat and subdued, or they could form quite high-relief features on the seafloor, with steeply dipping (up to c.40°) flanks or margins (Sevastopulo & Wyse Jackson 2009).

Lees (1994) made a detailed study of the growth forms of Waulsortian banks from a number of parallel sections, or faces, revealed during quarrying at a site near Loughrea in County Galway. The findings of this study are noteworthy as new forms of bank growth were recognised and it was also quite clear that the spatially complex carbonate facies architecture reconstructed was only possible because of the scale and nature of the outcrop (i.e. an active, working quarry). Lees (1994) stressed that this level of 3-dimensional understanding would not be possible in areas with poor exposure, or from investigation of drillcore alone.

Four depth-related phases have been determined for Waulsortian banks (A-D), based principally on composition of skeletal and non-skeletal clasts (Lees & Miller 1985, 1995). Phase A is interpreted as representing the deepest of these, and was perhaps produced in aphotic conditions in c.300m water depths. Diversity of components increases through the subsequent (progressively shallower) phases, and only the uppermost Phase D shows clear evidence for production within the photic zone.

2.3 BANK DEVELOPMENT: RISE AND FALL OF AN ECOSYSTEM

During the early Tournaisian, a major marine transgression inundated the landmass of Ireland and was followed by a period of carbonate ramp sedimentation (Hudson & Sevastopulo 1966; Clayton *et al.* 1980; Somerville & Jones 1985). The sediments of the ramp typically comprise interbedded argillaceous limestones and shales, and these have been termed the Ballysteen Limestone Formation or more informally the ABL (argillaceous bioclastic limestone). This particular facies has been recognised and mapped over a wide area of Ireland, reflecting a broad and uniform depositional setting. Waulsortian banks developed immediately above this level, and their palaeoenvironmental setting was in deep water (offshore) on the ramp that faced the South Munster Basin, located further to the south (Figure 3a).

The base of the Waulsortian limestone is diachronous when broadly traced from south to north across Ireland (Devuyst & Lees 2001; Sevastopulo 1982; Sevastopulo & Wyse Jackson 2009). The oldest occurrences are known from Cork, on the margins of the South Munster Basin, with the thickest developments located close to areas which had high rates of subsidence (such as the Dublin and Shannon basins, see Figure 3a-b). It is apparent that syn-sedimentary faulting played an important role in governing and mediating bank growth and development (e.g. Hitzman 1995, 1999, and references therein).

According to Lees & Miller (1995) stratigraphic and facies relations demonstrate that the Waulsortian complex spread from the Shannon area eastwards and northwards as the main phase of marine transgression crossed Ireland northwards during the Tournaisian. The Shannon Basin may have accommodated up to 1000m (stratigraphically) of Waulsortian limestone (Figure 3a); however, this thickness reduces dramatically moving further north and away from the main mound complex (Somerville & Strogen 1992). Geological Survey of Ireland [GSI] drilling between Gort and Loughrea in County Galway has shown that the unit thins to zero and essentially pinches out in the intervening area between these two districts, reflecting passage into what has been interpreted as the ‘breakup zone’ of the Waulsortian mound complex (Pracht *et al.* 2004; see Figure 3c).

The timing of the eventual collapse and demise of Waulsortian banks appears to generally coincide with a regional tectonic event (a phase of crustal extension) at the *'Lower Viséan'*-Arundian boundary (Bridges *et al.* 1995). In the Dublin Basin, this extensional event led to intrabasinal uplift and erosion of carbonate buildups (Philcox 1989). However, when examined in detail, the extinction of Waulsortian banks in Ireland is seen to be a decidedly more complex, and indeed diachronous, affair, and work remains to be done to provide a more complete impression of events.

3. HYDROGEOLOGY OF WAULSORTIAN LIMESTONE

3.1 INFLUENCE OF GEOLOGY ON GROUNDWATER FLOW & DISSOLUTION

From a hydrogeological perspective, Waulsortian limestone has generally been considered unproductive due to its massive or poorly-bedded nature, coupled with its typically very fine-grained lithology and the fact that all of the original primary pore spaces are now occluded by sparry calcite (Figures 2 and 3b). All of these lithological features are intrinsically related to the origin of these rocks as submarine carbonate banks, rich in lime mud. In a sense, the palaeoenvironmental context of their formation now informs the contemporary hydrogeological picture.

However, there is still potential for development of groundwater flow in Waulsortian limestone. The massive carbonate bank (or 'core') facies is not ubiquitous (Figure 3b-c) and, as noted above, carbonate buildup or 'reef' environments are inherently heterogeneous, resulting in considerable potential for lateral facies variation as a consequence. Darker, shaley inter- and off-bank bedded facies could present better opportunities for promoting groundwater flow, particularly along the interfaces between bedded and largely unbedded lithologies. In this respect, it is important to consider, or at least appreciate, the potential for spatial carbonate facies variation when working with Waulsortian limestone. This is true both geologically (*sensu* Lees 1994) and also hydrogeologically.

The relative purity of Waulsortian limestone makes it amenable, under the right conditions, to dissolution and karst development. The GSI classifies Waulsortian as the groundwater rock unit 'Dinantian pure unbedded limestones'[1]. Waulsortian rocks are very well exposed in the Tralee Bay area of County Kerry and the unit is classified there as both a locally important aquifer (karstified) and also, more generally, as a regionally important aquifer (karstified – diffuse). South of Crusheen in County Clare and in the Loughrea/Tynagh area in County Galway (Figure 3c) it is categorised by the GSI as a locally important aquifer (bedrock which is moderately productive only in local zones)[2]. The same is also the case for the Feltrim Quarry area in north County Dublin, which has been an area of Waulsortian investigation for some considerable time now.

3.2 FRACTURE FORMATION & DOLOMITISATION

Dissolutional weathering is clearly important for promoting permeability in carbonate rocks, but fracturing and cataclasis are equally, if not even more, significant mechanisms for providing conduits and pathways (e.g. Cook 2003; Bense *et al.* 2013). Knowledge of the overall structural framework or context in which Waulsortian limestone is developed is thus key, particularly as in some instances syn-sedimentary faulting appears to have played a role in mediating bank growth and development. Additionally, subsequent faulting (post-burial and lithification, some of which may have involved fault reactivation) may also have been influenced by the lithological contrast between the massive bank facies and its off-bank equivalents.

[1] 'Dinantian' is an older western European subdivision of the Carboniferous, broadly equivalent to the Tournaisian and Viséan stages combined, see Figure 1.

[2] Source: https://dcenr.maps.arcgis.com/apps/webappviewer/index.html?id=3400f393afa844538e5b81679552205d

Bense *et al.* (2013) note that fracture development and subsequent dissolution can greatly enhance permeability in fine-grained carbonate rocks, but that the observed patterns and responses are often complex: in some instances secondary mineralisation or smearing of impermeable materials (e.g. clays) through the fault zone can actually create a barrier to flow across the fault core (an aquitard), while flow in the adjacent damage zone can be enhanced (parallel to the fault). In the vicinity of the Tynagh mine site in east Galway, Henry (2014) reported that while the majority of local wells were poorly to moderately productive, two deeper domestic wells, both completed in the hanging wall of the damage zone of the North Tynagh Fault, were exceptionally productive, indicating the rapidity and ease of flow parallel to the fault core (both wells were completed in the Waulsortian). Drew & Jones (2000) noted that the residual ore body at Tynagh (comprised of a boat-shaped surficial unit approximately 600m long, 50m wide and 100m deep) developed by the in-situ weathering of Waulsortian limestone by chemically aggressive groundwater flowing along the same pathway. The Waulsortian weathered out first, followed by the overlying impure limestones and Drew & Jones (2000) suggested that this had perhaps occurred in the Neogene. Much remains to be resolved in terms of fully understanding of the link between fault and fracture formation and groundwater flow in Irish carbonate aquifers; however, this work is currently underway (e.g. Moore & Walsh 2013; Henry 2014; Moore *et al*. 2015; Wheeler *et al*. 2018).

Waulsortian limestone is also susceptible to Mg replacement and dolomitisation, particularly in discrete zones controlled by faulting, and this has been viewed as key to emplacement of most of the zinc-lead deposits hosted in this lithostratigraphic unit, particularly in southern and central Ireland (e.g. Wilkinson & Hitzman 2015, and references therein). At Lisheen in County Tipperary, large portions of the Waulsortian experienced regional dolomitisation, which increased the porosity and permeability of the host rock prior to the main phase of hydrothermally driven mineralisation (e.g. Hitzman *et al.* 2002; Wilkinson *et al.* 2005). The Waulsortian limestone around Lisheen is classified by the GSI as a locally important and moderately productive aquifer; however, in areas which have been dolomitised the aquifer classification is upgraded to regionally important aquifer (karstified - diffuse)[3]. The bulk of mine water make at Lisheen over the life of mine was associated with two major fault structures (F1 and F2), and the remaining make was almost entirely associated with deeper fault structures. Many of the latter made large volumes of water at discrete locations over extended periods, and one of the authors [TH] observed evidence of karstification at depths of >200m. Many of the fault structures that initially facilitated mineral emplacement during the Carboniferous now appear to facilitate modern groundwater flows at Lisheen and at Tynagh (*see above*).

Some of the deep-seated fault systems responsible for facilitating fluid flow in the past are now believed to be forming conduits for deep groundwater flow. In a recent study of Irish thermal groundwater springs, Blake *et al.* (2016a,b) noted that four (out of six) of their study springs issued from locations where Waulsortian limestone was in close spatial proximity at outcrop level, and that the pure carbonate lithology had apparently influenced groundwater hydrochemistry, particularly in relation to HCO_3 content. Moore *et al.* (2015) noted that vertical or sub-vertical groundwater flow paths could develop in discrete Waulsortian mounds with little lateral movement of water. In addition, Blake *et al.* (2016b) reported evidence of dissolutional features at depths between 250m-300m (and possibly up to 500m) which had been observed in core recovered from Waulsortian limestones in the Dublin basin, noting that these features could potentially facilitate rapid movement of thermal waters to the surface. In this area the broad aquifer classification is locally important[4], reflecting the regional low bulk permeability and porosity of the unweathered and unfractured rock, the type and thickness of the overburden, and the well-developed surface drainage pattern. However, recharge over a large area, slowly percolating as intergranular flows, concentrates in the deep structures and is moved rapidly upwards; reflecting the heterogeneity of the limestone properties.

[3] The groundwater rock unit in this area is classified by the GSI as 'Dinantian Dolomitised Limestones'.

[4] The regional aquifer classification is *Locally Important Aquifer - Bedrock which is Moderately Productive only in Local Zones*: https://dcenr.maps.arcgis.com/apps/MapSeries/index.html?appid=a30af518e87a4c0ab2fbde2aaac3c228

4. CONCLUSIONS

Waulsortian banks were originally produced during the late Tournaisian in a dynamic and complex palaeoenviromental setting. Awareness and appreciation of the potential for lateral facies variation and spatial heterogeneity in carbonate buildups of this type is key to better understanding their nature, particularly when considering them in hydrogeological terms. The underlying geology informs and influences broader scale patterns of carbonate dissolution, and also fracture and fault development (and vice versa in the case of syn-sedimentary faulting mediating bank growth). These features, in turn, serve to increase and enhance permeability, which has exerted considerable influence on fluid flow in this carbonate lithofacies, both in the past and also at present. The broader geological and hydrogeological system is perhaps better considered as a nexus - a series of closely interlinked sub-systems, which are best approached in an integrated manner.

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STRUCTURAL CONTROLS ON GROUNDWATER FLOW – FROM FIELD STUDIES THROUGH TO 3D MODELLING

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NOTES

QUANTITATIVE ANALYSIS OF CENOZOIC FAULTS AND FRACTURES AND THEIR IMPACT ON GROUNDWATER FLOW IN IRISH BEDROCK AQUIFERS

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ABSTRACT

Faults and fractures are the most important store and pathway for groundwater in Ireland's bedrock aquifers either directly as conductive structures or indirectly as the locus for the development of dolomitised limestone and karst conduits. From the quantitative analysis of the only intrinsically conductive fractures - Cenozoic strike-slip faults and joints - from over 100 outcrop, quarry, mine and cave locations, in a range of bedrock types, we have: (i) derived quantitative models for their depth dependency, lithological control and scaling systematics, (ii) conceptualised their impact on groundwater behaviour, and (iii) estimated groundwater parameters from fracture attributes and flow and head data. The quantitative models are important insofar as they provide constraints on connectivity of Cenozoic strike-slip faults and joints in different lithology and lithological sequences. However, the highest and most sustainable flows from Cenozoic fracture systems connected to or within limestone dominated sequences, arises from karstification, which is enhanced in zones of higher deformation intensity and in bedded, rather than massive, limestone sequences.

INTRODUCTION

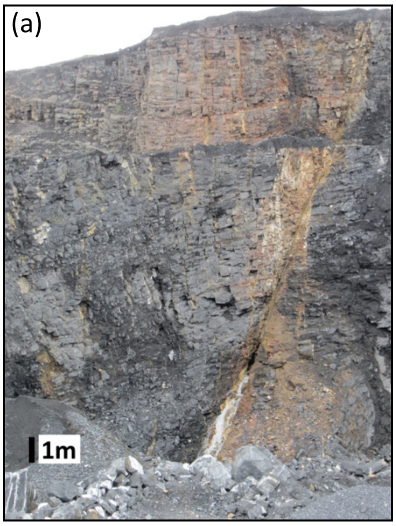
In Ireland there are many different types of faults and fractures that are important for flow, but in different ways. NE-trending early Carboniferous normal faults are sealing structures to groundwater flow, because of their shaley fault rock (gouge), shale smear and vein content (Moore & Walsh, 2013), a characteristic sometimes reflected in across-fault differences of groundwater head in mines and quarries. Variscan (late Carboniferous) NNW-N-NNE-trending veins and NE- and NW-trending strike-slip faults are characteristically vein filled and therefore also intrinsically sealing (Moore & Walsh, 2013). However, early Carboniferous and Variscan structures can localise karst along them which forms highly directional multi-km scale conduits, the geometries of which are well known within the classic karst region of The Burren in the west of Ireland (Moore & Walsh, 2013).

In this paper we briefly describe some of the quantitative characteristics of the most recent structures affecting groundwater flow in Ireland: Cenozoic strike-slip faults and stress-release related joints. The Cenozoic faults occur in conjugate pairs of approximately NNW- and NE-trending faults, which are dextral and sinistral respectively. These are relatively uncemented structures, often having vuggy vein infills, due to their formation and burial at lower confining pressures than their Carboniferous equivalents. As a consequence, Cenozoic faults yield the highest and most sustainable flows in Ireland (Moore & Walsh, 2013). One such fault, shown in Fig. 1a, is responsible for most of the inflow, of up to 7,000 m^3/d, into one of the biggest limestone quarries in Ireland (i.e. Huntstown quarry in north Dublin). The fault shows the characteristic pink veining and high densities of associated fractures of Cenozoic faults, with reddish-brown discolouration of surrounding rock due to accentuated fluid flow (Fig. 1a). Outcrop studies show that localised zones of accentuated aperture and flow are generated by strike-slip movements along vertical and horizontal releasing fault bends (e.g. Fig.1a; Moore & Walsh, 2013). These dilations combined with karstification mean that relatively small displacement faults can strongly localise groundwater flow: a ca 10m displacement NNW-trending dextral strike-slip fault within Lisheen mine (Central Ireland), produced 30,000 m^3/d when intercepted in 1999

(Moore & Walsh, 2013), only declining to 22,000 m^3/d on mine closure in December 2015 (Quaid pers. comm., 2016). Joints are the youngest and most ubiquitous structure in Irish fractured aquifers and they are always uncemented. Joint systems are intrinsically stratabound, displaying scaling properties which vary with layer/mechanical unit thickness (Price, 1966; Schöpfer et al., 2011). As unloading and stress release structures, joint apertures and densities (i.e. frequencies) increase towards the bedrock surface, changes which are responsible for increases in permeability towards the surface (Moore & Walsh, 2013).

QUANTITATIVE MODELS

Quantitative analysis of Cenozoic faults and joints indicates that their geometry and nature varies with lithological sequence and with spatial controls, such as depth and regional variations in deformation style and intensity. For example, Fig. 1b shows the densities of Cenozoic strike-slip faults in different lithological sequences. Although there is a variation in density due to strong clustering (e.g. the higher values at Navan and Huntstown), the density also varies in different lithologies. Higher densities occur within thickly bedded massive, and relatively brittle, limestone sequences, whilst lower densities are developed within argillaceous limestone and shale sequences within which deformation is more discrete and localised (Fig. 1b), partly because of the ductile nature of the host rock shales. Regionally, there is a westward decline in deformation intensity of Cenozoic strike-slip faults across Ireland: westwards, faults form lower density arrays and are less vertically persistent, appearing to be absent within The Burren, in the far west of Ireland. Eastwards, faults are more numerous and can have much larger displacements, e.g. the >9km lateral displacement on the Codling fault in the Irish Sea (Cooper et al. 2012). The regional changes are attributed to an eastward increase in Alpine-related N-S compressional deformation and the widespread development of smaller NNW-trending dextral faults, which have a major impact on flow, is attributed to the absence of large pre-existing faults in that direction.



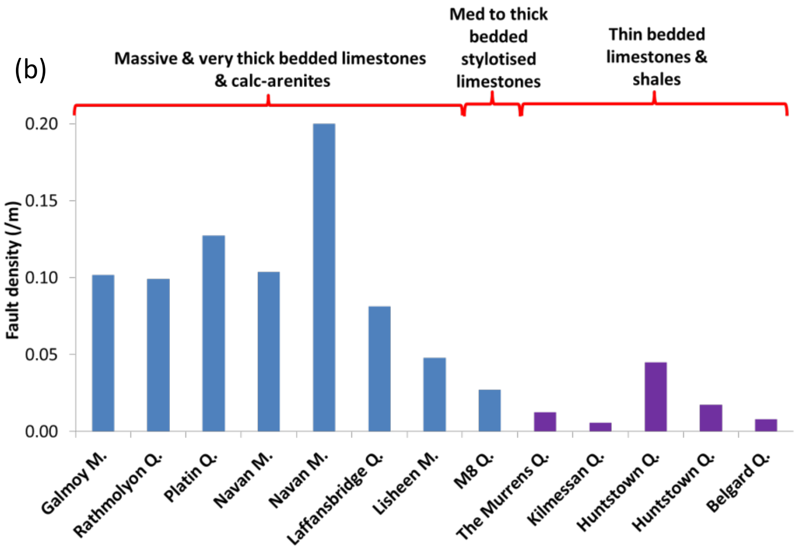


Fig. 1. A Cenozoic strike-slip fault with a cavity and groundwater flow localised on a fault bend at Huntstown Quarry, Dublin. (b) Density of Cenozoic strike-slip faults in different lithological sequences, measured as number of faults per metre along ca 100m long sections. Data are mostly from quarry (Q) and mine (M) exposures and two from mine maps (Galmoy & Navan): thickly bedded massive limestone sequences (blue) and argillaceous limestone and shale sequences (purple) are distinguished.

Due to their stratabound nature, joint densities show an inverse trend with bed thickness (Fig. 2b), with the scatter of data arising from other controlling factors, including proximity to bedrock surface (BS), the equivalent of depth. This is illustrated in Fig.2b in which layers which approach the BS (i.e. points circled on plot) have higher densities compared to similar thickness beds at greater depths.

Joint densities show an approximately exponential decrease with depth down to 9m (Fig. 2c; values were computed immediately adjacent to the vertical red line in Fig. 2a), supporting the stress release origin of these structures. The BS also cuts down through beds so that they have a lateral edge (Fig. 2a and inset). This is highlighted by 3 curves showing the left-to-right changes of joint spacing along individual beds (coloured lines in Fig. 2a inset) as the cumulative number with distance from the BS (Fig. 2d). All three profiles show steeper slopes in proximity to the BS, a feature which highlights the lateral changes in joint density, a characteristic which is principally a function of distance from the BS.

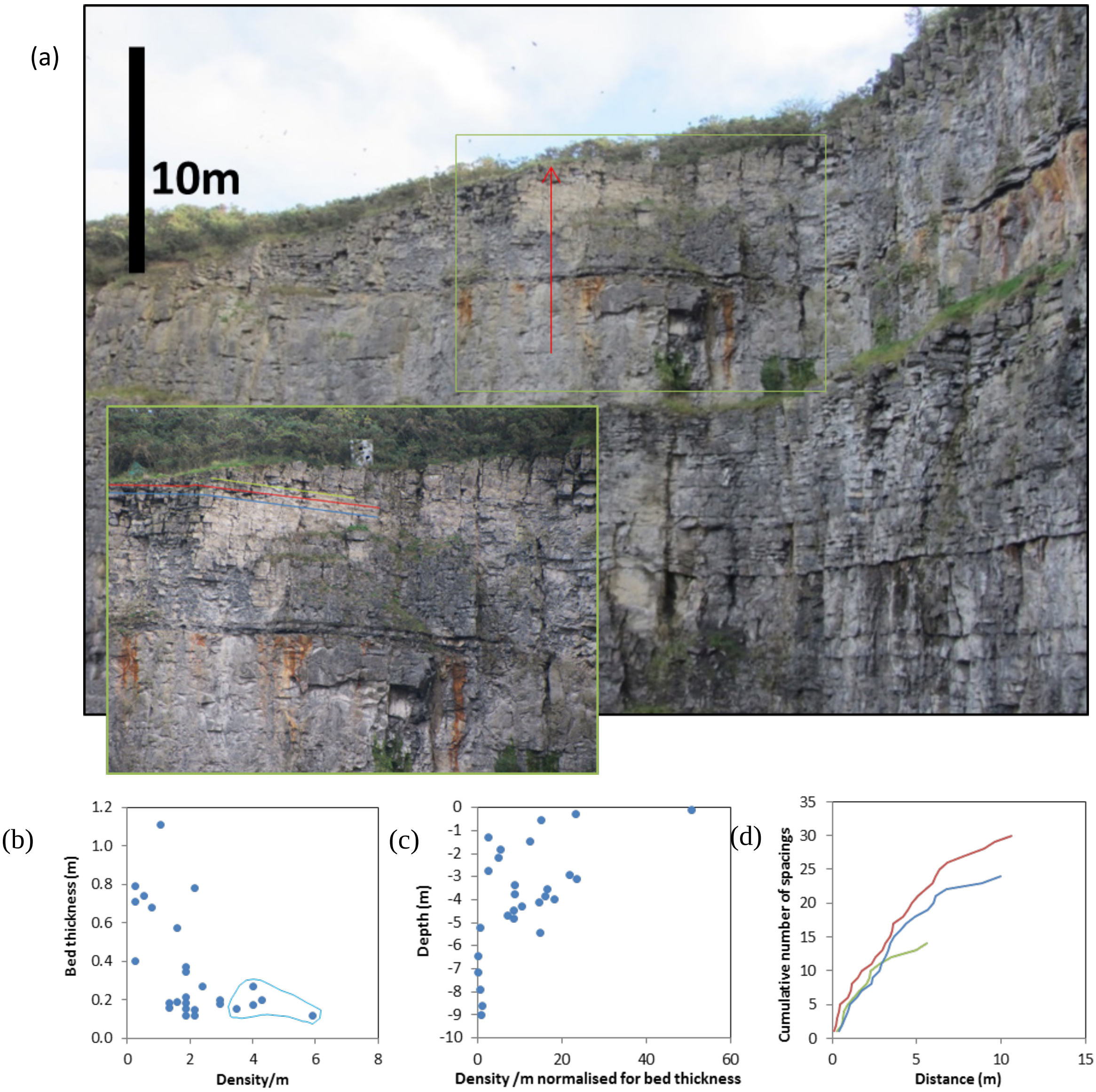


Fig. 2. (a) Joints developed with the upper part of the limestones in Ballyadams quarry, Kildare, central Ireland. The green box represents the inset photo, and some of the longer joints which extend deeper are jointed en-echelon veins associated with Cenozoic strike-slip faulting. The red arrow represents the path along which joint density measurements were measured for each of 25 beds (measured in 3.7m long sections), and then plotted versus bed thickness in (b) and depth in (c). (d) A plot of cumulative number of joint spacings with distance taken from left to right along the different coloured line samples shown on the inset photo in (a).

Estimating groundwater flow parameters

Groundwater parameters were estimated for the structures identified as intrinsically conductive: Cenozoic strike-slip faults and joints. Permeability (k) and porosity (p) were calculated for mechanical units of stratabound joints (Fig. 3), where k was estimated using the cubic flow law which assumes horizontal flow through regular spaced fractures with constant aperture. An increase in k associated with bed thickness (orange arrows on Fig. 3), arises from the consequently larger joint spacings and apertures, a feature which is compounded by the greater purity of thicker bedded limestones and their increased propensity to dissolution compared to more argillaceous thinner bedded limestones and shales. Depth-related upward increases in density and aperture result in higher k and porosity (red arrows in Fig. 3), with increased aperture and dissolution within thicker and purer limestone beds. The importance of this plot is not particular permeability values but the trends for different lithologies and with depth which reflect changes in joint density and aperture. However, the plot does not represent the connectivity potential of joint systems because, for example, it doesn't incorporate sub-horizontal delamination surfaces, which are important for connectivity between vertical joints, particularly where karstified. For example, the sub-horizontal jointing of bedding planes is likely to contribute significantly to why purer bedded limestones are considered more likely to provide a yield or better yields with a vertical well than massive limestones, such as the Waulsortian (Fitzsimons et al. 2005).

Groundwater flows and levels are used to parameterise the connectivity of NNW-trending Cenozoic strike-slip faults. This is illustrated for a system of Cenozoic strike-slip faults encountered along the K Zone of Galmoy Zn-Pb deposit, which lies within the hanging wall (and downthrown) side of a ca 200m displacement ENE-trending Carboniferous normal fault (Fig. 4). Flows intercepted on Cenozoic faults at the beginning of the K Zone (Fig. 4a) caused drawdown over 1Km in a N-NNW direction and 100m above in an adjacent borehole (the Ex B Drennan borehole, Fig.4a; Fig.5). In addition, smaller scale connectivity in the same, N-NNW direction is demonstrated by flow point A (Fig. 4a) having caused a decline in flows intercepted at the start of the K Zone, while interception of point B caused silting up of the main pumping well (WW2B), 390m to the N-NNW (Fig. 4a; McDermott pers. comm, 2017). The best measure of the connectivity between K zone flows and the resulting drawdown is the cumulative flows and the resulting drawdown. The cumulative flow until drawdown is 10,829 m^3/7 months and the cumulative flow until steady state has been reached, which appears to be from approx. Nov 07 (Fig.5a), is 247,934 m^3/59 months. It is the cumulative flows and the directional distance to which there is drawdown that represent the significant connectivity of the strike-slip faults along the K Zone, which is significantly aided by associated karstification in the limestone dominated Waulsortian Limestone Formation. The associated cumulative flows and drawdown could be used as targets for sustainable discharge from the K zone. Similar cumulative flows have been recorded on other Cenozoic strike-slip faults which generally represent the structures which most strongly localise groundwater flow and are therefore potential targets for groundwater supply. The WNW oriented horizontal K zone mine roadway (Fig.4a) represented a very efficient means of directly intercepting the higher flows from steep NNW-N trending faults compared to a vertical pumping well, a feature which reflects the anisotropic nature of associated aquifer properties and their classification.

ACKNOWLEDGEMENTS

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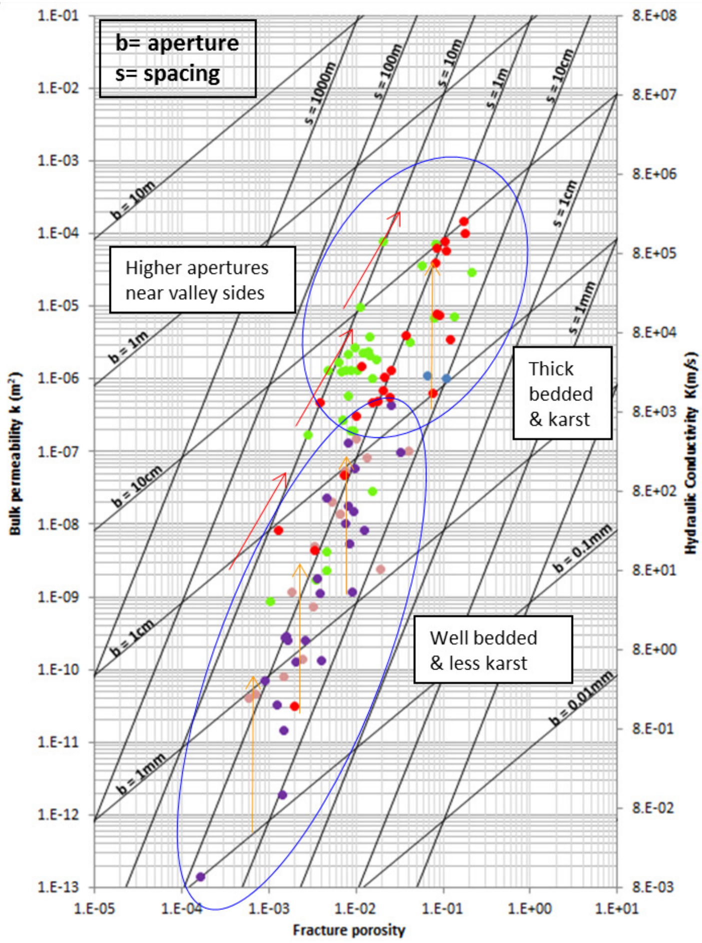


Fig. 3. Bulk permeability (k) derived from the cubic law, using average spacing ('s' on the lines of different spacing) and average aperture ('b' on the lines of different aperture) versus fracture porosity ($\frac{b}{s}$) for joints in individual beds/mechanical units in different lithologies (plot adapted from Reiss, 1980).

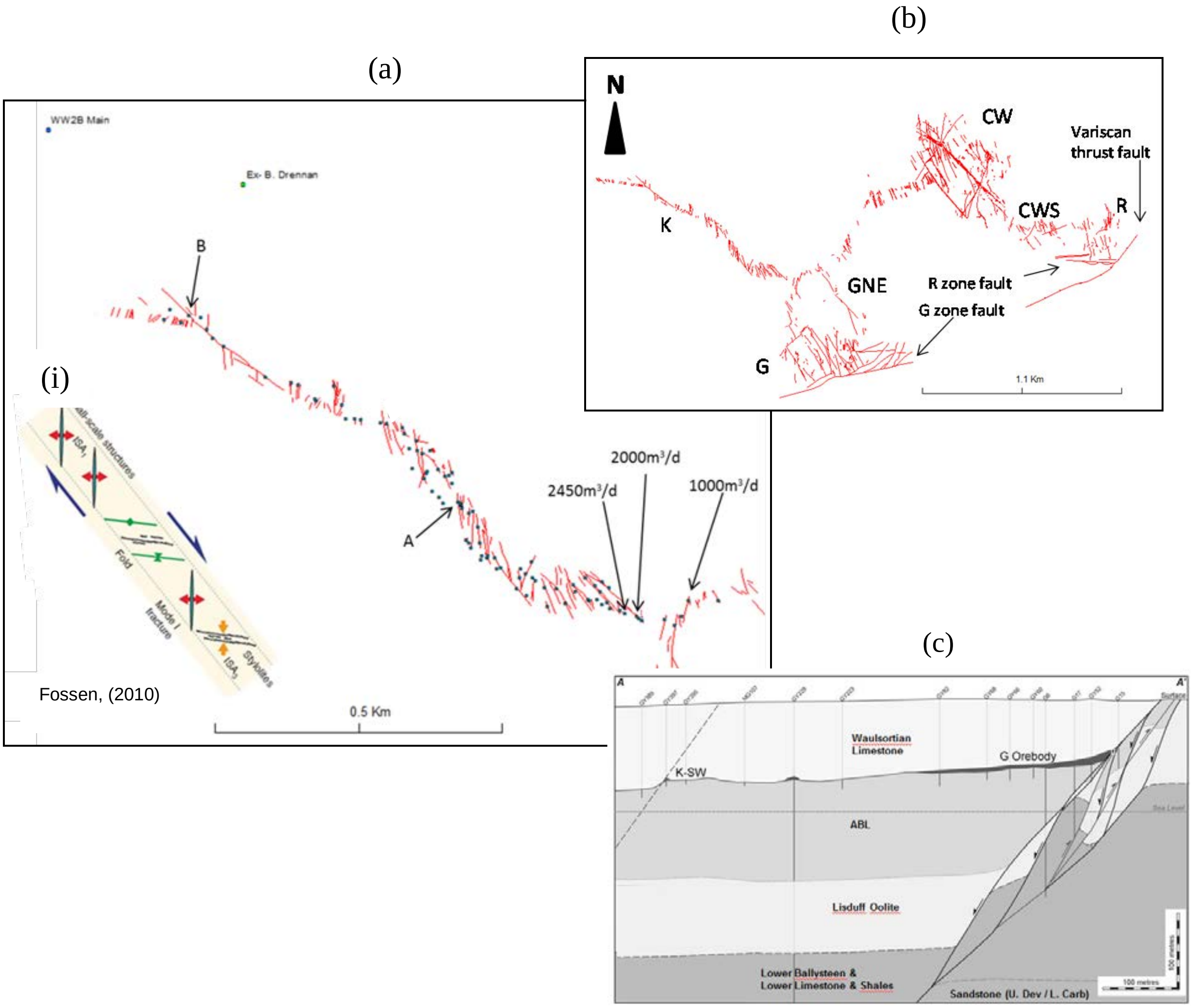
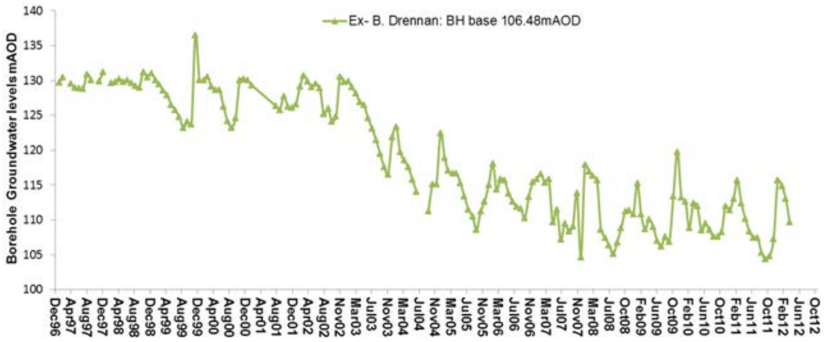


Fig. 4. (a) & (b) Maps of faults at base Waulsortian within the K zone roadway and the entire Galmoy Mine, respectively. Flow points (blue) of individual and clusters of Cenozoic strike-slip faults for which monthly flow time-series was recorded are shown in (a) and the three flow values labelled are some of the largest flows intercepted. The inset schematic diagram of (a) shows the orientations of minor structures associated with dextral strike-slip fault movement, including the more northerly dilatational fractures (Fossen, 2010). (b) An approximately N-S cross-section from the K zone through to the G zone ((a) inset), showing the G zone Early Carboniferous normal fault with its Variscan reactivation (Bonson et al. unpubl. research, 2012). The sequence and dip of the fault is the same as at Lisheen mine, 11km to the west. Both Lower Ballysteen and the Argillaceous Bioclastic Limestone (ABL) are argillaceous members that sandwich the limestone dominated Lisduff Oolite member, all within the Ballysteen Formation of the southern Irish Midlands (Archer et al. 1996).

(a)



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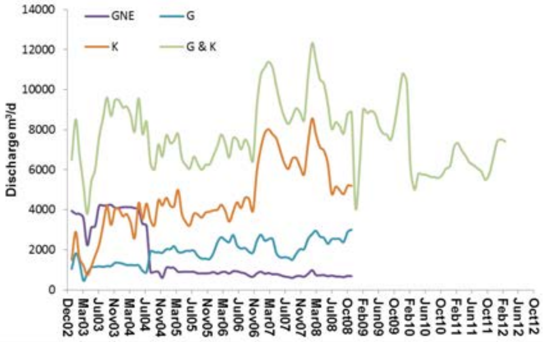

Fig. 5 (a) Groundwater levels in Ex B Drennan borehole. (b) Total flow time-series for G and K zones of Galmoy (Fig.4b). K and G flows were measured together from Dec. 2008. These data show that from approx. Nov 07 groundwater levels stop declining and flows generally match groundwater levels (see below), characteristics which are an indicator of steady state conditions.

GEOPHYSICAL INVESTIGATION OF STRUCTURAL GROUNDWATER PATHWAYS

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ABSTRACT

The on-shore and off-shore geometry of a fault zone is investigated using terrestrial and surface-towed marine DC electrical resistivity imaging, demonstrating groundwater flow and the tidal influence of seawater and in these zones.

INTRODUCTION

A variety of geophysical techniques can be employed to assist with the understanding of subsurface geology, while electrical and electromagnetic techniques generally prove most applicable in hydrogeological investigations e.g., (Gondwe et al., 2012; Martorana et al., 2014), in addition to seismic and potential field methods (see Table 1).

Table 1: List of commonly used geophysical methods in hydrology and the geophysical properties they sense (adapted from Binley (2015)):

	Geophysical Method	**Geophysical Properties**	**Examples of derived properties and states**
Electrical	DC resistivity e.g. VES, ERT	Electrical conductivity	Water content, clay content, pore water conductivity
	Induced polarization	Electrical conductivity, chargeability	Water content, clay content, pore water conductivity, surface area, permeability
	Spectral induced polarization	As above but with frequency dependence	Water content, clay content, pore water conductivity, surface area, permeability, geochemical transformations
	Self-potential	Electrical sources, electrical conductivity	Water flux, permeability
Electromagnetic	Electromagnetic induction e.g. FDEM, TDEM	Electrical conductivity	Water content, clay content, salinity
	Ground penetrating radar	Permittivity, electrical conductivity	Water content, porosity, stratigraphy
Seismic	Seismic e.g. Refraction, Reflection	Elastic moduli and bulk density	Lithology, ice content, cementation state, pore fluid substitution
	Seismoelectrics	Electrical current density	Water content, permeability
Potential Field	Nuclear magnetic resonance	Proton density	Water content, permeability
	Gravity	Bulk density	Water content, porosity

DC resistivity electrical imaging surveys have been used in a myriad of hydrogeological applications including groundwater/surface water interactions e.g., Nyquist et al. (2008), seawater intrusion e.g., Comte & Banton (2007) and Nguyen et al. (2009), salinity studies of lakes and water reservoirs e.g., Amidu and Dunbar (2008) and in the detection of zones of karstification and conduits in the examination of groundwater movement through highly heterogeneous karst regions e.g., Zhu et al. (2011). DC resistivity electrical imaging is also routinely used for fault detection e.g. Comte et al. (2012),Nguyen et al. (2007).

DC resistivity electrical imaging determines subsurface resistivities. The resistivity of a medium is predominantly a function of the porosity, pore fluid resistivity and clay content (Archie, 1942; Waxman and Smits, 1968). Variations in resistivities typically indicate changes in soil type e.g. from silts and clays to sands and gravels and changes in rock lithology e.g. from mudstones to clean limestones. Reduced resistivities within the rock can suggest weathering and/or karst zones with vertical low resistivities typical of fault zones.

Electrical imaging systems are also capable of operating in the marine environment to a limited capacity, allowing qualitative investigation of sub-seabed features (Belaval, 2003; Breier et al., 2005; Day-Lewis et al., 2006; Manheim et al., 2004). Surface-towed imaging systems provide an effect methodology to investigate beneath the sea/lake bed. In the towed system, a 2D pseudosection of the water column and sub-seabed apparent resistivities is generated. The depth of investigation and resolution of sub-seabed structures depends on factors including water column thickness (Day-Lewis et al., 2006; Loke and Lane (2004)) , salinity of the water column (Befus et al., 2014) and acquisition settings such as array configuration (Day-Lewis et al., 2006; Henderson et al., 2009; Manheim et al., 2004; Mansoor and Slater, 2007) and towing speed.

GROUNWATER FLOWPATH INVESTIGATION IN A KARST AQUIFER

The Bell Harbour catchment on the south coast of Galway Bay in Co. Clare (Fig.1a) is located in a pre-glacial valley. Limestone bedrock exposed in the surrounding hills comprises of gently dipping (~3º south), pure bedded and massive limestone (Pracht, 2004; Simms, 2005). Soil cover on the valley floor is generally 3m to 10m thick (GSI and RBD Consultants, 2004). The valley is open to the sea to the north and this region is characterised by a strong tidal range (Cave and Henry, 2011). Mapped faults limited to the south of the catchment, include the NNE-SSW trending MacDermot's Fault and minor parallel faulting. Faults have <200m sinistral displacement (GSI, 2005).

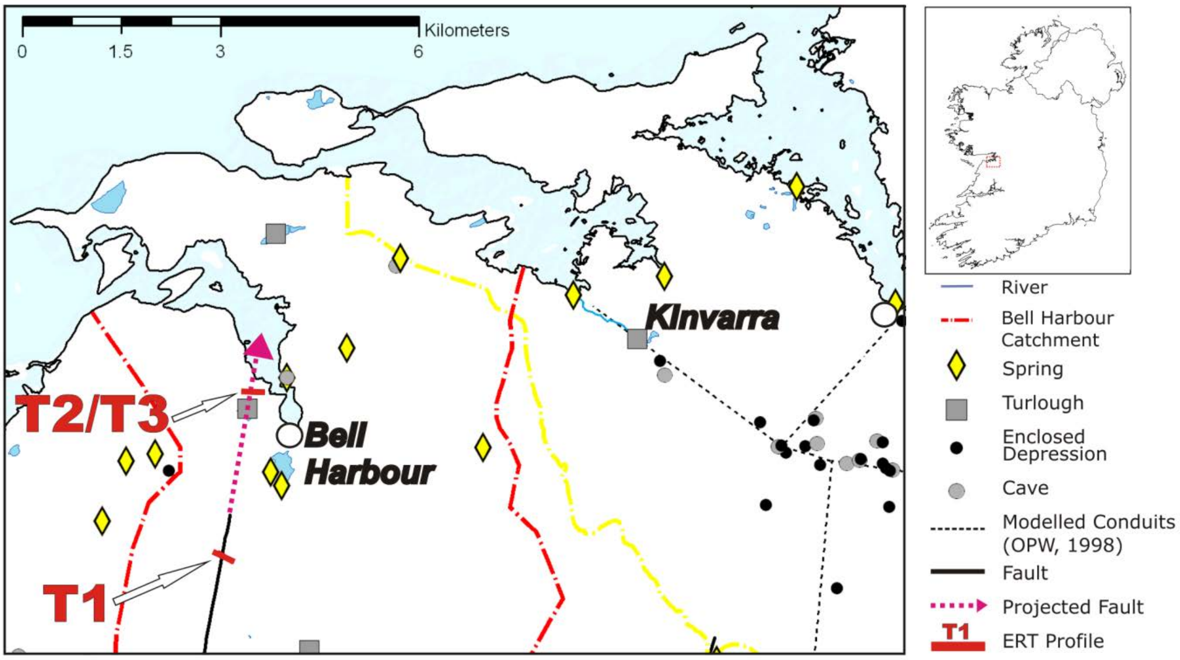

Fig.1: Regional setting of the Bell Harbour catchment showing selected hydrogeological and near-surface features (GSI, 2007) adapted from O'Connell et al. (2018). The location of terrestrial ERT profiles T1 to T3 and the extension of MacDermot's Fault are shown.

Bathymetric lidar data indicate that the coastal inlet in the north of the catchment is a shallow, flat-bottomed bay with seabed at elevations typically -1.5m to -2.5m OD ((Infomar, 2006); Fig.4). Seven circular seabed depressions were observed from aerial photographs and the lidar data, and have been interpreted as submarine sinkholes or submarine groundwater discharge (SGD) springs. There are three main groundwater-fed turloughs and a permanent, tidally influenced, brackish lake (Muckinish Lough) located within the catchment. Groundwater flow is dominated by near-surface (upper 5m to 10m) epikarstic flow and deeper linked pathways of fissures, joints and large conduits (Cronin et al., 1999; Perriquet et al., 2014). Projection of MacDermot's Fault northwards transects Muckinish Lough and six of the observed submarine sinkholes. Large variations in specific conductivities (SpC) for Muckinish Lough are linked to tidal movements, indicating a high hydraulic connectivity between the lake and the bay that may result from the development of conduits or weathered zones parallel to the fault core (Bense et al., 2013).

The influences of fault and tidal driven seawater ingress were examined by electrical resistivity tomography (ERT) profiles T1 to T3 (Fig. 1b). ERT profile T1 located approx. 3 km inland along MacDermot's Fault (Fig. 1, Fig. 2a) at elevations from 30 to 40 m OD, indicated thin soil cover (≤ 5 m). The inverse model resistivity for T1 is presented in Fig.s 2a and 2b, which show the results from two different array configurations, the Dipole-Dipole (DD) and the Wenner-schlumberger (WS). The limestone resistivities either side of MacDermot's Fault (black dashed line) are similar. A theoretical model (Fig. 2c) that simulates the field acquisition procedure for the T1 DD array was constructed to anticipate the subsurface structures giving rise to these inverse model resistivities. The forward model incorporated a thin soil layer and vertical low resistivity zones to represent fault and karst zones and the resultant inverse model resistivities is presented in Fig 2d for comparison with Fig 2b. The inversion of the theoretical model (Fig. 2d) provides a non-unique approximation for the observed DD (Fig. 2b). This model suggests Mac Dermot's Fault comprises of a 12m wide, low resistivity ~300 Ωm zone. Feature B to the west (white dashed line) may be a parallel fault and/or karst zone. Fault zones in carbonate rocks typically comprise a fracture-dominated zone flanking a fault core (Bense et al., 2013; Evans et al., 1997). This results in potentially increased effective porosities in the region parallel to the fault core.

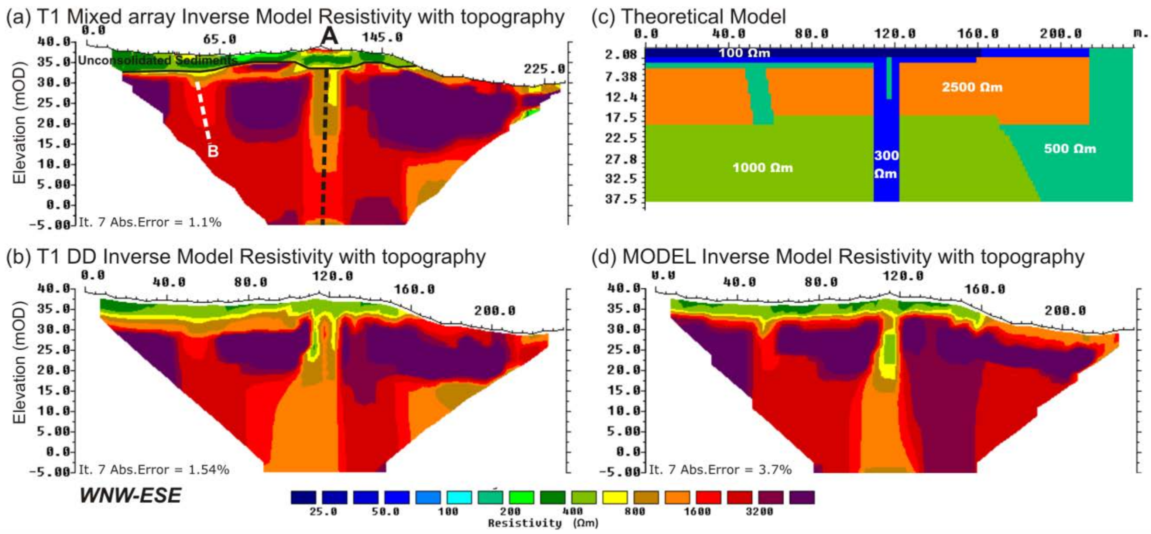

Fig.2: Modelled resistivities for T1 showing (a) Inverse model with topography using a mixed DD/WS array, (b) inverse model resistivities for DD array only, (c) the forward model and (e) inverse model resistivities adapted from O'Connell et al. (2018).

A nearshore ERT profile T2 recorded at distance of approx. 300m from the shore and an elevation of approx. 8 m OD (Fig. 1, Fig. 3a), indicates thin soils (typically <2m). Two vertical low resistivity zones (D and E) in the underlying bedrock have been interpreted as indicating two fault zones. Resistivities in the fault zones above sea level are typically 160 to 320 Ωm and drop to ≤30 Ωm below sea level suggesting seawater infiltration. Time-lapsed ERT was carried out across Zone E using a third higher resolution ERT profile (T3) over part of a tidal cycle during a prolonged period of low rainfall (T3, Fig.1, Figs. 3b and 3c). T3 confirmed the presence of low resistivities (~50 Ωm) in the fault zone at low tide and demonstrated an 80% drop in resistivity values (to < 10 Ωm) as tidal levels increased. This rapid resistivity change is indicative of saltwater flow in to this fault zone. Fault zone E, and possibly D, is therefore considered to be an extension of faulting through Muckinish Lough acting as a pathway for seawater movement into the lake.

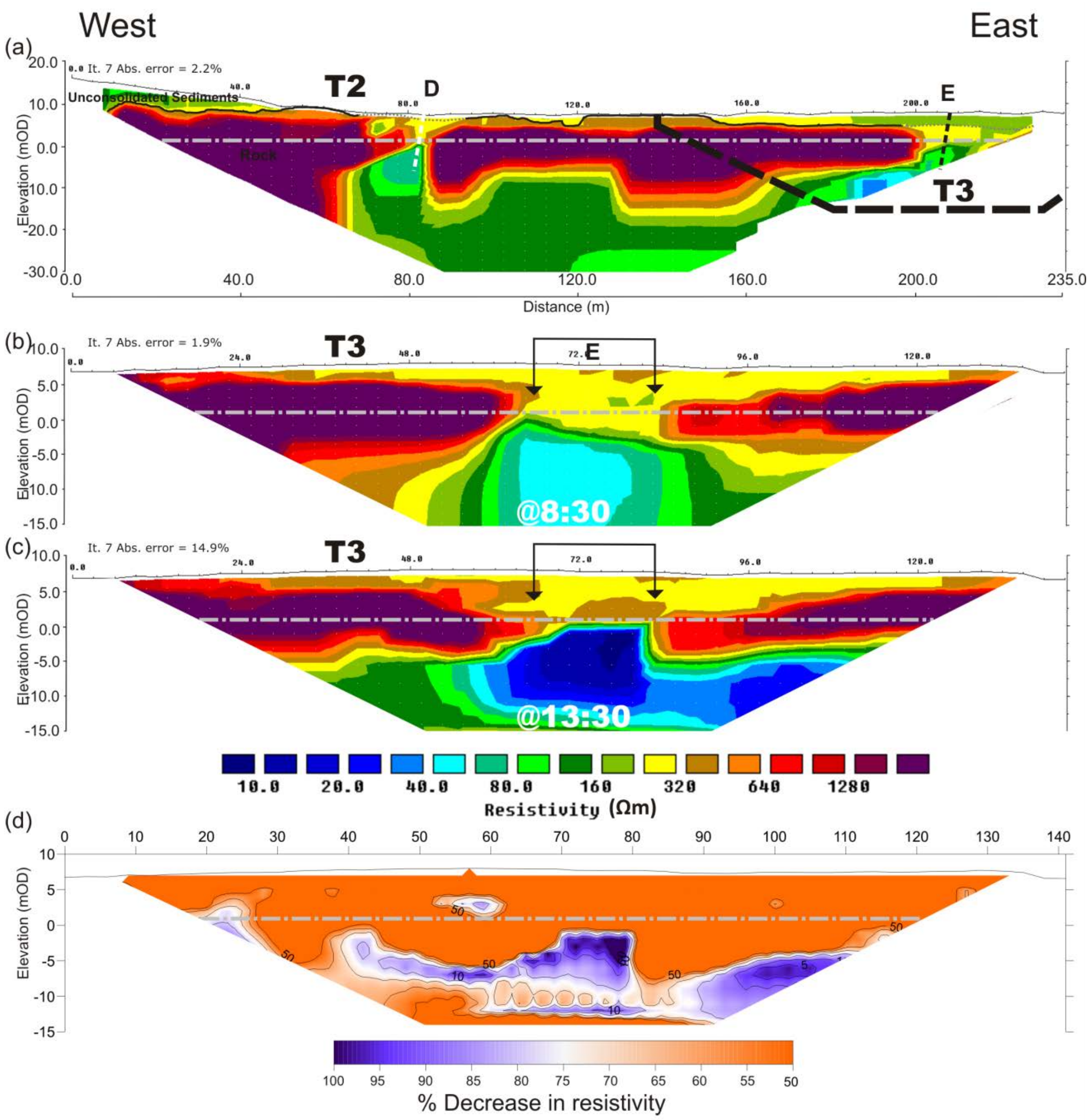

Fig. 3: Taken from (O'Connell et al., 2018) (a) Inverse model resistivities for T2 DD with possible fault zones D (white dash) and E (black dash). High water mark indicated by grey dashed line. Inverse model resistivities for T3 recorded across zone E at (b) low tide and (c) higher tide show a significant percentage decrease (d) in resistivities highlighting other flow-paths in addition to Zone E.

Surface-towed marine surveys were subsequently carried out at Bell Harbour to examine the extension of faulting off-shore towards the observed submarine sinkholes (Fig. 4). Surveys were conducted during medium to low tides using a 5m electrode separation and WS array. The depth of investigation below the seafloor achieved varied from 7m to 10m dependent on water depth and resistivity (Loke et al., 2013). The water depth was typically < 3m, but increased to as much as 11m over the sinkholes indicated in Fig. 4.

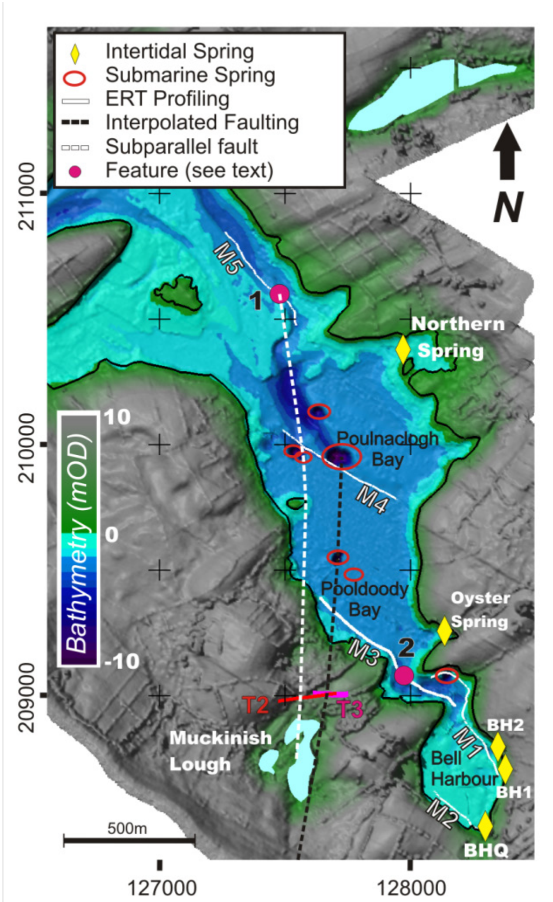

Fig. 4: Bell Harbour inlet bathymetry from combined digital echo sounder and lidar data (Infomar, 2006) showing the main intertidal springs, submarine springs/sinkholes and surface-towed marine geophysical profiles described in the text adapted from O'Connell et al. (2018). The inferred subterranean and submarine extension of MacDermot's Fault (black dashed line) and a possible NNW trending fault (white dashed line) are indicated.

The inversions of a sample of the surface-towed marine resistivity sections are presented in Fig.5. The sub-seabed sediment resistivities of ranged from 0.1-1.0 Ωm and were characteristic of unconsolidated seawater-saturated sediment (Befus et al., 2014). The surveys indicated that the sediments are generally < 3m thick in the south and along the edges of the inlet, and are up to 8m thick in Pooldoody and Poulnaclogh Bays in the centre of the inlet.

The underlying limestone bedrock resistivities were observed to be lower than their terrestrial equivalent, possibly due to current focussing in the saline water column (Day-Lewis et al. (2006). A number of vertical low resistivity zones observed in the bedrock (dashed black line on M3 and M4, Fig. 5a and 5b) have been interpreted as the indicating the northward extension of MacDermot's Fault towards the submarine springs. Other vertical low resistivity zones (dashed white lines on M4 and M5, Fig. 5b and 5c) similarily cut through a submarine sinkhole and appear to indicate a sub-parallel fault that may extend to the terrestrial Zone D on T2 (Fig.4, 3a). Increased resistivities within the sediments above this fault zone (see feature 1, Fig. 4, 5c) suggest possible groundwater discharge. Vertical low bedrock resistivities were also noted at other sinkholes/seabed depression locations e.g. beneath a seabed depression (feature 2, Fig 4, 5a), again with notable increased sediment resistivities suggest possible active groundwater discharge.

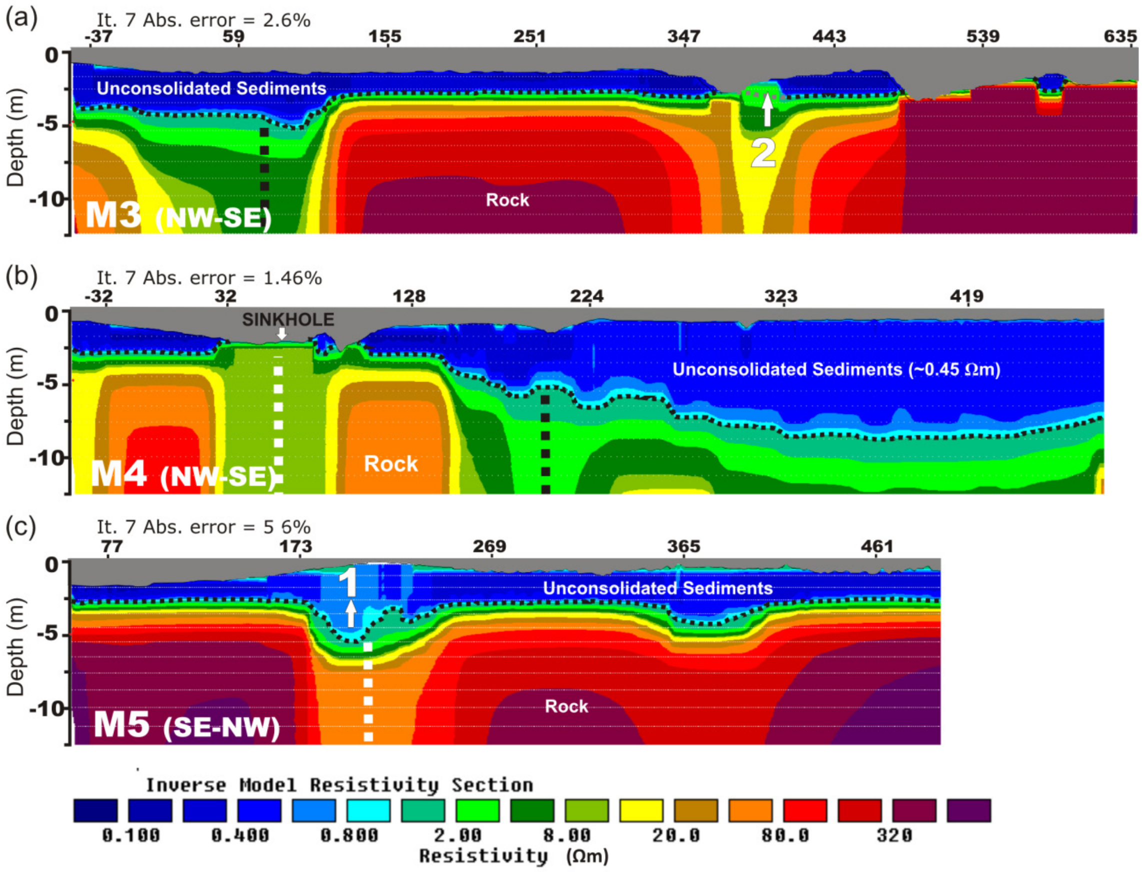

Figure 5: Surface-towed marine ERT profiles; with estimated base of unconsolidated sediments indicated by black dotted line (grey where the base is unclear), MacDermot's Fault extension indicated by black dashed line with subparallel faulting indicated by white dashed line, (adapted from (O'Connell et al. (2018))).

CONCLUSIONS

Groundwater discharge pathways have been examined with terrestrial and surface-towed marine electrical resistivity tomography. These geophysical techniques have provided evidence for structural influences on groundwater pathway development, complementing ancillary geological and hydrogeological evidence for fault controlled groundwater pathways. Surface-towed marine resistivity data confirmed the offshore extension of faulting and its influence on groundwater movement. Time-lapsed ERT surveying demonstrated tidally-influenced saltwater intrusion along MacDermot's Fault in the low lying part of the catchment.

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SESSION IV

FloodRisk2WellWater: A SOCIO-HYDRO(GEO)LOGICAL APPROACH TO COMBINING SCIENCE AND PRACTICE FOR MITIGATING FLOOD-TRIGGERED GROUNDWATER CONTAMINATION

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Keywords: Groundwater, flooding, health-behaviour, socio-hydrogeology, psychological models

ABSTRACT

Groundwater is the most extracted raw material worldwide and, in many cases, the least understood component of the water cycle. Thus, managing contamination threats to the subsurface is inherently challenging, both in terms of "Top Down" management and "Bottom Up" communication. Undesirable practises associated with non-expert groundwater users (e.g. choosing unsuitable extraction locations, lack of routine well-water testing and maintenance, etc.) can result in serious public health consequences (e.g. waterborne outbreaks). Moreover, additional groundwater management challenges arise when infrequent natural events, such as floods, trigger contamination episodes. Flooding can mobilize environmental pathogens via short-circuiting of hydrogeological pathways and subsequent negation of natural attenuation. To promote appropriate engagement between science and practice under sporadic hydrological conditions, an enhanced understanding of human-(ground)water interactions is required. In that context, Ireland represents a particularly relevant case-study, with high levels of private groundwater reliance (>720,000 private well-users), climatic and geological diversity, ubiquitous environmental pathogen sources, and increasing flood frequency/severity.

Accordingly, approximately 600 Irish well-owners were surveyed using two psychological models, namely "Risk-Attitude-Norms-Ability-Self-regulation" (RANAS) and the Health Belief Model (HBM). Employing established frameworks for examining human behaviour and risk perception is imperative due to the complexities associated with risk-based human-water interactions. For example, among well-owners that had not experienced flooding adjacent to their well (325/405), 29% believe water testing represents the most important post-event action. Conversely, less than 1% of respondents that had experienced flooding (80/405), proceeded to have their water tested, with 61% undertaking no post-event action of any kind. Moreover, 51% of respondents displayed optimism bias (i.e. underestimated likelihood of being affected by negative event). Study results may be used to identify current issues and develop increasingly successful, spatially and demographically bespoke flood-related interventions, including communication strategies between scientists and the public to promote desirable future practice, both in Ireland and further afield.

CHEMICAL ANALYSIS OF GROUNDWATER FOCUSING ON POTENTIAL ARSENIC CONTAMINATION OF DRINKING WATER SUPPLY BOREHOLES IN CHIKWAWA, MALAWI

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ABSTRACT

This M.Sc study was carried out to determine the potential for arsenic contamination of groundwater in the Kakoma Health District within the Traditional Authority of Chapananga, Chikwawa, Southern Malawi. Fieldwork was carried out in June and July 2015. This included collecting water samples from 93 boreholes in the study area. Electrical conductivity (EC) and temperature were tested in the field, along with arsenic using a Hach arsenic field test kit and microbiology using a HAWGO47S6 field kit. A hydrogeochemical analysis of collected samples was carried out to determine the concentrations of physical parameters (EC, total dissolved solids, pH and temperature) and chemical parameters (major anions and cations, total alkalinity, total hardness and arsenic).

Three water types dominated the data set - $CaCO_3$ type (T1), NaCl type (T2) and a third water type created from the mixing of T1 and T2 (T3). Using a Pourbaix diagram it was determined that the aquifer conditions were ideal for arsenic contamination, however no arsenic was discovered in the field or in laboratory results. Seasonal variation in the chemical properties of the aquifer was observed upon analysing data collected in 2014 with data presented in this study. This included dilution of most major ions and an increase in EC due to an increase in bicarbonate and sodium concentrations during the rainy season. Consequently, the following conclusions were reached:

- *Arsenic is not present in the geology, or is present in quantities lower than the detection limit of the field kit or;*
- *Arsenic concentrations in groundwater are seasonally influenced. If present in the geology it is not detectable during the dry season due to re-aeration of the subsurface but a sudden influx of water during the rainy season may change redox conditions within the aquifer, thereby remobilizing arsenic if present.*

AGRO-CHEMICALS IN IRISH GROUNDWATERS: PRELIMINARY FINDINGS OF ANTHELMINTIC DRUG OCCURRENCE IN IRISH KARST AND FRACTURED AQUIFERS

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ABSTRACT

Due to increased intensification of the food production system, agro-chemicals such as veterinary drugs have become a critical component in animal husbandry. Administration and application of these compounds to farm animals can potentially lead to their occurrence in groundwater. Anthelmintic drugs are widely used to control helminthic parasites that infect animals, particularly those exposed through pasture based production systems. There is very limited information available on the occurrence of anthelmintics in the environment, particularly in groundwater, which has resulted in them being considered potential emerging contaminants of concern. The aim of this work was to develop a comprehensive method for the determination of anthelmintic drugs (both parent and transformation products) in environmental water samples, in order to investigate the occurrence of these contaminants in an Irish groundwater setting. The preliminary findings are presented here.

A multi-residue Solid Phase Extraction Ultra High Performance Liquid Chromatography Tandem Mass Spectrometry (SPE-UHPLC-MS/MS) method was developed, validated and applied in a study for the determination of 40 anthelmintic residues in water samples, from high risk sites targeted in terms of source and pathway factors. In an initial pilot study in October 2016, up to five different anthelmintic compounds were detected in four of fifty-two groundwater samples (8%) and four of twenty surface waters (20%) analysed. Detections were of the order of 1-31 ng L^{-1}.During a second more comprehensive sampling round (March-April 2017), sixteen out of a total forty anthelmintic compounds were detected, with detections of one or more compounds at 22% of sites. Of these, up to six different anthelmintics were detected at 18% of groundwater sites, with up to five compounds detected at 39% of the surface water sites. Detections were of the order of 1- 41 ng L^{-1}.

[Keywords: agro-chemical, veterinary drugs, anthelmintics, emerging contaminant, groundwater, karst]

KARST "OPEN HEART SURGERY" TIME SERIES ANALYSIS METHODS AND VISUALISATION

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ABSTRACT

Karst aquifers have complex and original characteristics which make them very different from other aquifers: high heterogeneity created and organised by groundwater flow; large voids, high flow velocities up to several hundreds of m/h, high flow rate springs up to some tens of m3/s. They can be studied using very various methodological approaches. Still, the understanding of their internal dynamic behaviour remains very complex to assess as a result of the lack of knowledge about physical and structural information.

The use of different time series analysis, combined with other methods, gives access to a better understanding the internal behaviour of karst systems. Here we discuss the complementarity of some of those methods, with in particular the coupling of decomposition methods (multiresolution analysis and Ensemble Empirical Mode Decomposition) and rainfall-runoff (bucket-style) reservoirs, through the example of a karst system in France (Norville system in Normandy), and of a karst system in western Ireland (Manorhamilton, county Leitrim). In the case of Norville system, the simulated internal discharges of the model were showing interesting correlations with different observed time series (conductivity and turbidity), and with reconstructed signals from combined components of the decomposed discharge at the spring. This opens also perspectives regarding the application of a similar approach for distributed, numerical models. Ultimately, these insights on the internal functioning of karst systems can also be used in 3D models with specific attention in the visualisation of the hydrogeology of karst aquifers, which would also help to provide some tools for education and public engagement.

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POSTER ABSTRACTS

DESIGNING AN ARSENIC REMOVAL SYSTEM FOR MALAWI

Rashaqat Ali Siddiqui, B.Sc Geology; M.Sc Hydrogeology

ABSTRACT

Arsenic contamination in drinking water is a global concern with notable incidences of arsenic poisoning reported worldwide, particularly in developing countries. Contamination is generally a result of desorption of arsenic from its constituting geologic mineral. The aim of this study is to design an arsenic removal system applicable with Afridev pump and to establish its sustainability and efficiency to purify water.

The proposed design is structured to transfer abstracted groundwater to an overhead tank via showerheads. These will aerate and oxygenate the water. Newly oxidised iron will adsorb arsenic and precipitate. The water will filter through multiple sand layers, which will remove impurities and precipitated iron with arsenic. The removal rate of arsenic is dependent upon the amount of oxygen and iron/arsenic molar ratio present in water. The filtered water can be used for domestic purposes and will also be used to decrease the arsenic concentration in the aquifer via injection of oxygenated water.

Injected water will cause the aquifer to act as a geochemical reactor to adsorb arsenic to the iron present in the geology, and precipitate iron present in the dissolved state. This will potentially reduce the overall iron and arsenic concentrations hence remediating the aquifer.

HYDROGEOLOGICAL CASE STUDY OF TUFA SPRINGS AT TICKNICK PARK, DUBLIN, IRELAND

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ABSTRACT

The Ticknick Park development is part of the Cherrywood Strategic Development Zone. This development consists of four playing fields, associated roads and infrastructure, but will be constructed uphill of an area with European Union Habitat's Directive protected tufa springs. Results of a site investigation carried out between November 2016 and January 2017 showed the springs are fed from a shallow, thin limestone gravel aquifer overlain by a thin, incomplete aquitard and perched on boulder clay. The extent of the aquifer is estimated to be approximately 41,000m^2. Significant clay deposits are also present uphill of the aquifer, indicating the recharge zone is limited to areas of thin clay overlying the aquifer.

Monthly groundwater monitoring and water quality testing of the aquifer and springs, plus estimation of spring flow, was undertaken since February 2017. Results from this monitoring show groundwater flows from the north-west to south-east toward the springs. Based on spring flow, the area of contribution for the springs was found to be significantly greater than the estimated area of the aquifer. The additional spring flow is thought to be derived from uphill surface water run-off and throughflow infiltrating to the gravel aquifer.

U CONCENTRATIONS IN IRISH GROUNDWATERS: PRELIMINARY RESULTS FROM PRIVATE WELLS IN SE IRELAND

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Liam Morrison, School of Natural Sciences, National University of Ireland Galway, Ireland
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ABSTRACT

Uranium is a long-lived radionuclide typically present at the ppm level in rocks and soils, and at the ppb level in natural waters. Its presence in groundwater is a potential threat to human health (particularly linked to nephrotoxicity), due to its chemical toxicity and radioactivity (WHO, 2005). In the Irish context, elevated concentrations of U have been found in the past in some private wells, (EPA, 2005), leading to concerns about groundwater quality in some rural areas. Guided by geological and the Geological Survey of Ireland's Tellus stream sediment geochemical data, preliminary results for groundwaters from SE Ireland show elevated uranium concentrations in some private wells, in the vicinity of Baltinglass, Co. Wicklow, Hacketstown/Bagenalstown/Myshall-Nurney, Co. Carlow, and Castledermot, Co. Kildare. Results from Hacketstown suggest a link between dissolved U concentrations and groundwater bicarbonate alkalinity, indicating a control by the uranyl ion ($UO^{2+}{}_2$), likely linked to the occurrence of secondary calcite in the Tullow Pluton of the Leinster Granite. In the granite-derived groundwaters a strong correlation was also found between electrical conductivity and U concentrations implying that field-based conductivity measurements can be used as a rapid screening tool for elevated uranium contents in this geological setting. In addition, the nature of U sources (primary or secondary) is being evaluated by measuring the $^{234}U/^{238}U$ activity ratio of the dissolved uranium. Overall, a positive correlation between U and $^{234}U/^{238}U$ ratios was observed with two trends. Groundwater samples with the highest uranium contents also have the highest $^{234}U/^{238}U$ ratios suggesting secondary high-U minerals as sources. Furthermore, filtered and unfiltered samples were compared for their U concentrations and the $^{234}U/^{238}U$ ratios to understand the possible role of particulate matter and colloids in uranium transport.

Keywords. Uranium, Geochemistry, Groundwater, GIS

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RECHARGE CHARACTERISATION OF IRISH FRACTURED BEDROCK AQUIFERS AT CATCHMENT SCALE

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ABSTRACT

The hydrogeology of Ireland is characterized by fractured bedrock aquifers with low storativity and throughput capacity, which are often overlain by glacial tills. These two geological features have traditionally underpinned the approach used to estimate groundwater recharge within the Irish context. Furthermore, previous research has suggested that these two hydrogeological settings – and especially the aquifer storage capacity - have a larger control on local recharge than the meteorological factors.

Two-thirds of Irish aquifers are regarded as Poorly Productive. In terms of groundwater recharge calculations, the restricted capacity of these aquifers to accept and store water is translated into recharge caps. These caps, represent the maximum amount of water that an aquifer can accept per year and they are equal to 100 mm a^{-1} *or 200 mm* a^{-1} *depending on the corresponding aquifer sub-category. However, these values are approximate and improved estimations would be beneficial for more accurate recharge calculations and local groundwater resource assessments. Because of the impossibility of measuring the storage capacity of the aquifers directly, a recharge characterisation exercise has been carried out for two different study catchments with contrasting hydrogeological characteristics. A range of recharge calculation methods have been applied to each of the catchments to constrain recharge uncertainty and use it as a proxy to assess the specific yield. The approaches applied include: the water table fluctuation method, baseflow separation and Dupuit-Forchheimer calculations. The results obtained show a range of likely recharge values for each catchment, that would suggest some refined values for the recharge caps.*

SESSION V

ENGINEERED STREAMBEDS FOR WATER QUALITY ENHANCEMENT IN URBAN STREAMS

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ABSTRACT

The hyporheic zone (HZ) has potential to mitigate nonpoint source pollution in urban streams, but limited flows and inefficient exchange typically constrain effectiveness. Engineered streambeds, called Biohydrochemical Enhancements for Streamwater Treatment (BEST), are proposed to enhance water quality. BEST are subsurface modules that utilize hydraulic conductivity modifications to drive hyporheic exchange into the streambed and to control residence times. Reactive geomedia increase pollutant reaction rates. Groundwater modeling was performed using MODFLOW to obtain residence times (RT), and contaminant removal was calculated using rate constants from the literature. Contaminant removal potential was relatively consistent among BEST when pollutant reaction timescales were similar to RTs. However, BEST with very long RTs were less efficient. Most contaminants were attenuated within a series of BEST 50m in length, suggesting that BEST could be an effective stormwater Best Management Practice (BMP). Experiments were conducted in 15m long outdoor flumes: one with a sand-only engineered streambed, the other with BEST modules. Conservative tracer and resazurin (a surrogate for reactive pollutants) tests were conducted, with observations analyzed by stream transient storage models. Results demonstrated that BEST increased the effective HZ size and resazurin transformation by ~50% compared to the control. Numerical simulations of extended reach lengths up to 30m showed that BEST could achieve 1-log removal of resazurin in 125m, versus 190m in the all-sand BMP, and 460m and 750m in previously simulated urban streams. These results emphasize the potential of BEST to improve urban stream water quality.

INTRODUCTION

Degraded water quality in urban and agricultural rivers are widely recognized,[1] as is the potential of the streambed hyporheic zone (HZ) to treat contaminants.[2–6] HZ exchange is a growing focus of stream restoration.[7–9] Calls to increase HZ exchange fluxes during river restoration efforts[3,10] are laudable, but increasing HZ fluxes alone may not result in improved reach-scale water quality.[11–15] Many studies have emphasized the importance of matching HZ residence times to reaction timescales of interest to optimize contaminant attenuation,[16–21] but no study has attempted this in practice. Our research focuses on engineering urban streambeds to have increased residence time by designing streambed architecture and hydraulic properties, and to have enhanced pollutant removal by incorporating reactive geomedia.

Contaminants may have dramatically different reaction timescales.[22,23] HZ residence times in field studies span at least 6 orders of magnitude - from seconds to days.[24] Residence times are difficult to measure due to complex and variable spatiotemporal patterns.[25] Residence times and HZ fluxes at the reach scale are often modeled using a “dual-domain” approach wherein relatively slow hyporheic exchange flows are represented by immobile transient storage compartments.[26,27] Our recent study used a groundwater model to calculate residence times and 1-D flowpaths upon which reaction paths were superimposed.[54] Hyporheic restoration design efforts should be customized to enhance the removal of contaminants of concern, which are site-specific. The top three causes of total maximum daily load (TMDL) impairment as defined by the Clean Water Act in the U.S. are pathogen indicators, nutrients, and metals.[28] Each of these contaminant classes has different biogeochemical attenuation processes.[29–34] Pathogens and metals, and soluble phosphorus, can generally be attenuated (e.g., via sorption and inactivation/predation[35] or (co)precipitation,[31,36,37] respectively), and ammonia can be oxidized,[38] under aerobic conditions that are typical of short hyporheic residence times. Conversely, nitrate removal (denitrification) occurs predominantly under anaerobic conditions, which require 1) longer hyporheic residence times to develop in the bulk[17,39] or microzone[40] domains, or 2) mixing with anaerobic groundwater. Unfortunately, there is no hyporheic or stream restoration Best Management Practice (BMP) that explicitly controls hyporheic residence times or stream-groundwater mixing dynamics. Likewise, BMPs intended for stormwater quality improvement have essentially ignored the potential of HZ modifications. A crediting system for hyporheic denitrification via stream restoration was recently established as part of the Chesapeake Bay Nutrient TMDL.[41] This innovative framework grants HZ denitrification credits—based on volumetric denitrification rates derived from local studies—to restored sub-reaches with demonstrated hyporheic exchange.[41,42] However, practitioners need better BMPs to optimize hyporheic treatment of contaminants, especially for nitrogen.

As stream restoration crediting evolves,[43,44] new and improved BMPs are needed to meet site-specific water quality goals. For example, cross-vanes (V-shaped rock weirs) are one of the most popular and effective hyporheic restoration BMPs[45,46] and are specifically mentioned by the Chesapeake Bay TMDL program[41], yet they have minimal impact on in-stream nitrate concentrations at the reach scale.[47,48] Even when cross-vanes drive large hyporheic exchange fluxes, hyporheic residence times tend to be too short to create anaerobic, net-denitrifying conditions.[11] Cross-vanes have other benefits such as channel stabilization, habitat heterogeneity, stream aeration, and improved aesthetics,[45] but the above studies show that their hyporheic denitrification performance is underwhelming. Cross-vanes and similar structures also have minimum spacing requirements depending on discharge and slope (e.g., one structure every 10-200m of channel length[45]) and create only localized effects,[11,47] restricting the fraction of streamwater that can be treated in a given reach length. Taken together, these constraints suggest that meaningful water quality changes could require tens of kilometers of stream restoration, even in low-order streams.[47,48]

To effectively target removal of any given contaminant, hyporheic residence times should be tailored to promote appropriate biogeochemical conditions for the reaction of interest and ensure the reaction proceeds meaningfully toward completion.[12,16,49,50] Building on the concept of streambed hydraulic conductivity (K) modifications to drive hyporheic exchange,[51-53] direct engineering of streambed sediments with Biohydrochemical Enhancements for Streamwater Treatment (BEST) was proposed as a novel means to enhance hyporheic exchange and modify hyporheic residence time distributions.[54] In concept, BEST modules include alternating regions of relatively low- and high-K to drive hyporheic exchange, with reactive geomedia amendments (e.g., biochar, woodchips, recycled industrial materials) to increase contaminant attenuation rates. BEST modules have potential to control residence time distributions via the 1) spacing of low-K regions, and 2) careful selection of the permeability of high-K regions. Numerical modeling may demonstrate the potential to customize BEST modules according to these two properties to effectively treat various contaminants of concern, especially in small streams.[54] Experimental systems provide evidence on the effectiveness of BEST modules. Select modeling and experimental results are provided below.

BEST ENGINEERED STREAMBEDS FOR URBAN WATER QUALITY IMPROVEMENT

Figure 1 depicts our pilot-scale experimental system at the Mines Park Water Reclamation Test Site on Colorado School of Mines campus. The triangles are low-permeability blocks that drive hyporheic exchange from the surface water into the streambed. The areas between the triangles consist of porous media with relatively high hydraulic conductivity designed to cause hyporheic exchange and amended with geomedia designed to treat a specific contaminant or suite of contaminants, either within a single module, or with different BEST modules in series to target different contaminants. Figure 2 shows a single BEST module in an urban stream section. With a homogeneous streambed, HZ flow would occur approximately parallel to the stream flow, albeit at a much slower rate. With the low-permeability triangles, the stream flow is forced into the subsurface hyporheic zone (HZ). With the appropriate geomedia and geochemical conditions, and when the residence time of HZ flow is similar to the reaction time for a pollutant, the pollutant may be transformed.

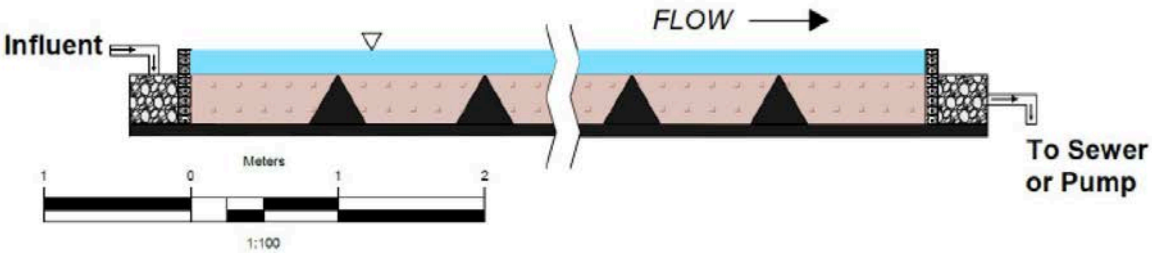

Figure 1. Schematic of pilot-scale experimental BEST engineered streambed at Colorado School of Mines.

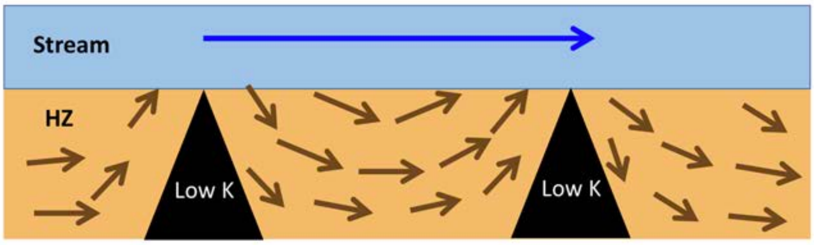

Figure 2. Conceptual model of a single best module, showing enhanced HZ flow and exchange.

GROUNDWATER MODFLOW MODELING FOR BEST ENGINEERED STREAMBEDS

Herzog et al.[54] presented a proof-of-concept modeling system for BEST modules for a variety of contaminants by using the MODFLOW groundwater model to calculate residence times and MODPATH to calculate resulting 1-D flowpaths upon which reaction paths were superimposed. Figure 3 shows an example of modeling results for one of several hypothetical geomedia simulated. For these simulations, the low-permeability blocks (in black) were simple rectangles (we subsequently determined triangles were more effective). Figure 4 shows the simulated removal of various contaminants from a 1 L/s, 1m wide stream at 1% slope within a single BEST module (1m downstream length). First-order reaction rate constants for numerous contaminants for various types of geomedia were taken from the literature, and the analysis uses representative geomedia rate constants from this compilation (for details, see Herzog et al.[54]).

The number of BEST in series needed to completely remove a given contaminant can be estimated. K2 and K3 BEST show good performance. Using K3 BEST, the majority of modeled contaminants could be removed by several log orders with only 50m of BEST in series: Cd(II), Zn(II), nitrate, and Pb(II) require 55.5, 85.5, 138, and 293 m, respectively. K1-K3 BEST are ineffective for very slow reactions (e.g., Pb(II) removal via Mn-oxide sands). 99% *E. coli* removal was simulated to be achieved in less than 40m of BEST in series.

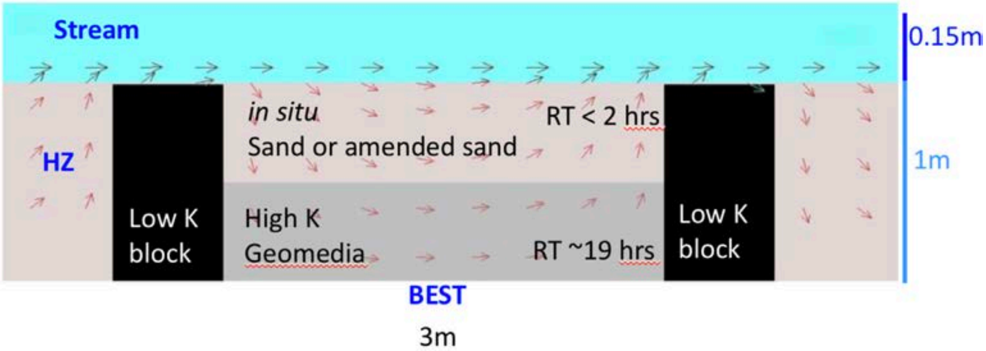

Figure 3. Spatially variable flow paths and residence times (RT) for a representative BEST system, as produced by MODFLOW/MODPATH. (Adapted from Herzog[57]; for more details see Herzog et al.[54])

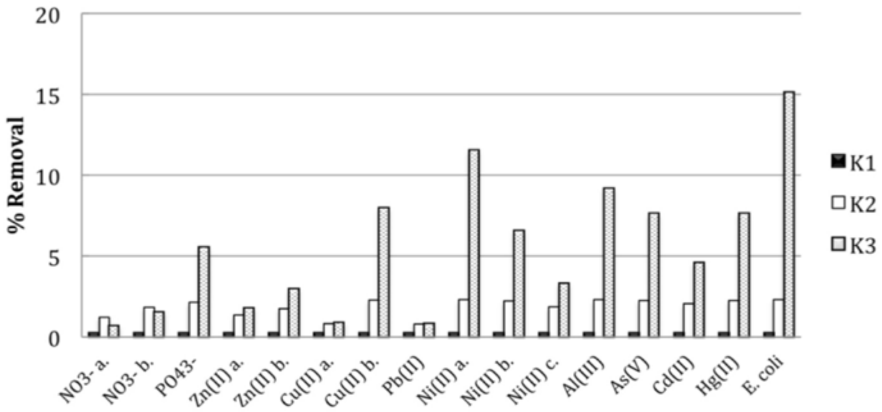

Figure 4. Simulated removal of various contaminants from a 1 L/s, 1m wide stream at 1% slope within a single BEST module.[54] K1 is relatively low permeability (fine sand/silt), and K3 is relatively high (coarse sand). (Adapted from Herzog[57]; more detail in Herzog et al.[54])

EXPERIMENTAL STUDY AT PILOT SCALE FACILITY USING CONSERVATIVE AND REACTIVE TRACERS

BEST modules at our pilot-scale facility (see Figure 1) were comprised of a sand-woodchip mix for general applicability to removal of numerous contaminants (see Herzog et al.[55]), particularly nitrogen and indicator bacteria.[54] The BEST stream and an all sand "control" (i.e., no low-permeability barriers) were installed side-by-side. To examine transport behaviors, tracer tests with NaCl salt (a conservative tracer) and Resazurin (Raz) salt were conducted. NaCl was used to test for differences in transient storage between the BEST and Control, whereas Raz and its transformation product Resorufin (Rru) were used as indicators to evaluate changes in water quality. Raz degrades to Rru under relatively aerobic conditions, so this system is analogous to transformation of other pollutants that degrade under oxygenated conditions. Tracer breakthrough curves were modeled using STAMMT-L,[27] a one-dimensional dual-porosity transient storage model that can simulate conservative and reactive transport in stream hyporheic zones. At the flow rate in this study, there was no observable surface transient storage (i.e., pools, eddies), so all transient storage identified in the model is interpreted to represent subsurface HZ transient storage. The calibrated model was then used to evaluate BEST performance over realistic stream reaches much longer than the pilot scale experimental system.

Using the STAMMT-L model, Raz "pollutant" removal via degradation to Rru in a hypothetical BEST system was compared to removal in actual urban streams in Wyoming, USA (Jackson Hole and Teton Pines), where STAMMT-L parameters were previously determined by Gooseff et al.[56] The all-sand "control" and a concrete channel were also evaluated using the model. The simulated Concrete channel showed negligible Raz transformation, even at extended distances (C/C_0 = 99.6% at x = 300m), due to the lack of hyporheic transient storage. This is consistent with literature describing minimal transformation of Raz in surface waters over experimental timescales. Both the Control and BEST stream simulations demonstrated substantial Raz attenuation, but BEST presented a clear improvement relative to the Control. Notably, BEST achieved 1-log removal of Raz at approximately 125m, compared to 190m for the Control. In other words, a sand-only Control stream would to be 52% longer than a BEST stream to achieve 1-log removal. Of course, the Control stream itself could be considered a sand-filter BMP that would operate much better than an actual urban stream. Thus, it is not surprising that the Control also exhibited substantial Raz attenuation or that both urban streams from Gooseff et al.[56] provided intermediate water quality benefits relative to the Control and Concrete channels. The example urban streams–Jackson Hole and Teton Pines–required 460m and 750m, respectively, to achieve 1-log Raz removal.

More recent experiments at our Mines Park Water Reclamation Test Site evaluated the removal of nutrients, metals and organics with BEST comprised of woodchip/sand mix. These results are currently being analyzed for manuscript preparation. Results are encouraging, particularly for nitrate and pesticides, although different geomedia for metals and trace organics are being evaluated for future use.

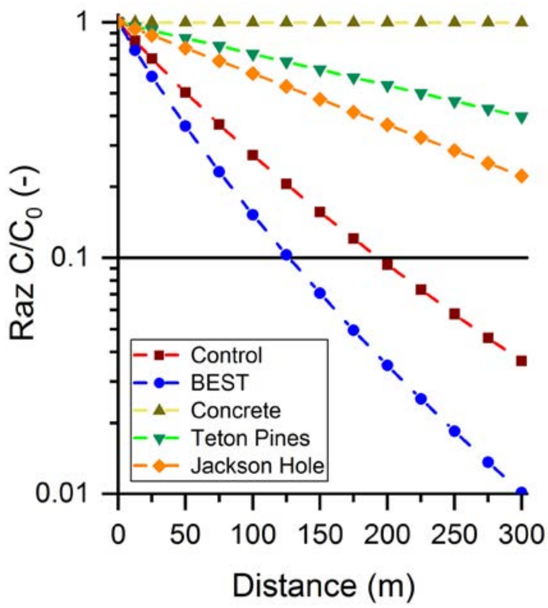

Figure 5. Steady-state Raz concentrations as a function of downstream distance in simulated Control, BEST, Concrete, and urban channels. (Figure adapted from Herzog et al.[57]; more details in Herzog et al.[56])

BROADER IMPACTS AND IMPLICATIONS

BEST can 1) drive hyporheic exchange, 2) be designed to achieve specific residence times, and 3) improve contaminant attenuation in real-world systems. These findings are directly relevant to stormwater management and stream restoration, which are increasingly being used for treatment of contaminants of concern. BEST offers a simple, passive, and customizable process by which existing stream channel modification efforts can be improved for better water treatment function. A treatment train approach pairing BEST with other BMPs could be especially effective. For example, BEST could be sited in the effluent channels of detention ponds, thereby combining the strengths and offsetting the weaknesses of both BMPs. Ponds attenuate peak flows and settle suspended solids that could otherwise bypass or clog BEST but are unable to attenuate many dissolved contaminants. BEST could attenuate these dissolved stormwater contaminants from an entire design storm as it is slowly released from the detention pond. BEST could also be used in many other analogous contexts. For example, use in agricultural drainage or return flow ditches is promising. BEST streams could be used instead of pipes to convey recycled water to receiving water bodies or aquifer recharge zones, improving the quality of recycled water and creating new stream-side habitat, greenspace, and recreation.

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SESSION VI

THE REMEDIATION OF THE EAST TIP ON HAULBOWLINE ISLAND

Cormac Ó Súilleabháin
Cork County Council

ABSTRACT

In August 2011 Cork County Council, as agent for the Minister for Agriculture, Food and the Marine, embarked on a programme for the rehabilitation of the East Tip, Haulbowline Island, Co. Cork. The objective is to address the legacy associated with the disposal of steelwork's waste on a sand spit in Cork Harbour over a 40 year period. Completion of works will see the site transformed into a public recreational amenity for the beneficial use of the local communities.

Whilst the regularisation process was initiated on foot of a European Court of Justice judgement (ECJ494/01) and associated Letter of Formal Notice [C(2010)6536] the Irish State is committed to ensuring that the remedial solution and amenity development are completed in accordance with current relevant national and international best practice and guidance.

The design of the remedial solution for the East Tip and the preparation of the various application documents (i.e. Planning Application, Waste Licence Application and Foreshore Licence Application) was predicated on the findings of the Detailed Quantitative Risk Assessment (DQRA) - it's function being the quantification of risk to human health and the environment posed by the site and the identification of the remedial solution pertinent to the mitigation of those risks. This in turn was informed by the results of a comprehensive site investigation. Planning permission for the proposed design solution was granted on May 1st 2014 and a waste licence was granted on the 19th June 2014. Construction works are scheduled for completion in December 2018. Further information on the project is available in the Latest News section of the project website www.corkcoco.ie/haulbowline.

PLANNING AND DEVELOPMENT WITHIN A KARST DOMINATED LANDSCAPE IN COUNTY MONAGHAN: CASE STUDIES AND EXPERIENCES

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ABSTRACT

County Monaghan has a concentrated area in the south of the county dominated by karst landscape. A number of local features are present including turloughs, swallow holes, depressions, springs and caves. Planning and development within this area represents unique challenges as most other parts of the county with some exception are dominated by poorly productive aquifer overlain by poorly drained gley soils. Three case studies represent the types of issues faced through the planning process in this karst area. The 1st example is a duck rearing unit which wants to landspread all organic waste locally. The 2nd example is a nursing home discharging wastewater effluent to ground and the 3rd example is an industrial development. Each example lacked basic hydrogeological information from the outset making it difficult to make an informed decision. For example no hydrogeological reports on any of the application were submitted. Groundwater quality in the area is good based on the most recent EPA assessments however nitrate concentrations in surface water are more elevated in this area compared to all other parts of the county. Furthermore cryptosporidium detection occurred in the local drinking water supply in 2009. This assessment demonstrates that sound hydrogeological assessments including source pathway and receptor linkages are needed in this case for larger scale developments in a karst dominated area and that often such assessments are absent in most applications.

INTRODUCTION

County Monaghan is located in the north east of the Republic of Ireland. It is a relatively small county with a population of 60,000 approximately. The county is known as the drumlin county and for good reason. The name “drumlin” originates from the Irish “dromnin” which translates to “low hill”. Monaghan is home to some of the most dramatic formations of drumlins found anywhere else on the island. Throughout the county there are rolling drumlin ribbed moraines from north to south. The county is divided into different geological areas with the point of interest for this paper originating in the far south of the county around Carrickmacross. The area is well known locally for its various karst features and disappearing streams. There are a number of karst features that have been surveyed previously including enclosed depressions, turloughs, caves, springs and sinkholes. The area is dominated by freely draining subsoils underlain by mainly Lower Carboniferous limestones and areas of namurian sandstones, shales and permo Triassic sandstones, mudstones and gypsum. The area is home to a large gypsum mine. The area is also home to a regionally important karstified aquifer which is the main water supply for the greater Carrickmacross area with a number of boreholes located around the area. This is unique in itself as the county is predominately poorly productive aquifer (generally unproductive except in local zones).

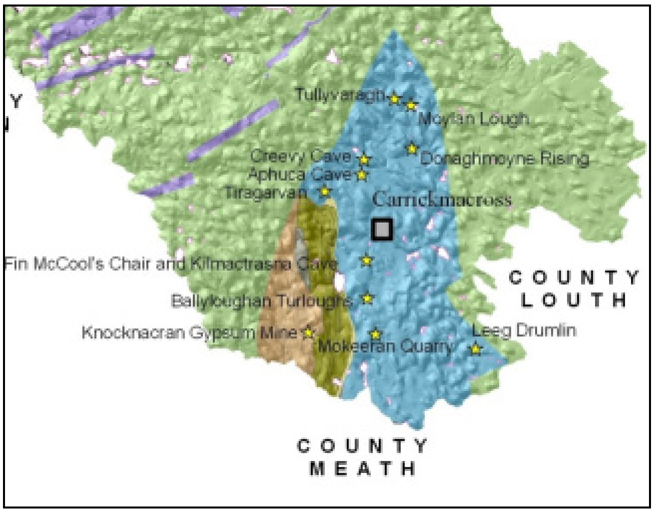

Fig 1. Map of Carrickmacross underlying geology with some noted karst features. Source: (Robert Meehan et al, 2013)

The area has some spectacular, unique features however this presents an increased risk to groundwater quality as the pathway linkages from surface to ground are rapid due to the limestone character of the area. Here I will give examples of my experience in Monaghan County Council water quality unit on assessing planning applications for different types of developments within this unique area and explain the various problems and pitfalls often associated with assessing such applications for development.

PLANNING AND DEVELOPMENT

Monaghan's main industry is the food and agriculture sectors. Dairy and dry stock farming can be found throughout the county. In addition something unique about Monaghan is the number of poultry production units. The latest data from the department of agriculture indicates that Monaghan is home to approximately 10 – 13 million bird places at any one time with actual annual throughput of birds being much larger. This includes production of broiler, duck, layers, turkey and a number of hatching facilities. Year on year this sector continues to grow. In addition to this sector a large number of piggeries and mushroom production units can be found throughout the county. There is also a large number of rural one of housing, industrial estates, small villages and towns and commercial developments. National policy on food production sets the bar high for increased output with Harvest 2020 and Foodwise 2025 the main frameworks for such development. As the sector grows Monaghan has seen a large increase in the numbers of planning applications for the food production sector including agriculture.

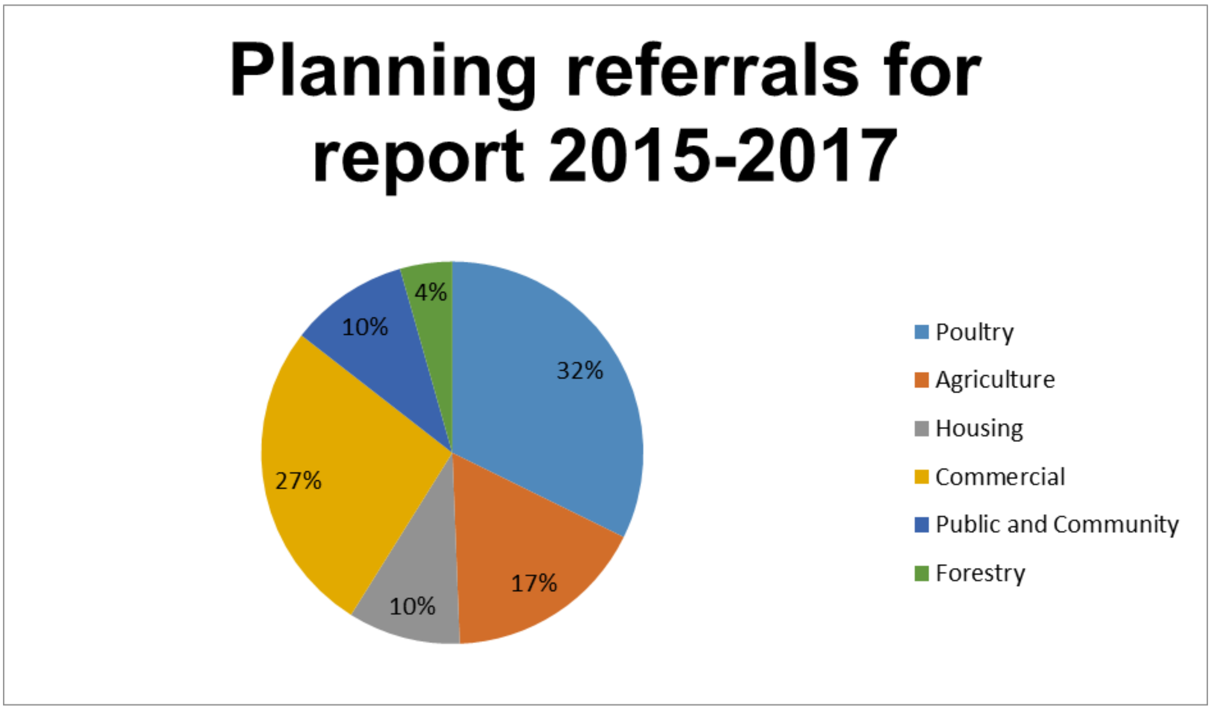

Fig 2. Development type referrals from 2015 – 2017 (total number of referrals for this period is 725).

With such a large volume of applications it is essential that they are adequately screened for any potential impacts they may have on groundwater especially in the karst area of the county. Two case studies will be presented here to demonstrate the experience of the water quality unit when trying to assess any such impact. The water quality unit is made up of 4 environmental technicians, 1 chemist and 1 engineer. Planning applications are referred to the team on a weekly basis for report. Generally our reports cover all potential environmental impacts that may occur to surface and groundwater quality, fisheries and habitat impact, and waste management.

PLANNING POLICY

Key policy for the protection of groundwater is included in the current county development plan and the new draft county development plan. The summary of the most important policies are:

Policy WPP3 To protect known and potential groundwater reserves in the county. In assessing applications for developments the planning authority will consider the impact on the quality of water reserves and will have regard to the recommended approach in the Groundwater Protection Response Schemes published by GSI. The employment of the methodology identified in the 'Groundwater Protection Scheme Reports for County Monaghan public supply sources' (available at www.gsi.ie) and 'Guidance on the Authorisation of Discharges to Groundwater' (available at www.epa.ie) will be required where appropriate.

Policy WPP4 To require submission of a water protection plan and detailed site drainage plans with all planning applications. Maps of sensitive areas waters, a Water Protection Plan Checklist (Appendix 16) and latest water body status information at www.catchments.ie will assist in the preparation of plans at application stage.

Policy WPP8 Ensure that industrial or intensive agricultural developments generating manure, organic fertilisers or sludge, that are dependent on off-site recovery or disposal take account of sensitive area mapping including lands with impaired drainage/percolation properties, steeply sloping topography and lands where rock outcrop and extreme vulnerability of groundwater is present. The EPA guidance document 'Landspreading of Organic Waste' shall be consulted when assessing land suitability.

Policy WPP9 To restrict the use of imported manure/slurry in relation to water supply source catchments, high status waterbodies and "At Risk" water bodies. Consult www.catchments.ie for maps of waterbodies and their classifications.

Policy WPP10 Development within the vicinity of groundwater or surface water dependant Natura 2000 sites (Kilroosky Lough Cluster SAC) will not be permitted where there is potential for a likely significant impact upon the groundwater or surface water supply to the Natura 2000 site. Where appropriate, the applicant shall demonstrate with hydrogeological evidence, that the proposed development will not adversely affect the quality or quantity of groundwater or surface water supply to the Natura 2000 sites.

Policy WPP11 Development which would have an unacceptable impact on the water environment, including surface water and groundwater quality and quantity, river corridors and associated wetlands will not be permitted.

CASE STUDY 1

This example relates to a nursing home with 40 beds and additional housing units, which also required a discharge license to groundwater. The discharge license application was not submitted at the same stage as planning permission therefore the application for a discharge license had to address the lack of treatment the existing discharge was receiving. The original planning application did not include a detailed report on the potential impacts to groundwater this development may have. The main difficulty for this site was the proposed location for discharge of final treated effluent via a polishing filter. It is located beside an area known locally as Tullyvaragh which is an active sinkhole. The area has a small stream which flows in a southerly direction which sinks north of an area known locally as the dry bridge. Existing treatment on site was inadequate as effluent was discharging partially treated and disappearing. There were also other issues on site with misconnections of stormwater and foul water networks resulting in additional non treated effluent entering the stormwater discharge network. This site due its close proximity to this type of feature required a detailed hydro geological assessment.

Some questions were raised by the applicant as to why they needed this level of detail and additional costs. Although the applicant new of some local caves and disappearing streams they were very much unaware of the sensitive nature of the underlying hydrogeology. From our point of view without our detailed GIS which has been built up over a number of years with lots of local information and layers from the EPA and GSI, we probably would not have been aware of the high risk the site wastewater treatment location posed to the underlying aquifer. The applicant complied with all requested information. The hydro geological report submitted in additional to a site suitability report also contained recommendations for monitoring to be carried out in proximity to the proposed polishing filter location. The recommendations in the report were incorporated into the discharge license conditions which are still in operation. Recommendations included the location and depths of a series of boreholes to measure groundwater quality. The licensee has recently requested removal of the condition to monitor at the borehole locations. The license also contains a condition on surface water monitoring, however this is not always possible as the river only flows during prolonged wet conditions.

This development and subsequent discharge license presented a challenge to the local authority as the underlying connectivity was largely unknown and without the aid of GSI mapping incorporated into our own GIS it may have went unnoticed. In this scenario an understanding of underlying hydrogeology was essential not just for background information but also to assist in the conditioning of authorisation to discharge to groundwater and location and sizing of appropriate treatment options for wastewater on site. An important factor here also is the importance of continued enforcement of the license conditions and close liaison with the license holder.

CASE STUDY 2

This example relates to an application for a duck rearing facility within the kasitified location around Carrickmacross. The site location for the duck rearing facility although important was not the main concern for groundwater. The spreadlands however were a significant concern and the applicant proposed to spread all of the duck slurry on local lands in the area within close proximity of the proposed development. The application included proposal to landspread on neighbouring farms but no other information relating to the landbanks were included. A request for additional information was issued to the applicant to include a detailed fertiliser plan for the lands, landbank maps for all land proposed to be used for landspreading and an assessment of the suitability of the land for lanspreading taking account of the development plan policies including reference to EPA/GSI guidance groundwater protection responses on landspreading of organic waste. When the information was received a detailed assessment of the landbanks were carried out and large portions of the land were located within R4 areas (not suitable for landspreading),R3(2) (not generally acceptable unless a thickness of 2m of soil and subsoil can be demonstrated) and R2(1) (Acceptable subject to a maximum organic nitrogen load (including that deposited by grazing animals) not exceeding 170 kg/hectare/yr).

Response Matrix for Landspreading

VULNERABILITY RATING	SOURCE PROTECTION AREA		RESOURCE PROTECTION Aquifer Category					
			Regionally Important (R)		Locally Important (L)		Poor Aquifers (P)	
	Inner	Outer	Rk	Rf/Rg	Lm/Lg	Ll	Pl	Pu
Extreme (E)	R4	R4	R3[2]	R3[2]	R3[1]	R3[1]	R3[1]	R3[1]
High (H)	R4	R2[1]	R1	R1	R1	R1	R1	R1
Moderate (M)	R3[3]	R2[1]	R1	R1	R1	R1	R1	R1
Low (L)	R3[3]	R2[1]	R1	R1	R1	R1	R1	R1

Fig 3. Response Matrix for lanspreading of organic waste from intensive farming enterprises, sewage sludges, poultry litter and industrial wastewater treatment plants.

“The reader is referred to Groundwater Protection Schemes (DoELG/EPA/GSI, 1999) for an explanation of the role of groundwater protection responses in a groundwater protection scheme. The appropriate response to the risk of groundwater contamination is given by the assigned response category (R) appropriate to each protection zone (Table 1). R1 Acceptable, subject to normal good practice. R21 Acceptable subject to a maximum organic nitrogen load (including that deposited by grazing animals) not exceeding 170 kg/hectare/yr. R31 Not generally acceptable, unless a consistent minimum thickness of 1 m of soil and subsoil can be demonstrated. R32 Not generally acceptable, unless a consistent minimum thickness of 2 m of soil and subsoil can be demonstrated. R33 Not generally acceptable, unless it is shown that there are no alternative areas available and detailed evidence is provided to show that contamination will not take place. (No spreading will be allowed within a 50 m radius of a groundwater source.) R4 Not acceptable. These responses assume that there is no significant groundwater contamination problem in the landspreading area. Should contamination by nitrate (or other contaminants) be a problem in any particular area, then more restrictive responses may be necessary. Monitoring carried out as part of any Local Authority or Agency authorisation will assist in determining whether or not a variation in any of these responses is required” (EPA, 2004).

This resulted in a large portion of the proposed lands being excluded from the application and conditions for other lands not to be used without proving a minimum depth. The agent involved in this application was perplexed at this reasoning. Their focus was only on the soil nutrient content and not the underlying hydrogeology and subsequent vulnerability to landspreading. Duck slurry is an extremely mobile type of slurry and this activity in a karst area poses a high risk. The most challenging part of this application was obtaining the right information to make a decision. A further difficulty in imposing land use restrictions even with detailed planning conditions is the ongoing enforcement of restrictions on landspreading. This application also had the added complication that lands included were not owned by the applicant however the planning section agreed with our interpretation that all the proposed spreadlands had to be included in the overall assessment and could not be ignored. In this scenario a hydrogeological report was not requested but reference to the EPA/GSI guidance of landspreading of organic wastes was critical.

GROUNDWATER QUALITY

The groundwater quality in the area around Carrickmacross is currently at good chemical and quantitative status according to the most recent EPA water quality report for Ireland (EPA, 2017). Interestingly surface water quality for most of the rivers in the Carrickmacross area has the highest concentrations of nitrate for the county. This demonstrates also the high degree of hydrological connectivity between groundwater and surface water in this area. Although there is no environmental quality standard for nitrate in the Environmental Objectives (Surface Water) Regulations 2009 a surrogate of 1.8 mg/l as N can be used as a guide for good ecological status for ambient surface water quality (EPA, 2013). Microbial contamination of the local water supply has occurred previously in 2012 with breaches detected for cryptosporidium. This was due to the absence of adequate barriers in the treatment process used at the time but this has since been addressed through the construction of a new water treatment plant serving the Carrickmacross area. This breach of drinking water quality standards emphasises the continued risk to local water sources due to the freely draining nature of the underlying subsoil and limestone.

CONCLUSION

This paper provides a brief insight into some of the difficulties faced by local authorities when assessing developments within unique karst areas such as Carrickmacross. The range of skills needed to assess firstly, what information is required and then the adequacy of information submitted crosses many different professional fields such as environmental science, hydrogeology, geology, hydrology, ecology, chemistry and biological science to name a few. There are currently no hydrogeologists employed in Monaghan County Council. From time to time the skills required are sought through external consultants. Planning applications often do not consider the source, pathway and receptor linkages for surface water and groundwater. This is more prevalent in higher risk areas such as the one described here.

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GROUNDWATER NITRATE ATTENUATION VERSUS DISSOLVED GAS PRODUCTION: A HIERARCHY OF SCALE

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ABSTRACT

At the hillslope scale, an array of environmental, hydrogeological and physicochemical characteristics combine to regulate the distribution of groundwater nitrate (NO_3^-). The efficiency of NO_3^- removal (via denitrification) versus the ratio of gaseous reaction products, dinitrogen (excess N_2) & nitrous oxide (N_2O), remains poorly understood. Spatial and temporal monitoring was undertaken along four hillslopes in two Irish catchments. Both catchments are characterised by well drained soils, but exhibit contrasting subsurface lithologies and agronomy The capacity for groundwater denitrification was assessed by measuring the concentration and distribution patterns of N species (2013-15), denitrification reaction products (excess N_2 & N_2O), aquifer hydrogeochemistry and aquifer hydraulic properties in monthly samples from a network of piezometers (n=37). Agronomy, water table elevation and permeability determined the hydrogeochemical signature of the aquifers, which acted as the dominant control on denitrification rates. High permeability, aerobic conditions and a lack of bacterial energy sources in the slate catchment resulted in low denitrification rates (0–32%), high NO_3^- and comparatively low N_2O emissions. In the sandstone catchment, denitrification rates ranged from 4 to 94%, with greatest NO_3^- transformation occurring in deeper groundwater and near stream zones. Reduction of NO_3^- to N_2 occurred in anaerobic conditions, while at intermediate dissolved oxygen, N_2O was the dominant reaction product. While stream N_2O was substantially lower than groundwater, mean values were significantly greater than atmospheric equilibrium, particularly in the sandstone catchment. The positive environmental effect of NO_3^- reduction was therefore concomitant with a net source of harmful greenhouse gas emissions.

Introduction

The application of fertiliser N to agricultural environments, while essential to replenish soil nutrient levels and increase farm productivity has significant environmental consequences. When N inputs to a catchment exceed the utilisable output, the potential for N surpluses occur (van Meter et al., 2016). The cascade of this surplus through a catchment can lead to contamination of potable supplies, surface water eutrophication, aquatic acidification, greenhouse gas emissions and loss of habitat diversity. Globally, denitrification is regarded as the dominant nitrate (NO_3^-) attenuation mechanism in groundwater (Seitzinger et al., 2006). Denitrification is a microbially mediated process whereby NO_3^- is reduced to dinitrogen (N_2) gas. In baseflow dominated catchments, groundwater denitrification has the capacity to mitigate stream water N enrichment by returning N to the long residence time atmospheric pool (Heffernan et al., 2012). Denitrification can represent an environmentally positive NO_3^- removal process; however such a characterisation is subject to an important caveat. The reaction is sequential and as such there are several intermediary products including nitrite (NO_2^-), nitric oxide (NO) and nitrous oxide (N_2O). The differentiation between which reaction product is dominant is of key environmental concern: N_2 gas is environmentally benign whereas N_2O is a potent greenhouse gas, while NO contributes to stratospheric ozone depletion, eutrophication and formation and accumulation of surface ozone (Vitousek et al., 1997). In complex geological environments, an entire aquifer or catchment cannot be characterised as having high or low denitrification potential.

Denitrification is enhanced in certain spatial zones or hot spots (Jahangir et al., 2012) and it is the location and intensity of these hot spots in relation to a receptor e.g. a stream, which is paramount to characterising the potential for natural attenuation of N in an aquifer. Great uncertainty surrounds the spatial and temporal distribution of denitrifying zones, owing to a confounding hierarchy of scale. The geological history of the aquifer (mineralogy, stratigraphy and weathering) at the catchment scale controls the distribution and availability of bacterial energy sources, aquifer flow paths; permeability and connectivity at the sub metre scale (Seitzinger et al., 2006). These physical factors in turn determine the hydrogeochemical signature and N attenuating capacity of the aquifer

The results presented herein form part of a PhD which examined the influence of hydrogeological and agronomic setting on the spatial and temporal distribution of groundwater and stream nitrate (NO_3^-). Research was undertaken in two contrasting settings: a **sandstone** catchment with grassland agriculture in Co. Cork (**Figure 1**) and a **slate** catchment with arable agriculture in Co. Wexford (**Figure 2**). Each catchment contains two instrumented hillslopes, within which multilevel monitoring wells were targeted to intercept shallow and deeper groundwater pathways. Each hillslope intersects with a stream at it base, which acts as a receptor for up-gradient processes (**Figures 1 & 2**). The results of a comprehensive monitoring and numerical modelling regime were interpreted in terms of groundwater NO_3- attenuation, as described in detail by McAleer et al. (2017).

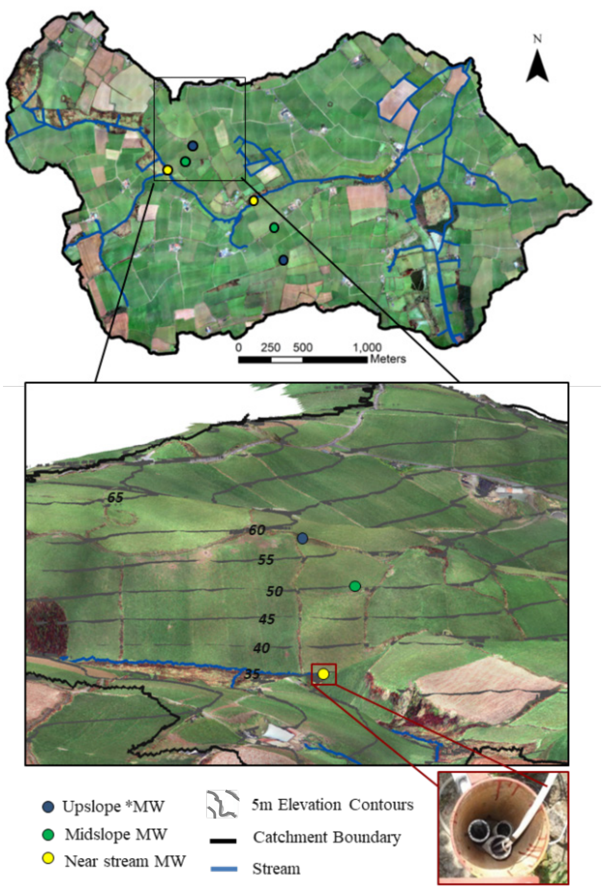

Figure 1. Sandstone catchment hillslopes and monitoring infrastructure, grafted onto a digital elevation model of the catchment.

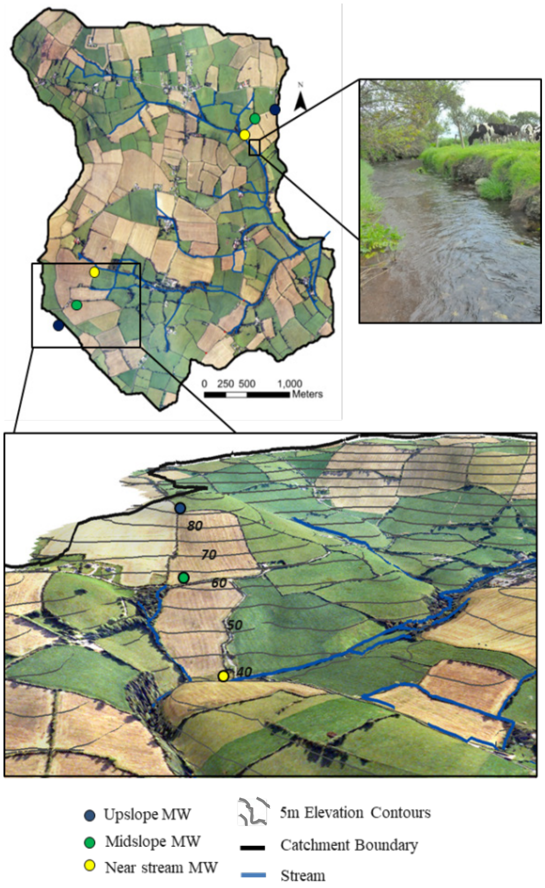

Figure 2. Slate catchment hillslopes and monitoring infrastructure, grafted onto a digital elevation model of the catchment.

A Question…
Prior to entering into a detailed description of the processes within each study catchment, and to place the article in context, **Figure 3** illustrates the contrasting hydrogeochemical scenarios at each catchment.

Why does the catchment with almost triple the N loading have ~30% less stream

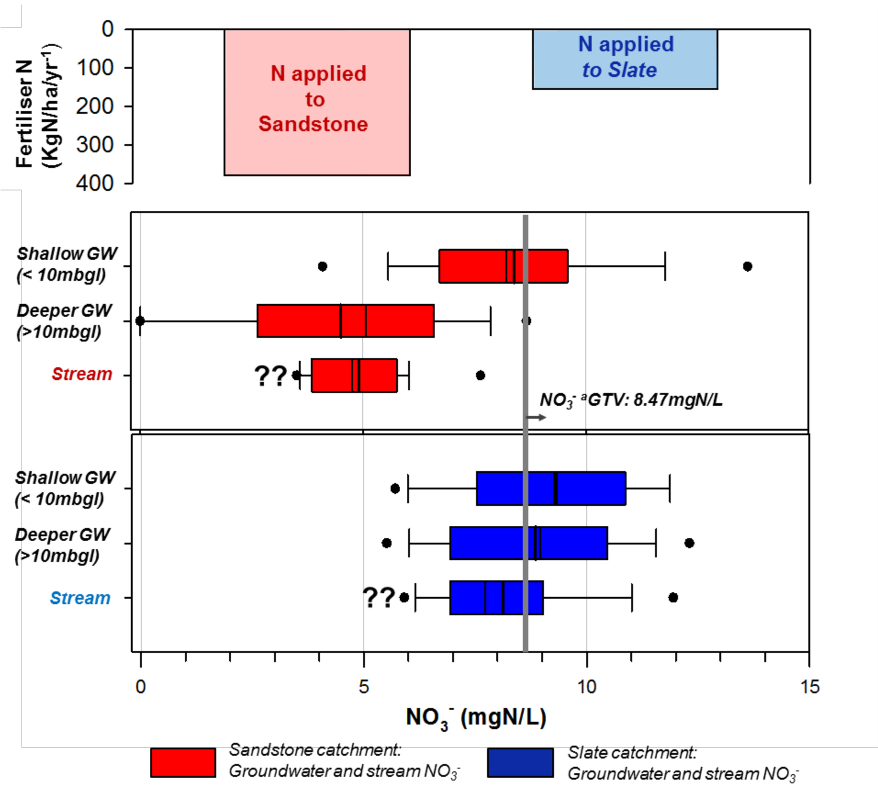

Figure 3: Agricultural N loading versus boxplots of near stream shallow groundwater (<10mBGL) and stream NO_3^- concentrations during two hydrological years (2013/15) at the **sandstone** and **slate** catchments. The lower and upper hinges of the boxes correspond to the first and third quartiles of the data. The solid black line represents the median of the data, while the red line describes the mean. The top and bottom whiskers of the plot define the 5th and 95th percentiles.

Agricultural N loading is plotted against shallow groundwater NO_3^-, deeper groundwater NO_3^- and stream NO_3^-concentrations in one of the study hillslopes from each catchment (**Figure 3**) over two hydrological years (2013-15). Mean stream NO_3^- concentrations in the **slate** catchment significantly exceeded the sandstone streams. The reader's attention is drawn to the contrasting relationship between shallow groundwater and stream NO_3^- at both hillslopes. At the **sandstone** hillslope, NO_3^- in shallow groundwater was consistently more than double that of the stream. Conversely at the slate hillslope, stream NO_3^- and shallow groundwater NO_3^- concentrations were tightly linked. In addition, whereas shallow and deeper groundwater NO_3^- concentrations in the slate catchment were comparable, NO_3^- in the deeper groundwater of the sandstone catchment was significantly lower than shallow. This suggests that NO_3^- is being consumed in the sandstone hillslope and reducing the concentration of NO_3^- delivered to the stream. Agricultural N loading to the sandstone hillslope was substantially greater than the slate catchment. In contrast, sandstone stream NO_3^- concentrations were significantly lower than slate stream NO_3^-. This leads to the question: *Why does the hillslope with almost triple the N loading have ~30% less stream NO_3^-?*

Denitrification

Groundwater denitrification has the capacity to mitigate stream water NO_3^- enrichment by returning N to the long residence time atmospheric pool. Denitrification is a microbially mediated process whereby NO_3^- is reduced to dinitrogen (excess N_2) gas. The reaction is sequential with several intermediary products including nitrite (NO_2^-), nitric oxide (NO) and nitrous oxide (N_2O). The differentiation between which reaction product dominates is of environmental concern: N_2 gas is benign whereas NO and N_2O are potent greenhouse gases. Denitrification rates vary significantly both between and within catchments. A combination of hydrological, hydrogeological and hydrogeochemical parameters act to regulate denitrification rates and the relative apportionment of gaseous reaction products.

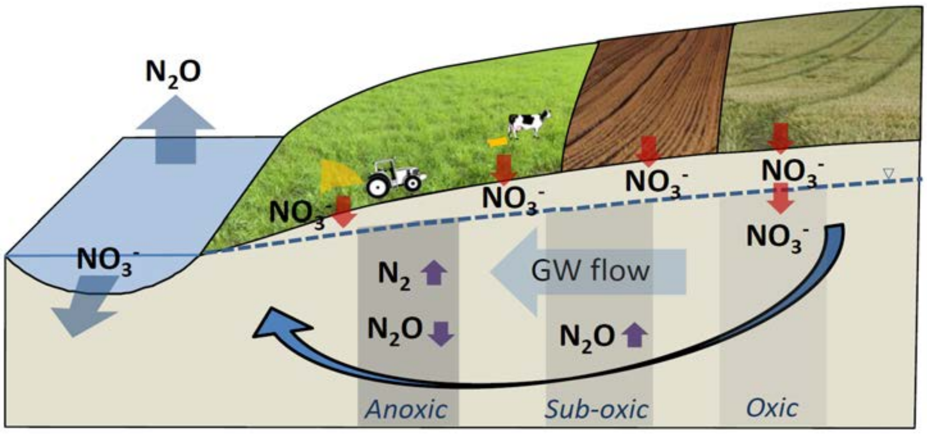

Figure 4. Conceptual model of groundwater NO_3^- reduction via denitrification versus aquifer oxygen levels & reaction products (N_2 & N_2O).

At its core the denitrification reaction requires **1) Low oxygen** conditions (**Figure 4**): Denitrifying bacteria are facultative anaerobes, that is, they can metabolise either aerobically or anaerobically. Dissolved oxygen yields greater energy than NO_3^-, therefore it is only once oxygen is consumed that bacteria utilise NO_3^-. **2) A bacterial energy source**: This can be heterotrophic i.e. dissolved organic carbon (DOC) or autotrophic i.e. oxidation of solid phases within an aquifer such as Iron (Fe) and Manganese (Mn). **Denitrification capacity** was assessed by measuring the concentration and distribution patterns of groundwater and stream nitrogen (N) species, gaseous denitrification (N_2 & N_2O) products, bacterial energy sources (DOC, Fe & Mn) aquifer hydro-geochemistry (dissolved oxygen & redox potential, stable isotope signatures ($^{15}NO_3^-$ & $^{18}NO_3^-$) and aquifer hydraulic properties (hydraulic conductivity & water table elevation). Samples were collected on a monthly basis in from 2013 to 2015.

Catchment hydrogeology

Sandstone catchment: The sandstone catchment is characterised grassland agriculture on well drained soils and subsoils. The underlying aquifer is categorized as Locally Important with Bedrock that is Moderately Productive only in Local Zones (GSI, 2004a) and exhibits a high average baseflow index of 73% (mean: 2012-13). Baseflow Index describes the proportion of flow in a stream which is supplemented by groundwater discharge and was calculated after Mellander et al. (2012). Bedrock consists of a three dimensional pattern of mudstone and Devonian sandstone with minor siltstone and exhibits varying degrees of weathering. Slug test measurements of hydraulic conductivity (Ksat) at both sandstone hillslopes (range: 0.09-2.8m/day) indicated a layered distribution of permeability becoming less permeable with depth.

Slate catchment: The slate catchment is dominated by arable agriculture and is also well drained. The aquifer characterised as unconfined and Locally Important, with Moderate Productivity only in Local zones (GSI, 2004b) and a baseflow index of 77%. Bedrock consists of Ordovician slate and siltstone.

Ksat measurements revealed that the slate underlying the study hillslopes is highly permeable (range: 0.08 to 5.2m/day) owing to the density and vertical extent of bedrock fracturing.

The elevated baseflow indexes in both research catchments indicate that quality of groundwater dictates' the quality of streamwater.

Results and discussion

FracLEACH

FracLEACH describes the quantity of dissolved N leached from soil to groundwater as a proportion of the total N load applied at the land surface via agricultural practises. Over both sandstone hillslopes, a mean FracLEACH of 18% was calculated (**Table 1**). In the slate hillslopes, the mean FracLEACH of 43% highlighted a propensity for greater N leaching losses in arable catchments. While FracLEACH was considerably higher at the slate hillslopes, the associated N loads reaching the water table were comparable with 55 and 60 kgN/ha/yr^{-1}. reaching the water table in the sandstone and slate catchments respectively. Comparing shallow groundwater (<10 mBGL) NO_3^- with stream NO_3^- concentrations in both catchments revealed a 43% reduction in NO_3^- from groundwater to stream in the **sandstone** catchment versus only a 7% reduction in the **slate** catchment. It is likely therefore that a combination of agricultural practises and denitrification acted to mitigate stream N enrichment in the sandstone catchment. Conversely, conditions in the slate catchment did not act to suppress stream N enrichment. The following results sections will explore that assertion.

Table 1. Hillslope landuse, surface applied N, N leached to groundwater and FracLEACH.

Sandstone catchment				**Slate** catchment			
Hill-slope	Land use	[a]Applied N (kg N/ha/yr.)	**Frac-LEACH**	Hill-slope	Land use	[a]Applied N (kg N/ha/yr.)	**Frac-LEACH**
Sandstone N	Dairy Grassland	295	**14**	*Slate N*	Arable (Spring barley)	143	**41**
Sandstone S	Dairy Grassland	380	**21**	*Slate S*	Arable (Spring barley)	155	**44**

Groundwater denitrification

The effect of hydrogeological setting

In both the **sandstone** and **slate** catchments, highest NO_3^- concentrations were observed in high permeability Quaternary deposits. Underlying the Quaternary deposits in the sandstone catchment a layered distribution of bedrock permeability (Ksat) was evident, becoming less permeable with depth. Weathered bedrock zones with high Ksat allowed a fast migration of NO_3^- contaminated groundwater with limited scope for microbial attenuation. Lower Ksat with depth resulted in a longer residence time of both groundwater NO_3^- and DO. With a longer residence time in the sandstone catchment, denitrification was promoted, resulting in lower NO_3^- concentrations. This contention was supported by significant negative correlations between Ksat and NO_3^- and Ksat and DO (**Figure 5**). High permeability weathered zones ranging in thickness from 4 to 18m in the slate catchment, aligned with a lack of correlation between Ksat and NO_3^- suggested that rapid groundwater flow restricted NO_3-reduction.

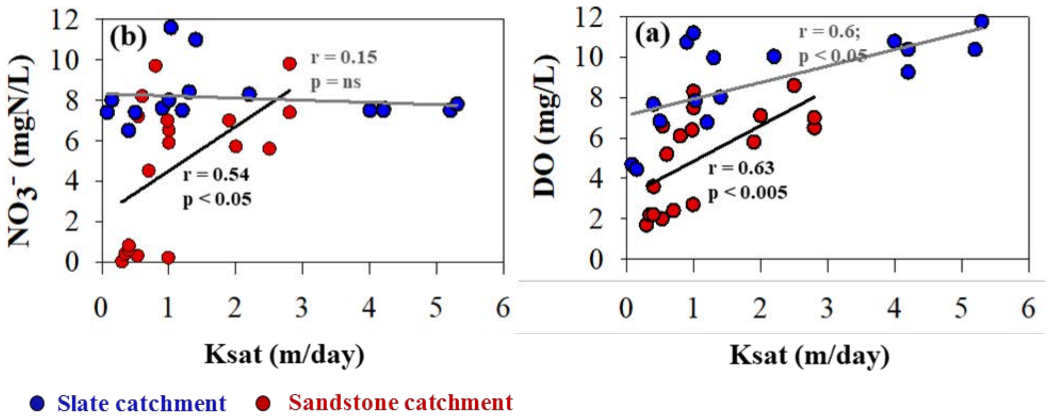

Figure 5. Linear regression analysis of Ksat, DO and NO_3^- in the sandstone and slate catchments. The black and grey correlation lines represent the sandstone and slate catchments respectively

The effect of hydrogeochemical setting: ***Oxygen***

It is clear from **Figure 5** that the physical setting of an aquifer impacts the hydrogeochemical setting. The hydrogeochemical setting of the aquifer in turn regulates NO_3^- reduction and dissolved gas (excess N_2 and N_2O) production. During aerobic respiration, dissolved oxygen is used as the electron acceptor in the reaction. When a certain **lower threshold of oxygen** is reached, NO_3^- is the next most energetically favourable compound for bacteria to reduce. While there is little consensus, given all other prerequisites are met, it is likely that significant denitrification will occur at concentrations of 1 to 2 mg/L (Rivett et al., 2008).

In the **sandstone** catchment, a strongly positive correlation was identified between groundwater DO and NO_3^- ($r = 0.78$, $p < 0.001$) (**Figure 6**). NO_3^- was absent at DO concentrations of <3mg/L). DO was highly negatively correlated with excess N_2 ($r = -0.79$, $p < 0.0001$). Results indicated complete reduction of NO_3^- to the environmentally benign N_2 gas, at low oxygen concentrations. The relationship between N_2O and DO in the sandstone catchment, while statistically positive ($r = 0.77$, $p < 0.05$) was complex. Highest N_2O occurred at DO between 4 and 8 mg/L with significantly lower concentrations between 0 to 3 mg/L and 8 to 10 mg/L. This has important implications, as N_2O represents a potent greenhouse gas. In contrast to the sandstone catchment, groundwater in the **slate** catchment was consistently aerobic, with no significant correlations identified between DO, NO_3^-, excess N_2 or N_2O (**Figure 6**).

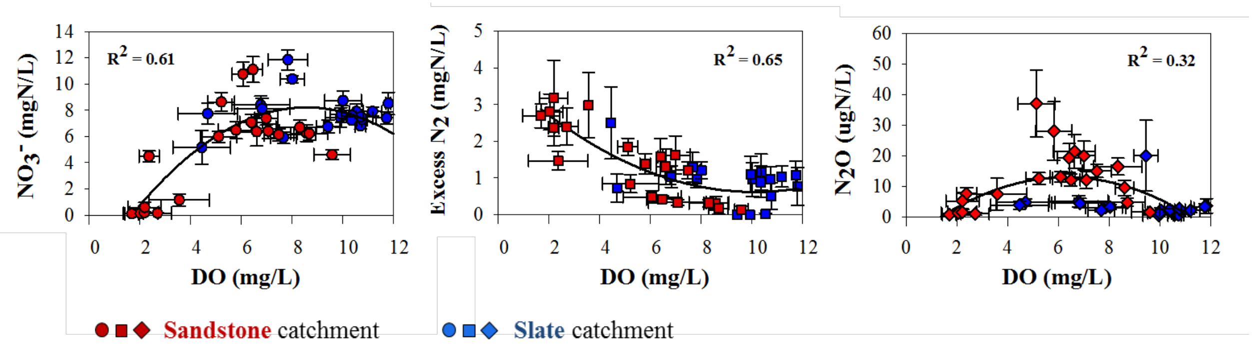

Figure 6. Groundwater dissolved oxygen (DO) versus NO_3^-, excess N_2 and N_2O for the sandstone (red symbols) and slate (blue symbols) catchments.

Groundwater denitrification

*The effect of hydrogeochemical setting: **Bacterial energy sources***

In the **slate** catchment, concentrations of solid phase bacterial energy sources (Mn^{2+} and Fe^{2+}) were typically low. Concentrations of Mn^{2+} and Fe^{2+} in the **sandstone** catchment were significantly higher and were elevated in deeper groundwater and near stream zones. Strongly negative relationships were shown between Fe^{2+} and Mn^{2+} with NO_3^-. Strongly positive correlations were identified between Fe^{2+} and Mn^{2+} and excess N_2. Concentrations of reduced metals (Mn^{2+} and Fe^{2+}) were highly dependent on aquifer aerobicity, signifying increased dissolution in low oxygen environments.

Groundwater denitrification

Rates, reaction products and a hierarchy of scale

In order to calculate groundwater denitrification rates, it was assumed that denitrification along a groundwater flow path resulted in the reduction of NO_3^- and the production of dissolved N gases. As such, the initial nitrogen concentration was calculated as the sum of residual N substrates and accumulated N gases. Denitrification reaction progress was calculated as the ratio between products of denitrification and the starting substrates. Calculated denitrification rates in the **sandstone** catchment were significantly higher ($p < 0.005$) than the **slate** catchment. In the sandstone catchment, highest denitrification rates (range: 4% to 95%) were measured at depth (corresponding to decreased permeability) and in near stream zones (corresponding to higher water tables). In the slate catchment, denitrification rates ranged from 2% to 34%, with a mean value of 9%. No significant relationships were identified between rates and permeability or water table elevation.

As eluded to in the title of this article, there existed a **hierarchy of scale** in each catchment whereby physical factors including permeability and water table elevation determined the hydrogeochemical properties of the aquifer. The hydrogeochemical signature (DO and bacterial energy source availability) can in turn either support or suppress denitrification and subsequent NO_3^- reduction. DO concentration was the dominant control, explaining 87%, 78% and 77% of the variance in groundwater denitrification rates, NO_3^- and N_2O respectively in the denitrifying sandstone catchment. Permeability distribution and water table elevation exerted a significant influence on the concentration of oxygen in the aquifer. Low oxygen conditions promoted the dissolution solid phase bacterial energy sources, which drove denitrification, NO_3^- reduction and dissolved gas production. In catchments were organic inputs are not sufficient to promote DO reduction, and residence times are too short to facilitate solid phase electron donor dissolution (as in the slate catchment), denitrification progress is arrested, with correspondingly higher stream and groundwater NO_3^- abundance.

Conclusion

At the beginning of this article, a question was posed: *Why does the catchment with almost triple the N loading have ~30% less stream NO_3^-?* The answer to this question is twofold. **Firstly**, agronomy played a major influence. A significantly greater proportion of fertiliser N applied to the arable catchment was leached to groundwater. The **sandstone** catchment had higher N uptake due to the permanent grass cover, a longer growing season, and a lack of autumn cultivation. Although N losses from the sandstone catchment were substantially lower than the **slate** catchment when expressed as a percentage of total N inputs (FracLEACH), since the N inputs to the sandstone catchment in absolute terms were three times higher, N losses to shallow groundwater in both catchments were comparable. **Secondly**, denitrification was a significant mechanism for NO_3^- transformation and removal in the sandstone catchment, with rates of 4 – 94%. In essence, an aquifer can be conceptualised as an environmental ecosystem, which is capable of removing between 0 – 100% of reactive N. The geological history of the aquifer e.g. mineralogy, stratigraphy and weathering at the catchment scale controls the distribution of permeability and effective porosity at the hillslope scale. Hydrogeological variables were instrumental in determining the contribution of aquifer flow paths to the stream and the hydrogeochemical signature of the aquifer (dissolved oxygen and the availability bacterial energy sources). The combination of these factors acted to promote significant groundwater NO_3^- removal in sandstone catchment, whereas in the slate catchment denitrification was constrained. While NO_3^- reduction in the sandstone catchment was positive from a water quality perspective, groundwater N_2O represented net source of harmful greenhouse gas emissions to atmosphere.

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SESSION VII

PESTICIDES AND METABOLITES IN GROUNDWATER

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ABSTRACT

Pesticides applied to various land uses may reach further afield than their target crop. The extent of pesticides and their metabolites entering groundwater varies vastly across the World based on the extent of awareness, monitoring, and research. Between 2008 and 2012 a range of sites in Ireland with differing hydrogeological characteristics were selected, installed with wells and samples analysed for pesticide parent active substances and their main metabolites. The objective was to determine the concentrations and occurrence frequency of parent and metabolites in these various sites. Monthly sampling over 2 years revealed that metabolites occur more frequently and at higher concentrations than the parent active substance. The highest concentrations were observed at two sites with contrasting hydrogeology: an intergranular sand and gravel aquifer and a poorly-drained soil and Irish Sea Till subsoil interbedded with gravel lenses above a fractured volcanic aquifer. An artesian aquifer sampled beneath this Irish Sea Till did not have frequent exceedances of parent active substances or metabolites, indicating the protective properties of the soil and subsoil here. Although residues at the freely-drained soil site (I/KWDa) with intergranular and karst diffuse aquifers were more common compared to the other sites, concentrations were a magnitude higher in samples from gravel lenses at the poorly drained site FvPDa. The transport of pesticide metabolites beyond gravel pathways at such sites warrants further investigation.

1. INTRODUCTION

Within the EU, pesticides and their metabolites are currently regulated according to directives 98/83/EC (Drinking Water Directive; DWD), 2006/118/EC (Groundwater Directive) and 91/414/EEC (Plant Protection Products Directive). Metabolites are chemical substances that result from decomposition of the parent compound (Lewis *et al*., 2016) and are often more likely to reach groundwater compared to parent active substances (a.s.) with short degradation half-lives (DT_{50}) values. Based on the toxicity profile of metabolites, they may either be subject to a parametric value of 0.1 µg/L, as are parent a.s., or 10 µg/L based on criteria from SANCO/221/2000. Since implementation of 91/414/EEC, 74% of pesticides have been withdrawn or banned in the EU (Cross and Edwards-Jones, 2011).

Quite often a selected suite of a.s. are chosen for monitoring, many of which are already well documented in international literature. The aim of this study was to evaluate the existence of commonly used pesticide a.s. and their main primary metabolites in groundwater at selected sites across Ireland. Previous analysis of a national dataset in Ireland assessed only parent a.s. with frequent occurrence of mecoprop and MCPA (McManus *et al*, 2014). Metabolites had not yet been assessed before in an Irish context and some have not been assessed in groundwater on a Global scale. Through observing occurrences of these compounds in groundwater from a range of sites, the intention was to understand where exceedances above regulatory triggers most often occur, which could help land managers spend resources on more targeted monitoring. The focus of this paper will be on the sites with the highest detections from the 2-year monitoring programme published elsewhere (McManus *et al*. 2017).

2. SITES SELECTED

Sites were selected with varying intrinsic vulnerabilities based on conceptual understanding of how pesticides and metabolites may move through an environmental compartment. It was also necessary to select locations that were not only vulnerable, but also represented a range of Irish conditions. Arable fields with well-drained and poorly-drained soils and subsoils were selected with intergranular, karst and fractured aquifer types.

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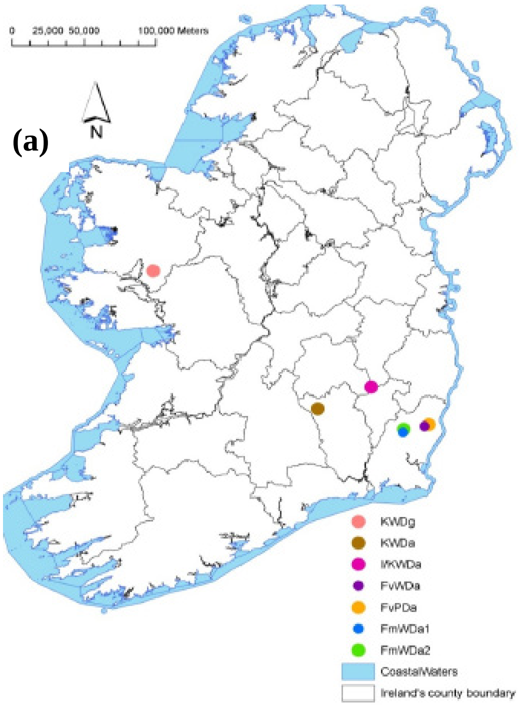

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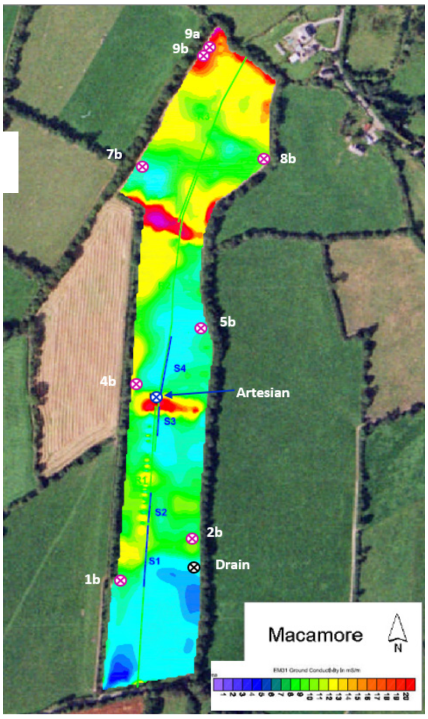

Figure 1 (a) Sites selected for monitoring and **(b)** EM31 ground conductivity and piezometer locations at FvPDa (Macamore soil). Ortho photography printed under Licence No. 6155 from the Ordnance Survey Ireland.

Across the seven sites (Figure 1a), 37 sample points were available. These were a mixture of springs, installed boreholes and at one site, an artificial subsurface drain (FvPDa). Boreholes were constructed using air-rotary drilling methods and contained nested piezometers with screens targeting shallow, interface and deeper groundwaters. EM31 ground conductivity to 6m depth was conducted at FvPDa by Minerex Geophysics Ltd to map variations in bulk conductivity in the soil and subsoil. Low conductivity values (blue Figure 1b) indicate more gravel rich deposits, while increases in conductivity suggests increases in clay and water content (orange and red Figure 1b). Table 1 lists the main characteristics at each site.

3. SAMPLING AND ANALYSIS

Monthly samples were collected from March 2010 to March 2012 from all sample points based on procedures outlined in ISO BS 5667-11 (British Standard, 2009). Low-flow purging was adopted with hydrochemical measurements recorded to ascertain when groundwater had stabilised. Stabilised readings of turbidity, pH, dissolved oxygen, electrical conductivity, temperature and oxidation-reduction potential were collected for each sample. Samples were collected in amber glass bottles to prevent photodegradation and sorption, stored chilled and analysed using a quantitative method with a limit of quantification (LOQ) less than the DWD parametric value.

Unfiltered samples underwent a clean-up step using solid phase extraction (SPE) followed by analysis using ultra high performance liquid chromatography tandem mass spectrometry (UHPLC-MS/MS). Each analyte had a unique primary quantification transition and confirmatory transition except for mecoprop and mecoprop-p which had the same transition (213 $\rightarrow$ 141 *m/z*) making their differentiation impossible using this method. Mecoprop contains two isomers, with the R+ form being herbicidally active (mecoprop-p). This method was unable to differentiate between the two isomers.

Table 1 Site Characteristics

Site ID	Principal soil association	Subsoil	Aquifer type code	Sample points	Borehole	Groundwater depth† (m bgl)
KWDg	Rendzina	none	Rkc	1 springs	n/a	
KWDa	Minimal grey brown podzolic	none	RKd	2 springs	n/a	
I/KWDa	**Grey brown podzolic**	**Limestone gravels**	**Rg & Rkd**	**5 wells**	**Upper:** **Lower:**	**3, 9, 25** **9, 19**
FvWDa	Acid brown earth	Weathered bedrock	Rf	2 wells	Lower: Upper:	16 10
FvPDa	**Gley**	**Irish Sea Till**	**Rf**	**9 wells**	**Artesian:** **Piezos.:**	**11** **2-9 (mean* 5.3)**
FmWDa$_1$	Acid brown earth	Till from sandstones and shales	Ll	9 wells	Lower: Middle: Upper:	5, 15, 31 6, 14, 38 10, 16, 37
FmWDa$_2$				9 wells	Lower: Middle: Upper:	2.5, 10, 47 4, 26, 36 3, 12, 27

* mean of mid-point screened section within each of the 8 piezometers.
† Groundwater zones shallow, interface and deep targeted in each borehole.
Sites in **bold** discussed further in results and discussion.

4. RESULTS AND DISCUSSION

4.1 Groundwater pesticide occurrence across the 7 sites

Of the 730 samples analysed, the most commonly detected parent a.s. were mecoprop-p, 2,4-D, and MCPA. The most commonly detected metabolites were PAC, DBA and 4C2MP. Only DBA and PAC regularly exceeded the DWD drinking water standard (DWS) with a maximum concentration (120 µg/L) of DBA observed at FvPDa. The karst sites in Co. Mayo and Co. Kilkenny had the least analytes detected and the lowest concentration ranges. The springs are located within large catchments of 32 km^2 for KWDg (Mellander *et al*., 2013) and 35 km^2 for KWDa (Deakin *et al*., 2013). These large contributing areas combined with less arable land use intensity across the catchment may provide one reason why fewer detections were found at KWDa and KWDg in comparison to I/KWDa, and FvPDa.

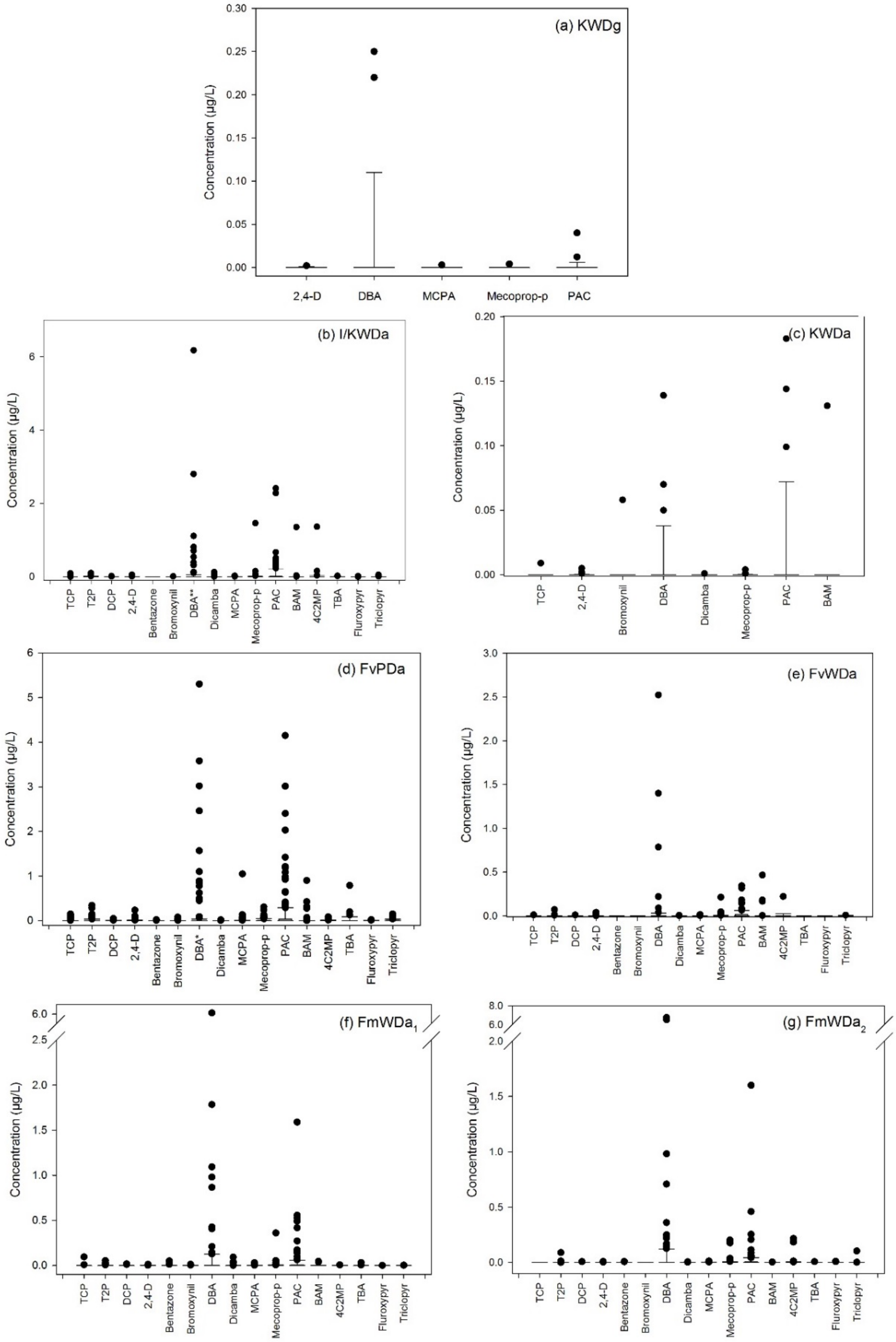

Figure 2 Box Plots indicating the residue concentration range for each analyte at each site. Only analytes with detections above the limit of detection included. **At I/KWDa (b), 1 sample with DBA at 14.2 µg/L not shown in graph. *At FvPDa (d), 4 samples had DBA residues at 11, 24, 36 and 120 µg/L not shown in graph. Note different y-axis scales between sites.

4.2 Comparison between FvPDa and I/KWDa

The eight piezometers at FvPDa were installed with screened sections at various depths up to 9m bgl in gravel lenses within Irish Sea Till. The artesian well which samples the Ordovician volcanic aquifer regularly had negative oxidation-reduction potential values indicating anaerobic conditions. Shallow soil cores collected during well installations revealed grey and orange mottles which form as a result of reducing conditions. These conditions reflect a lack of oxygen present for soil microbes to use during respiration. While sampling piezometers at FvPDa, hydrogen sulphide gas was often noted, further indicating a reducing environment at FvPDa (Table 2). These reducing conditions could prevent degradation of a.s. and metabolties, and potentially be the reason that higher concentrations were detected at FvPDa in comparison to sites with aerobic conditions.

Table 2 Comparison of groundwater physicochemical properties between sites I/KWDa and FvPDa. Average values from all samples collected.

Measurement (units)	I/KWDa	FvPDa
pH	7.6	7.4
Oxidation-reduction potential (mV)	140	-75
Dissolved oxygen (mg/L)	16	2.4
Electrical conductivity (µS/cm)	440	282
Turbidity (mg/L)	243	239
Temperature (°C)	11.6	11.9

Sites with the highest frequency of parent a.s. and metabolite detections were FvPDa and I/KWDa (McManus *et al*., 2017). At FvPDa samples collected from wells installed in gravel lenses had notably higher concentrations compared to I/KWDa. Although the gravel lenses harboured residues, the artesian aquifer beneath had very few in comparison. The poorly-drained gley Macamore soils at this site and Irish Sea Till offer protection to groundwater in the artesian aquifer directly below, although the recharge area for this confined aquifer extends beyond the field boundary. The fate and transport of the a.s. and metabolites observed in these gravel lenses is unknown and warrants further investigation.

Gravel lenses within Irish Sea till at FvPDa regularly had high exceedances of metabolites DBA and PAC (Figure 2). The average concentration for DBA and PAC from all samples collected in gravel lenses was above the DWS of 0.1 µg/L (Figure 3). Of all samples collected in the artesian well and analysed, only the TBA average exceeded the drinking water standard (Figure 3). Due to sample storage stability issues only 6 samples from the artesian well were used in the analysis of TBA (McManus *et al*., 2017): 2 of these were above the DWS at 0.79 and 0.2 µg/L. The artesian well also had 3 other samples with exceedances above the DWS: PAC twice with 0.158 and 0.326 µg/L and triclopyr at 0.11µg/L. Overall, samples collected from the gravel lenses often contained regular exceedances above 0.1 µg/L. In the 137 gravel lens samples analysed, 56 had exceedances above the DWS (40%). The most frequent of these exceedances were from DBA and PAC (Figure 3).

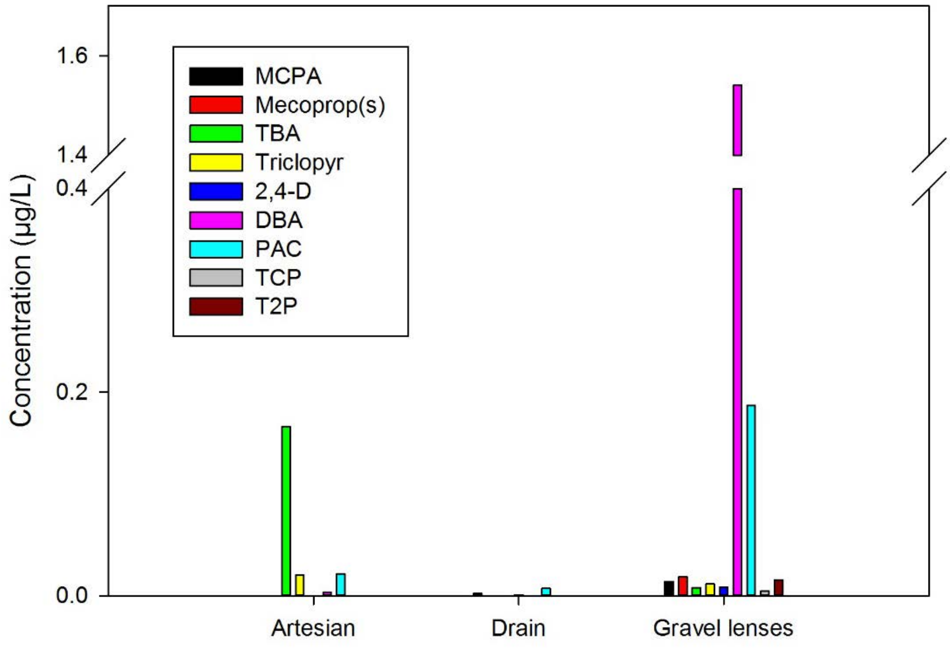

Figure 3 Average pesticide and metabolite concentrations in all samples at FvPDa.

At I/KWDa, only the down-hydraulic gradient MP2 well had averages above 0.1 □g/L for analytes measured over the course of monitoring (Figure 2b). The highest of these averages was for 4C2MP (0.23 µg/L) and PAC (1.4 µg/L) in the piezometer targeting shallow groundwater (Figure 4). MP2 shallow is screened in sand between 3-5 m bgl. All samples collected from the interface and deep piezometers at MP2 had average concentrations for PAC of 0.12 and 0.18 µg/L, respectively. The sandy well-drained soils above the intergranular and karst aquifers do not offer much protection to recharging water entering the saturated zone. This combined with the high intensity of pesticide use at I/KWDa, explains the high frequency of detects at I/KWDa. The phenoxyacid herbicides applied to the tillage land at I/KWDa were mecoprop-p on six occasions between April 2006 and March 2012, and dicamba which was applied in May 2010 and March 2012.
At I/KWDa, DBA exceeded the DWS in 12 samples, 8 of these collected from shallow groundwater at MP2. PAC occurrence was more widespread amongst all three sample points at MP2 (shallow, interface and deep groundwater).

From both sites, the highest and most frequent detects were in shallow sample collection points. This may be a consequence of degradation before parent a.s. and metabolites reach deeper groundwater, or dispersion in larger volumes of water present in deeper strata of the saturated zone.

The objective of this research was to identify differences in pesticide a.s. and metabolites between sites in an Irish context. Metabolites which were not analysed before in Irish groundwaters were found in elevated concentrations, exceeding the EU drinking water standard of 0.1 µg/L (PAC and DBA). Metabolites were found more regularly and in higher concentrations than parent a.s., indicating that more emphasis should be placed on identifying these substances in groundwater. The focus of this research was on groundwater, but where higher residues are found in gravel pathways within poorly drained material, consideration should be made on the fate and transport from these pathways to surface waters.

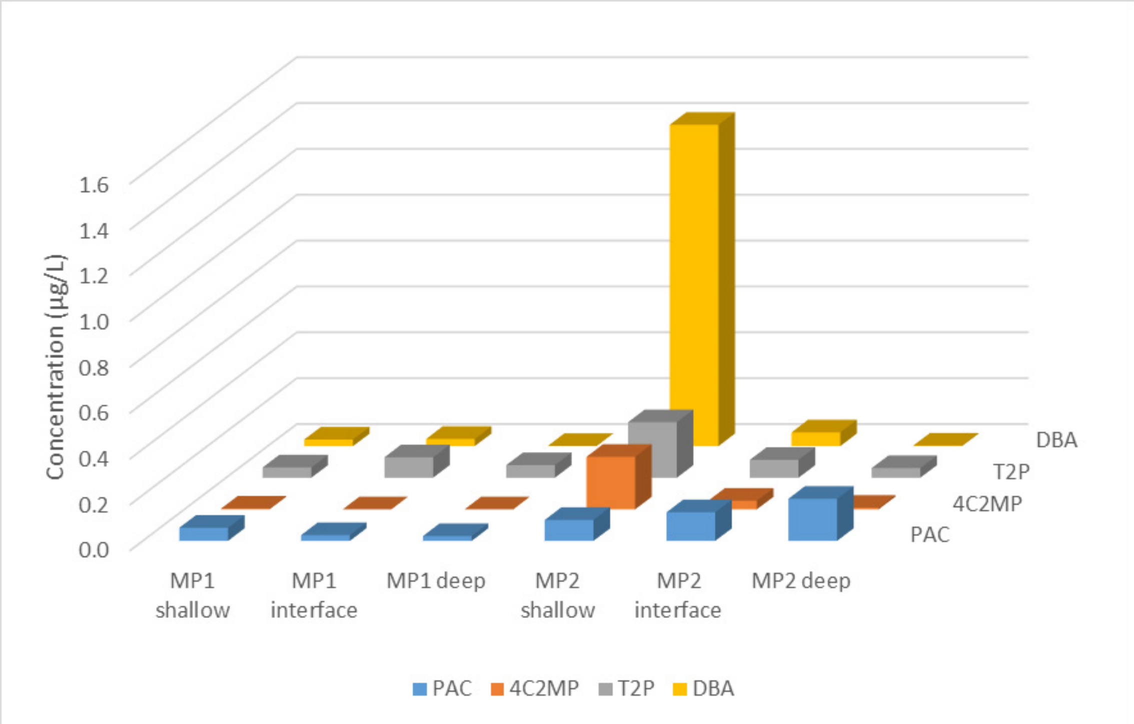

Figure 4 Average concentrations for each phenoxyacid analyte measured from all samples collected at available sample points at I/KWDa.

5. CONCLUSIONS

- Metabolites were more commonly detected in groundwater than parent active substances.
- Pesticides were observed in locations with high permeability sands and gravels.
- Shallow sampling points often contained more detections than deeper confined groundwater aquifers.
- Higher concentration ranges of parent active substances and metabolites were found in gravel lenses within lower permeability subsoils subject to reducing conditions.
- The fate and transport of pesticide active substances and metabolites observed in this study requires further investigation.

ACKNOWLEDGEMENTS

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GROUNDWATER AS A SOURCE AND PATHWAY FOR ANTIBIOTIC-RESISTANT INFECTION IN THE REPUBLIC OF IRELAND

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ABSTRACT

Antibiotic-resistant (pathogenic and non-pathogenic) organisms and genes are now acknowledged as significant emerging aquatic contaminants with potentially adverse human and ecological health impacts, and thus require monitoring. This study is the first to investigate levels of resistance among Irish groundwater (private wells) samples; Escherichia coli isolates were examined against a panel of commonly prescribed human and veterinary therapeutic antibiotics, followed by determination of the causative factors of resistance. Overall, 42 confirmed E. coli isolates were recovered from a groundwater-sampling cohort. Resistance to the human panel of antibiotics was moderate; nine (21.4%) E. coli isolates demonstrated resistance to one or more human antibiotics. Conversely, extremely high levels of resistance to veterinary antibiotics were found, with all isolates presenting resistance to one or more veterinary antibiotics. Particularly high levels of resistance (93%) were found with respect to the aminoglycoside class of antibiotics. Results of statistical analysis indicate a significant association between the presence of human (multiple) antibiotic resistance (p = 0.002–0.011) and both septic tank density and the presence of vulnerable sub-populations (<5 years). For the veterinary antibiotics, results point to a significant relationship (p = <0.001) between livestock (cattle) density and the prevalence of multiple antibiotic resistant E. coli. Groundwater continues to be an important resource in Ireland, particularly in rural areas; thus, results of this preliminary study offer a valuable insight into the prevalence of antibiotic resistance in the hydrogeological environment and establish a need for further research with a larger geological diversity.

THE RISE AND FALL OF THE ANTIBIOTIC ERA

Since the discovery of the antimicrobial properties of penicillin by Alexander Fleming in 1928, the development and use of antibiotics has revolutionised medicine and vastly improved public health. Throughout the early to mid-20th Century, there were major advances in the development of antibiotics; new classes of antibiotic agents were established (Fig.1) and with that, we saw a noticeable increase in human life expectancy. The late 1940s and early 1950s were the golden age of antibiotic discovery and antibiotic chemotherapy came into full fruition. Unfortunately, however, all good things must come to an end. With the development of each new antimicrobial agent, the development of resistance followed, often quickly, in succession.

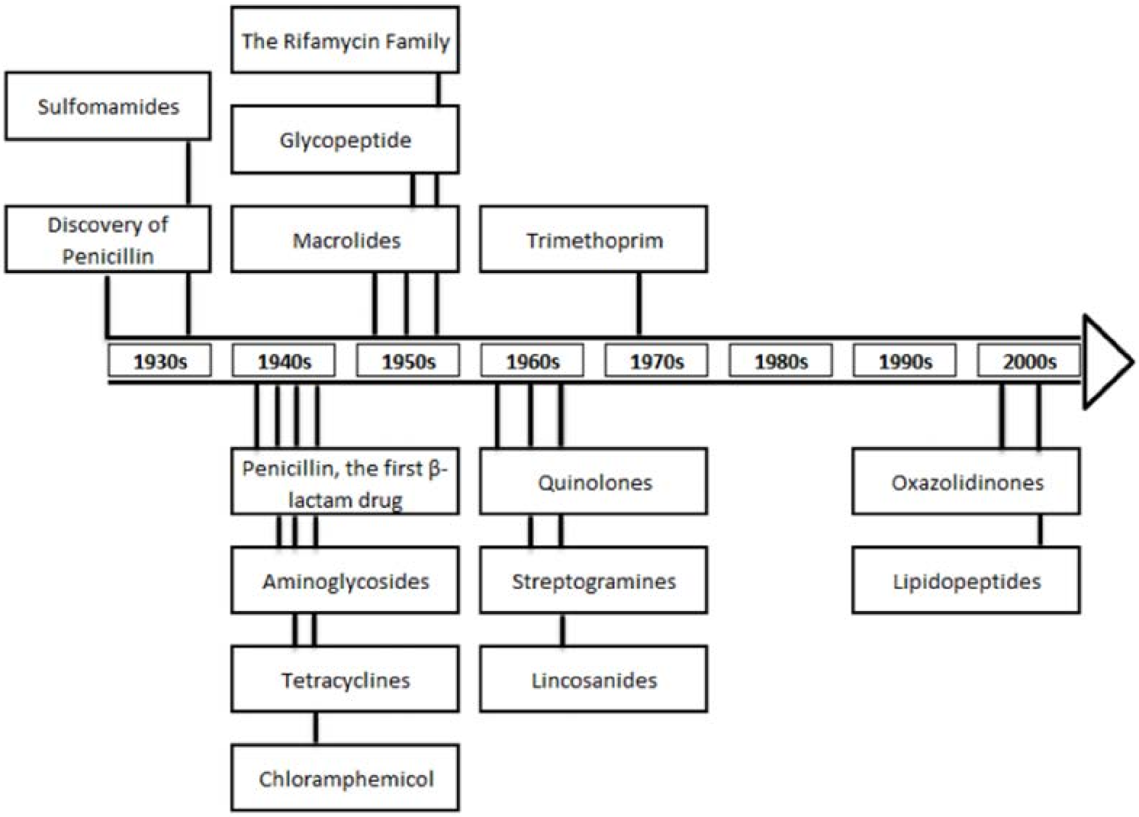

Fig. 1 Timeline of new antibiotic classes. The timeline illustrates when the major antibiotics were developed during the past 70 years. During the 1950s new antibiotics peaked, this is known as the golden era, this is when most of the antibiotics that we used today were discovered. The lean years followed from about 196; this was a low point in antibiotic discovery and development.

Through Darwinian Evolution, micro-organisms adapt to changes in their environment in order to survive; this process is governed by myriad physiological and biochemical mechanisms, all of which are naturally occurring phenomena. However, the current levels of antibiotic resistance noted globally are a result of years of selective anthropogenic pressure via overuse, underuse and misuse of antibiotics. More recently, the role of the natural environment in the proliferation of antibiotic resistance has become a keen area of interest. Studies have demonstrated that the presence of non-metabolized antibiotics and/or their by-products in the natural environment results in qualitative and quantitative effects on resident non-pathogenic and pathogenic organisms. This results in the development and selection of resistant (and multi resistant) bacterial strains through a process known as horizontal gene transfer and the clonal spread of this now resistant bacteria. As a result, we are in a period of public health turmoil, whereby organisms are becoming resistant faster than new and novel therapies are being developed. In an attempt to curtail this, efforts have been made not only to increase innovation but also to quantifiably assess the role of anthropogenic pressures and environmental transport on the development of resistance to prevent further spread and this includes water.

ANTIBIOTIC RESISTANCE AND WATER

Antibiotic-resistant organisms and genes are now acknowledged as significant emerging water contaminants with potentially adverse human and ecological health impacts. Of imminent concern is the presence of antibiotic resistant bacteria within drinking water supplies; untreated water supplies posing a substantial risk. In Ireland, the high reliance on unregulated, private water wells and on-site domestic wastewater treatment, in conjunction with a dispersed yet locally dense rural settlement pattern, a unique agricultural profile, and diverse (hydro)geological settings, creates a 'perfect storm' in terms of the source and transfer of microbiological contamination; including antibiotic resistant bacteria. The presence of pathogenic and non-pathogenic organisms in groundwater in Ireland is well established [1-4]. Yet, research investigating the proliferation of antibiotic resistance in the subsurface environment is lacking, in spite of Ireland's high usage of antibiotics; for example, 43% of surveyed Irish residents reported antibiotic usage during the previous 12-month period, compared with a European mean of 35% [4]. Similarly, antibiotic usage is high within veterinary practice with tetracycline in particular accounting for 36% of all antibiotics sold in Ireland for veterinary use in 2013 [5]. However, the presence and fate of antibiotics (and pathogenic bacteria) in the subsurface environment is not just a factor of the antibiotic source, but is also highly dependent upon local physical–chemical properties, prevailing climatic conditions, and hydrogeological setting, in addition to a variety of other local/regional environmental factors. Accordingly, this recent study sought to investigate the presence of antimicrobial-resistant bacteria in Irish groundwater, and the role of anthropogenic (i.e. sources) and natural (i.e. pathways) drivers on levels of encountered resistance.

STUDY AREA

The research area was the Midwest region of Ireland, consisting of counties Limerick, Clare and North Tipperary (Fig.2).

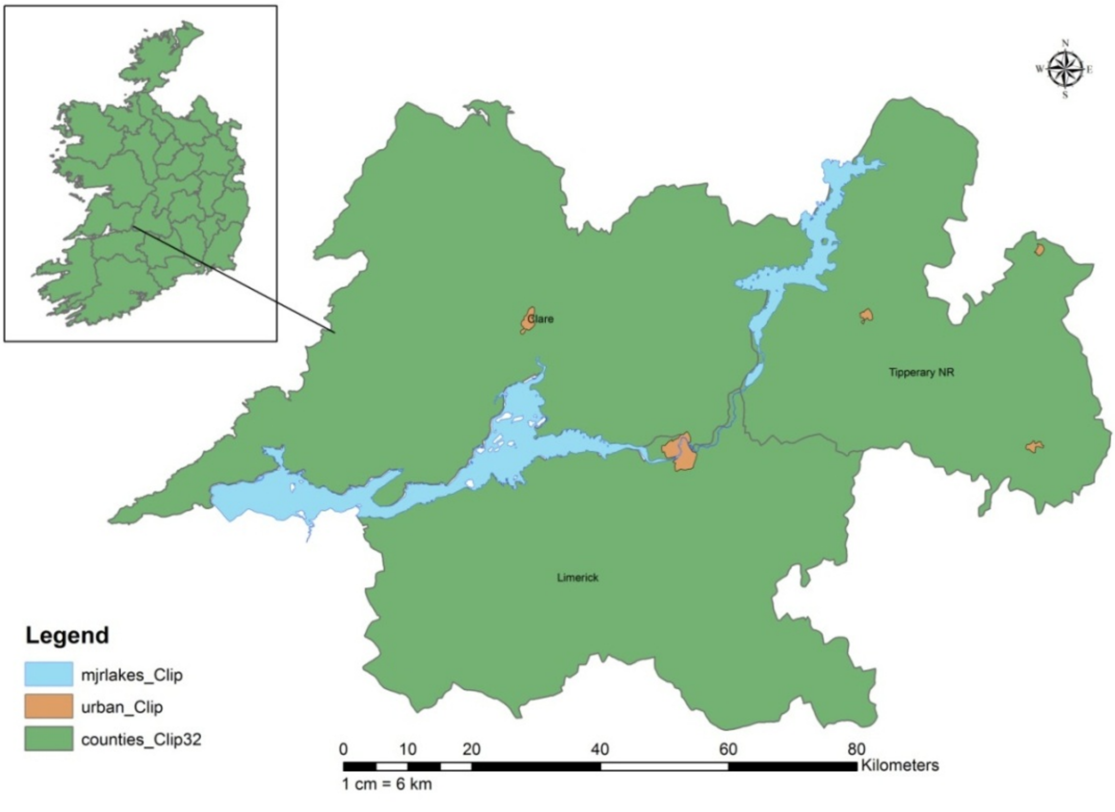

Fig.2 Map of the research area consisting of counties: Clare, Limerick and North Tipperary and forms the Mid-Western Health Board of Ireland.

The region is geologically diverse and is variously underlain by bedded and un-bedded Dinantian limestone and Devonian sandstone derived bedrocks, in addition to volcanics and shale deposits (Fig.3). Regional subsoils are similarly diverse; limestone, sandstone and shale tills are predominant in North Tipperary and Limerick, while large regions of County Clare are characterised by karstified outcrop/subcrop and therefore lacks substantial subsoil deposits.

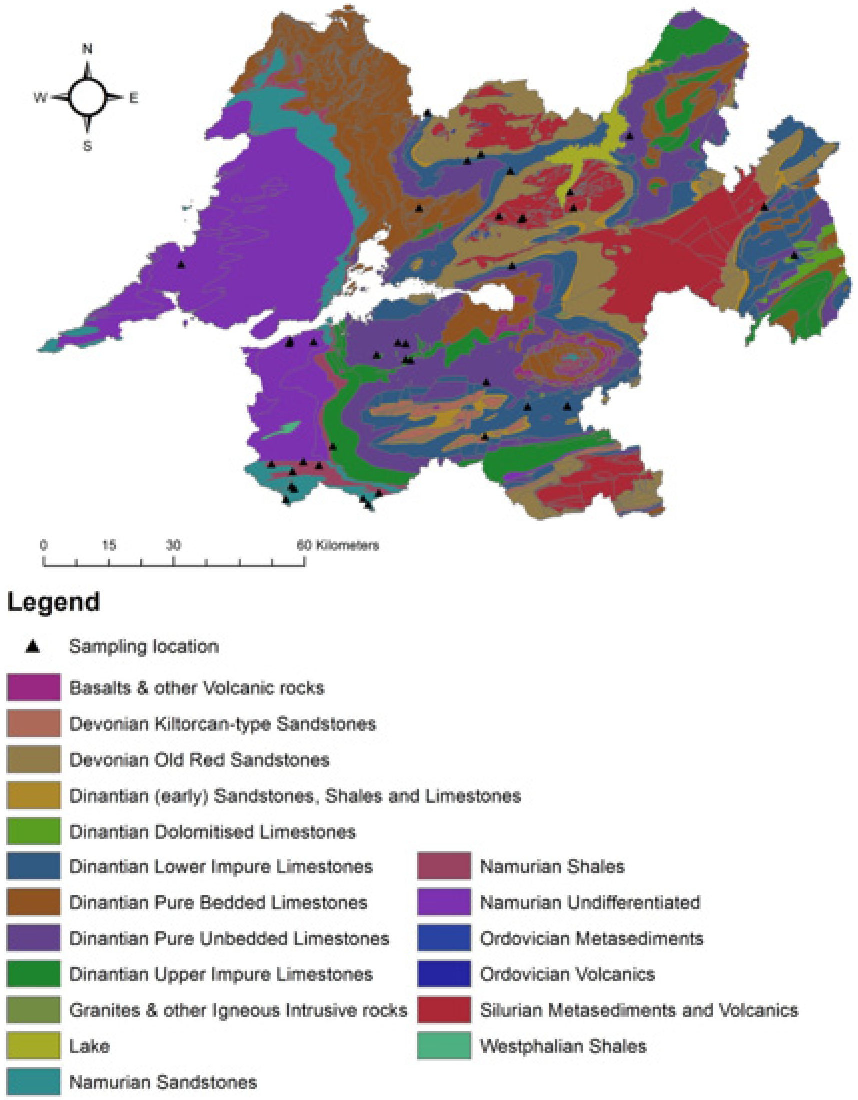

Fig. 3: Geographic distribution of the sample sites overlain on the geological attributes of the area.

METHODOLOGY

Microbiological Analysis

For microbiological analysis, water samples were taken from the taps of domestic wells users (n = 132) which were sought through an online advertisement on Boards.ie. Where *Escherichia coli* (*E. coli*) was (n = 42) identified and isolated, it was examined against a panel of commonly prescribed human and veterinary therapeutic antibiotics using the Disk Diffusion method. Simply, Agar plates were lawned with a pure *E. coli* culture after which commercially prepared disks, each of which are pre-impregnated with a standard concentration of a specific antibiotic, were evenly dispensed and lightly pressed onto the agar surface. Following overnight incubation, the bacterial growth around each disc was examined and recorded. If the test isolate (*E. coli*) was susceptible to a particular antibiotic, a clear area of “no growth” (Fig.4) will be observed around that particular disk. However, if the isolate is resistant, varying degrees of growth will remain. It is possible for an isolate to be resistant to one antibiotic (antibiotic resistance) or multiple antibiotics (multi-antibiotic resistance).

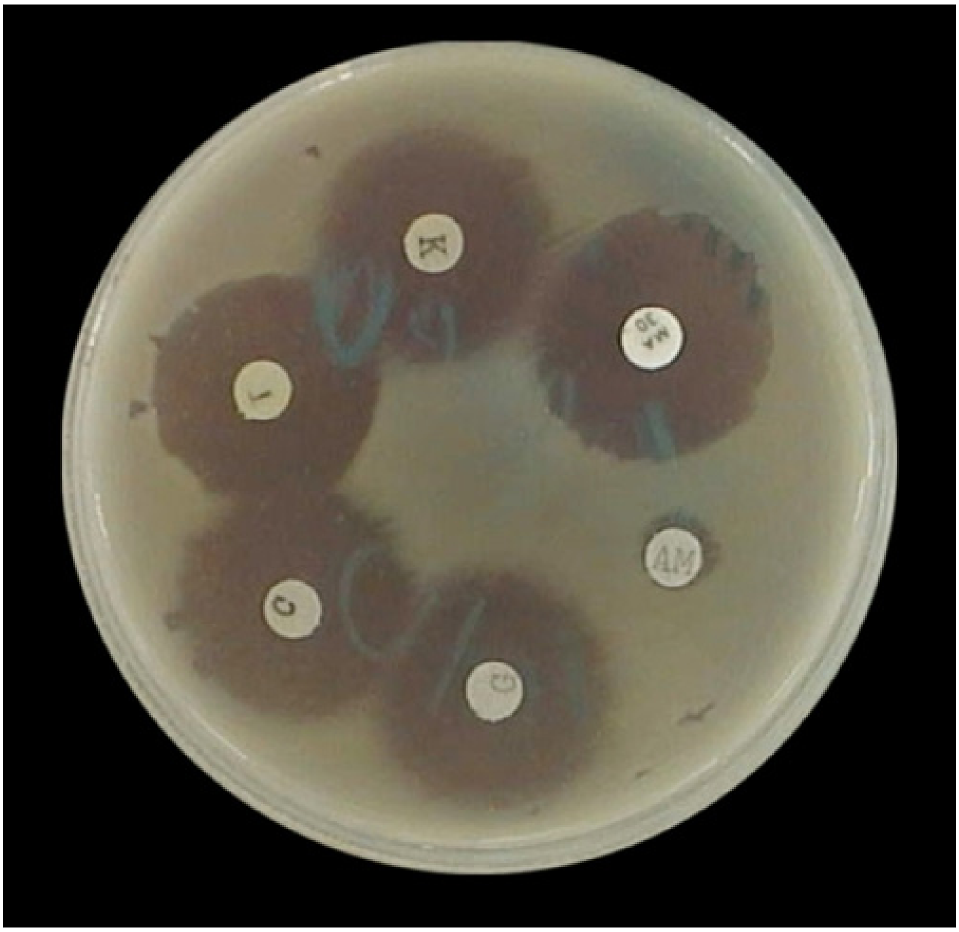

Fig.4: Example of the Disk Diffusion methodological approach. Where the bacteria is susceptible to the antibiotic, a period of no-growth can be seen around the antibiotic disk. Conversely, when the bacteria are resistant to the antibiotic, there area of no-growth is missing or reduced.

Geo-referencing and Statistical Analysis

In order to determine causative factors of resistance, site-specific and regional hydrogeological, agricultural and infrastructural features that could be sources and/or pathways of resistance were identified through literature review. Subsequently, relevant data sources were identified, extracted and collated via a Geographical Information System (ESRI ArcMap 10) in order to develop a spatially linked database associated with all confirmed *E. coli* isolates. Data pertaining to household composition, and particularly the presence of potentially vulnerable household residents ($\leq$ 5 years and $\geq$ 65 years), were recorded via a self-administered questionnaire which was completed in concurrence with groundwater sampling. The frequency (and regional density) of domestic wastewater treatment system (DWWTS) (i.e. septic tank) reliance were extracted from the CSO Census of Ireland 2011 dataset, followed by spatial indexing to one of 3,400 pre-defined Census enumeration divisions termed “Electoral Divisions” which are the smallest legally defined administrative areas in the State for which Small Area Population Statistics (SAPS) are published. Agricultural census data were spatially aggregated and used to calculate livestock (cattle) populations and associated densities for each Electoral Division. Hydrogeological parameters including groundwater vulnerability and aquifer type were spatially extracted using Geological Survey of Ireland (GSI) mapping resources, while local subsoil permeability data/layers were similarly extracted and assigned using An Teagasc (Agriculture and Food Development Authority) mapping data. For statistical analysis, both univariate and multivariate analyses were undertaken and Logistic regression (LR) models were constructed using sensitive/resistant profiles of *E. coli* isolates during the study period to identify predictive factors.

MAIN FINDINGS

Resistance to Human Panel of Antibiotics

Resistance to the human panel of antibiotics was found to be moderate with 9 (21.4%) *E. coli* isolates demonstrating some level of resistance to $\geq$1 human antibiotic; the highest levels of resistance were associated with the 1st and 2nd generation broad spectrum antimicrobials including ampicillin (14.3%), a β-lactam antibiotic first introduced in 1948, and familiar to most people. Typically, broad spectrum antibiotics are more frequently prescribed for non-fatal acute infection and thus, these antibiotics are characterised by a higher prevalence of resistance within human populations. Notably, resistance was also found within the fluoroquinolone class of antibiotics, with 4.8% (n = 4) of isolates exhibiting some level of resistance. This represents a particular concern, as this antibiotic class is frequently employed in the treatment of salmonellosis, an enteric infection with potentially high human health effects within specific subpopulations including the elderly, the young, and the immunocompromised, with hospitalisation often required.

Resistance to Veterinary panel of Antibiotics

In contrast to the human panel, higher levels of antibiotic resistance were found against the veterinary panel of antibiotics, with all isolates presenting resistance to at least one antibiotic. Particularly high levels of resistance (93%) occurred within the aminoglycoside class; high levels of resistance to aminoglycoside antibiotics (e.g. streptomycin and neomycin) in *E. coli* isolates have been reported in food-producing animals (cattle, sheep, and pigs) in Europe [6]. Tetracycline resistance was also prevalent in *E. coli* isolates (19.1%), which was expected as tetracycline has been extensively used as a therapeutic agent and growth promoter in animal feeds since its approval in 1948 and may thus infiltrate the subsurface environment. The use of tetracycline as a growth promoter in animal feeds is no longer authorised within the European Union, however, bacterial tetracycline resistance has been reported over a decade (126 months) after cessation as a feed additive or therapeutic agent within swine flocks [7].

Sources of antibiotic resistance

Within the environment, the prevalence of antibiotic resistance is attributable to numerous factors, including source and pathway dynamics, soil type, and excretion rates associated with un-metabolized antibiotics themselves. The majority of therapeutic antibiotics are water-soluble and therefore about 90% of the dose may be excreted in urine, while up to 75% may be released in animal faeces [8]. In the current study, strong statistical relationships were found between the presence of both human antibiotic resistance (p =0.011) and human multiple antibiotic resistance (p =0.002) and DWWTS reliance per Electoral Division, indicating that regions characterised by a higher density of on-site treatment systems are associated with the presence of antibiotic resistant *E. coli*. This was corroborated through regression analysis which indicated that antibiotic resistance to the human panel of antibiotics increased in line with an increase in DWWTS density per ED. Furthermore, a significant association was found between households comprising children $\leq$5 years of age and the presence of both human antibiotic resistance (p = 0.022) and human multiple antibiotic resistance (p <0.001). Further analysis demonstrated that households with small children were over eleven times more likely to have antibiotic resistant *E. coli* in their water supply. A recent longitudinal study undertaken in Ireland reports that 18.4% of children aged $\leq$3 years were prescribed $\geq$3 courses of antibiotics in the previous 12 months, with two-thirds (66%) of three-year-olds having received at least one course of antibiotics during the previous 12 months [9]. With reference to veterinary antibiotics, results from the current study suggest a significant association (p = <0.001) exists between cattle density/ED and the prevalence of veterinary multiple antibiotic resistant *E. coli* isolates.

Environmental Fate of Antibiotic Resistance

In the current study, no significant associations were found between extracted local hydrogeological parameters and the prevalence of resistance within both antibiotic panels. However, it should be noted that the current research formed part of a larger overall study which sought to investigate the susceptibility of differing subsurface environments to faecal contamination [3]. Accordingly, due to the overarching objectives of the primary study, *E. coli* isolates were primarily sampled from regions with characteristically high levels of susceptibility to groundwater contamination, and are as such indicative of specific hydrogeological characteristics considered conducive to contamination. For example, results from the aforementioned study have shown that the presence of *E. coli* can be predicted relative to aquifer type and the presence of karst features; bedrock aquifers with karst geomorphology were more conducive to *E. coli* contamination. Accordingly, the relatively small number of *E. coli* isolates characterised by human/veterinary resistance in concurrence with the high level of homogeneity associated with the study samples represent the primary study limitations, particularly with respect to elucidation of subsurface occurrence and movement.

CONCLUSION AND FUTURE RESEARCH NEEDS

Our findings suggest that antibiotic and multi-antibiotic resistant *E. coli* are not uncommon to the environment of rural groundwater supplies in Ireland. The current study, while limited in its hydrogeological scope, is invaluable insofar as it is the first to present irrefutable evidence of the presence and extent of antibiotic resistance in the Irish groundwater environment, which represents the primary daily source of drinking water for ≈750,000 people, in addition to many more on a transient basis. Moreover, all isolates were sampled from groundwater sources for domestic human consumption, thus the presence of, in some cases multiple antibiotic resistance, cannot be overstated; it has been established that water contaminated with antibiotic resistant *E. coli* has been associated with the carriage of resistant *E. coli* in humans. As groundwater continues to be an important source of potable water for a significant proportion of the Irish population, the results presented provide an invaluable benchmark to highlight the need for, and provide guidance for further research into antibiotic resistance in the subsurface environment. Further work should focus on prevalence of resistance within defined and preselected hydrogeological environments using more ubiquitous indicators (e.g. antibiotic resistance genes) to facilitate knowledge transfer of resistance transport in the subsurface environment. Nevertheless, this study has provided valuable insight into previously uncharacterized antibiotic resistance in the Irish groundwater environment and provides a benchmark for future studies.

Details of full paper

O’Dwyer, J., Hynds, P., Pot, M., Adley, C. C., & Ryan, M. P. (2017) 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*, 1-13.

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CRYPTOSPORIDIUM IN IRISH WATERS: RISK, PREVALENCE AND INTERVENTION. THE IMPACT OF NOVEL LIFE-CYCLE STAGES.

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ABSTRACT

Cryptosporidium is among the most prevalent causes of protozoan diarrhoea in the world. Rates in Ireland are the highest in Europe, which is a cause for concern particularly with the expanding population of at risk groups including the immunocompromised. Difficulties in detection and treatment of this organism are widely know, but recent discoveries have compounded these issues. The discovery of novel life-cycle stages outside those traditionally known has complicated an already difficult risk calculation. Environmentally prevalent, non-oocyst stages that are not detected by traditional methods have been characterised. Additionally, these novel stages appear capable of surviving in biofilms, sites traditionally resilient against UV treatment, often the current preferred option for attenuation of *Cryptosporidium.* Understanding these new risks is critical to the accurate estimation of population risk and to the design of adequate drinking and waste water treatment plans to protect the population from infection.

Cryptosporidium spp. were first described in mice in 1907 and have since gained recognition as an important emerging protozoan parasite. Recent data from the Global Enteric Multicentre Study (GEMS) indicate that *Cryptosporidium spp.* are among the leading causes of moderate to severe diarrhoea in children under the age of 2. Incidence in Ireland has varied significantly since it became a mandatory reportable disease with no definitive trend noted (Fig. 1), although Ireland consistently has the highest notification rate of infection.

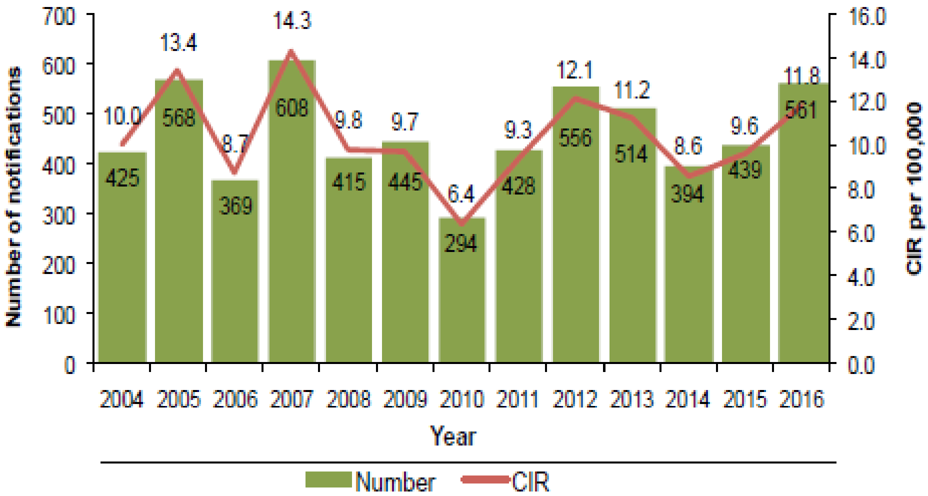

Fig. 1. Annual number and crude incidence rate of cryptosporidiosis in Ireland from 2004-2016. From http:www.hpsc.ie

The increase noted from 2015 to 2016 was consistent across all HSE areas and so not associated with any one contamination event or source making the reason for the increase difficult to identify and future trends difficult to predict (HPSC, 2017).

As with other countries, studies indicate a significant portion of Cryptosporidiosis in Ireland originates from water. What is more concerning is the incidence of outbreaks associated with treated water (Mahon and Doyle, 2017, Mirhashemi et al., 2016, Agency, 2011). A recent investigation of a 2012 outbreak of 12 linked cases concluded that the source was the public drinking water supply (Mahon and Doyle, 2017).

The risk in Ireland stems, at least in part, from the large proportion of drinking water that originates from surface water (>80%) (Agency, 2011, Doris et al., 2015). These reservoirs are inevitably at greater risk of contamination and the inherent difficulty in both detecting and removing the organism add to the increased risk of infection (Agency, 2011, Amoueyan et al., 2017, Armon et al., 2016, Doris et al., 2015, Thompson et al., 2016, Efstratiou et al., 2017). While appropriate wastewater treatment can attenuate *Cryptosporidium* (King et al., 2017) the significant risk to Irish surface waters from agricultural run-off, potentially made worse by changing weather patterns, means treatment at point of delivery is also necessary (Stewart and Elliott, 2015).

Cryptosporidium spp. are members of the Apicocomplexan parasites and of the 31 potentially pathogenic species, *C. parvum* and *C. hominis* are responsible for the majority of human infections (Amoueyan et al., 2017, Armon et al., 2016, Cacciò et al., 2015).

Clinical symptoms of infection appear 2-14 days post infection and include those often associated with gastrointestinal pathogens: profuse watery diarrhoea, abdominal cramps, nausea, vomiting and a low grade fever. In immunocompetent people, infection is usually self-limiting and lasts 1-3 weeks, while infection is prolonged in the immunocompromised (Davies et al., 2017, HPSC, 2017). Additional complications associated with infection can be seen in these immunocompromised hosts and include malabsorption, bile-duct infections with associated jaundice or symptoms of pancreatitis. In the most vulnerable group, those under 5, infection can be a contributory factor to mortality particularly in the event of a severe infection or an already malnourished host (Davies et al., 2017, HPSC, 2017).

The thick-walled oocyst is the primary mode of transmission, either by zoonotic transmission (direct contact with infected animals) or by the more common non-zoonotic transmission by water or food. Infection is by oral ingestion of the oocysts. Symptomatic stages of infection are associated with the release of a sporozoite from the oocyst after passage through the stomach. This sporozoite infects an epithelial cell, forcing the cell membrane to enclose the parasite in an extra-cytoplasmic (epicellular) parasitophorous sac (Clode et al., 2015, Ryan et al., 2016) (Fig 2.).

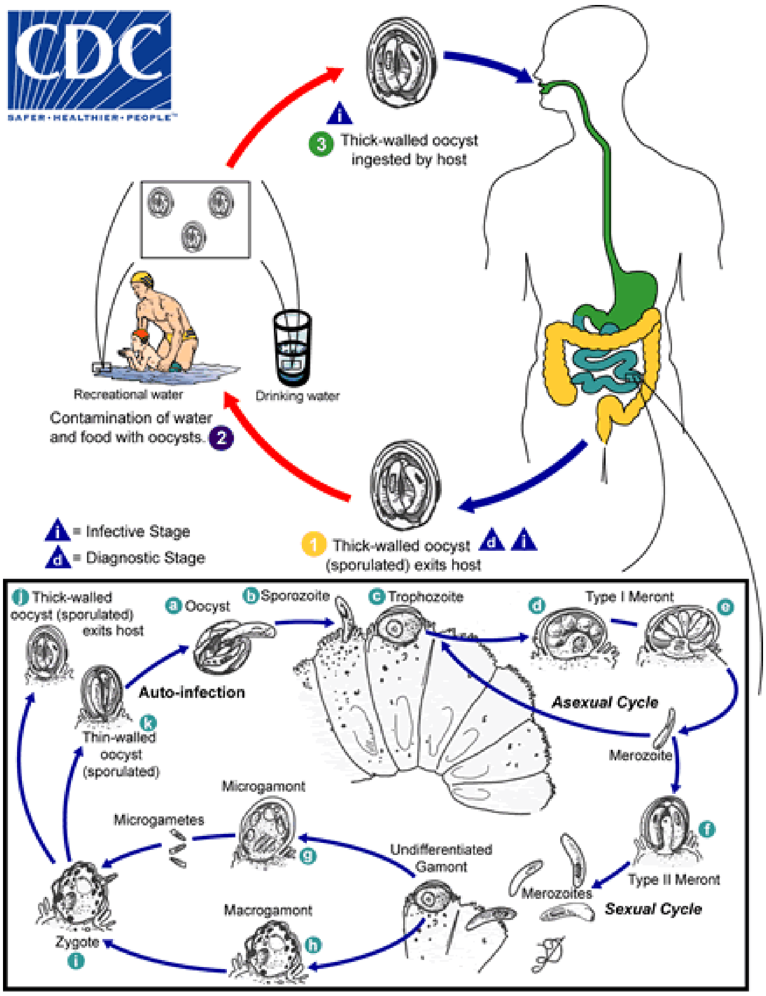

Fig. 2. Schematic of the life cycle of *Cryptosporidium* from https://www.cdc.gov/dpdx/cryptosporidiosis/index.html

Studies on cultivation methods of *Cryptosporidium* in a laboratory setting had indicated and since confirmed that there is a significant portion of the parasite life cycle that occurs extra-cellularly, independent of host cells (Clode et al., 2015, Morada et al., 2016, Ryan and Hijjawi, 2015, Ryan et al., 2016, Yang et al., 2015). The source and role of these gamont-like stages of the life-cycle are as yet unclear. It may be a form of sexual reproduction, or have developed from sporozoites that failed to penetrate a host cell but all are as yet these theories are unconfirmed. Initial theories that these stages were an anomaly were disputed after a number of studies found large quantities of gamont-like stages in the faeces of infected hosts indicating they may be a normal part of the parasite life-cycle (Clode et al., 2015, Morada et al., 2016, Ryan and Hijjawi, 2015, Ryan et al., 2016, Yang et al., 2015).

These recently discovered life-cycle stages, while interesting from a clinical and parasitology perspective, may have more significant implications for the water treatment industry, particularly in determining risk in distribution systems. If, as has been indicated, these stages can survive and thrive as part of bacterial or complex biofilms (Koh et al., 2013, Koh et al., 2014, Ryan et al., 2016) the current risk assessments may need to be revised.

The initial problem is with detection. Cryptosporidium is a difficult organism to detect and the use of antibody based detection methods have prevailed. Two main classes of antibodies are currently used targeting the oocyst or the sporozoite/trophozoite stages. As the oocyst was considered the only environmentally viable stage of the organism ISO, BS and US standard methods on detecting cryptosporidium in water have focused on antibodies specifically against antigens present on the outer surface of the oocyst. A number of recent studies have shown that these antibodies were not able to stain novel gamont-like stages of the parasite present in biofilms, although there was a contradictory report indicating that there may be a certain environmentally resilient gamont-like stage that can be stained by traditional methods. To clarify these contradictions further studies need to be undertaken, but clarity is critical for an accurate estimation of actual risk (Clode et al., 2015, Ryan and Hijjawi, 2015, Ryan et al., 2016).

Environmental survival of oocyst stages of the parasite is well defined, with a die off rate in water currently estimated at 0.005-0.037 $\log_{10}$ units per day. The fate of these new stages is as yet unknown. Current survival studies are focused on the ability of biofilms to act as a reservoir for these parasites. Data from environmental samples has focused on the detection of oocysts in biofilms but recent studies on artificial biofilms established under controlled conditions have shown the presence of all stages of the cryptosporidium life-cycle including gamont-like cells and extra-large gamont-like stages by scanning electron microscopy and flow cytometry. The possibility of viable infectious parasite stages emerging from these systems is currently being investigated (Clode et al., 2015, Ryan and Hijjawi, 2015, Ryan et al., 2016, Yang et al., 2015).

Cryptosporidium is the most resistant to chemical disinfection, particularly chlorination and by virtue of its size is the hardest to consistently remove by filtration when compared to other water bourne pathogens. The dual-layered thick walled oocysts are also resistant to ozone and chlorine dioxide under normal water treatment temperature ranges and conditions experienced in Ireland placing limitations on the efficacy of these methods due to the high Contact Time (Ct) required for *Cryptosporidium* inactivation at low temperatures. Inactivation using UV disinfection is effective but in its absence, management of risk to human health from pathogenic protozoa relies mainly on their removal by water treatment process such as coagulation/filtration. The implications to water treatment if these stages can survive and produce infective stages in biofilms is obvious: Biofilms are often if not resistant to can be resilient against UV treatment (King et al., 2017, Ryan et al., 2016, Thompson et al., 2016).

In essence, *Cryptosporidium* treatment may be more complicated than previously thought.

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SESSION VIII

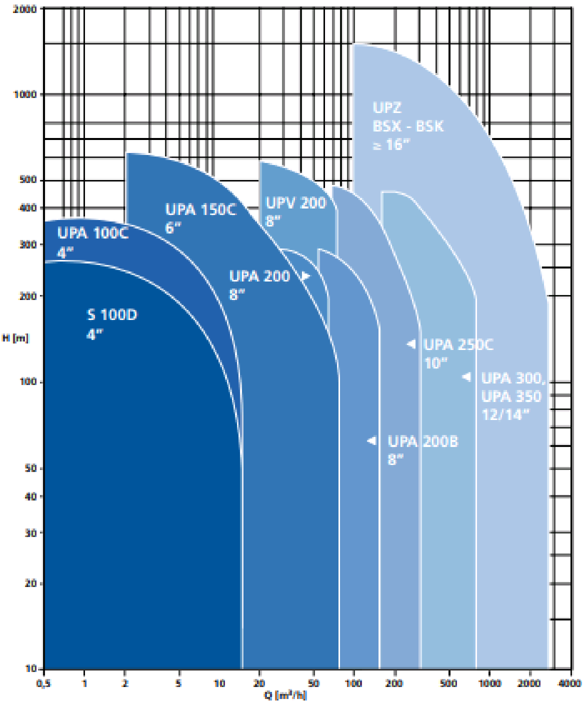
EFFECTIVE AND EFFICIENT BOREHOLE PUMPS

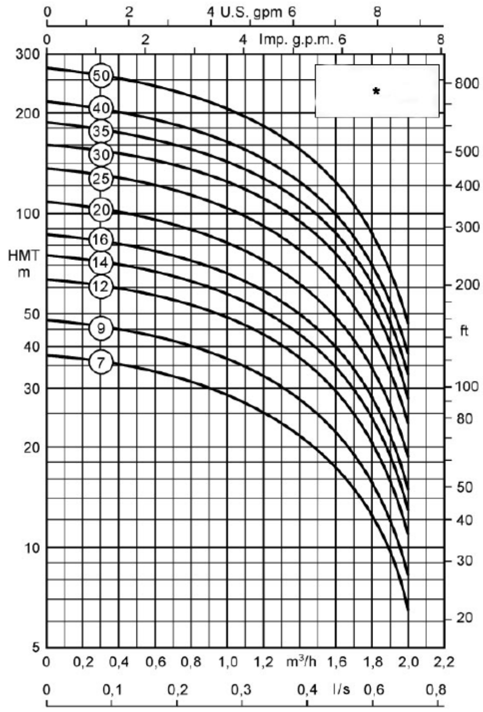
John Calder, Dura Pump

To ensure a pump system is effective and efficient we must understand the interaction of all the component parts, all the differing operating conditions and the capabilities of the pump.

CORRECT PUMP SELECTIONS

To ensure a bore hole pump is effective and efficient we must establish the exact operating conditions that the pump will be subjected to. This will include the position of the pump within the borehole, the variation in water level within the borehole while it is being pumped and its adjustment was seasonality, we must also understand the discharge conditions, in other words the demands and its variation on the discharge. Once we have these factors and look at the extreme points of variation to begin the pump duty point's specification.





Variable Speed Drive

The variations will often mean the use of a variable speed controller is critical. This controller allows us to adjust the duty of the pump to match these varying conditions. For example, if we have an increased demands on the discharge we could increase of speed of the pump to meet this, similarly as the water level within the borehole drops we can also increase the duty points of a pump to match this.

The use of the variable speed drive allows the demand to be met in the most energy efficient way as demonstrated in the chart below.

Water consumption Average	Energy consumption			Period	Savings
	Before	Afterwards	Difference		
by 20 m³/h	5,0 kW	3,5 kW	1,5 kW	6h	9,0 kWh
by 40 m³/h	10,5 kW	7,0 kW	3,5 kW	5h	17,5 kWh
by 65 m³/h	16,0 kW	13,0 kW	3,0 kW	5h	15,0 kWh
by 70 m³/h	17,0 kW	14,0 kW	3,0 kW	4h	12,0 kWh
by 80 m³/h	21,5 kW	16,0 kW	5,5 kW	4h	22,0 kWh
			Savings per day		75,5 kWh
			Yearly savings		27.557,5 kWh

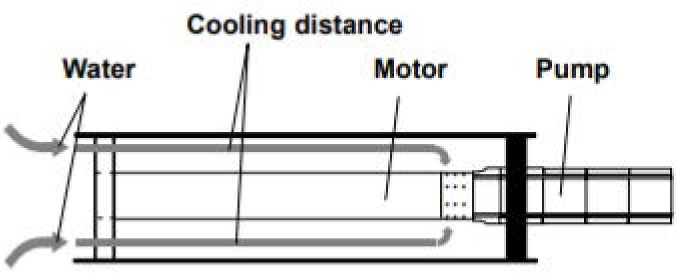
When using drives in submersible pump systems, there are however a few complications that users need to be aware of, but these can generally be overcome with some careful planning. For instance, motors in borehole pumps can have a motor cable as long as 100 metres and it is often necessary to fit output reactors or sine filters. These are quite effective at reducing the rate of voltage change (du/dt) and the peak motor voltage. Considering all these factors we must also consider the power demand on the system. This includes the inverter, pre and post filters and cables.

Water Content

Having recognised all of these mechanical and electrical requirements of the pump we must also consider the water content. That is the water composition, minerals, solids and chemicals within the water. There may be high levels of fines/sand for we must make allowances and the use of correct materials within the pump specifications. Corrosion caused by highly acidic / alkali water is another factor that needs to be checked.

Bore Hole Motor Cooling

The other factor we must also remember is where a water supply is coming from within the bore hole. This is whether it's from above or below the pump. This is to ensure sufficient motor cooling. The motor on a borehole pumps is cooled by the flow of water into the pump past the motor. Water past the motor is typically between 0.2 m/s and 1.5m/s, which ensures optimum pump operation. Maintaining the correct velocity is key to the reliability of the motor. A cooling shroud may be used to achieve an increased flow velocity if required.



Variables Monitoring

To ensure the effectiveness and efficiency of the pump we must understand how we monitor the operating conditions. These both include the water level in the hole and the demand for water. We can do this by monitoring the level in the hole using a submersible pressure transducer. The demand for water can be measured via a flow metre to provide a constant supply at a fixed volume, or we can use a pressure transducer where there is a varying demand with a constant pressure requirement. Processing this information to an inverter or a PLC the optimum conditions can be maintained for the pump and the water user.

A PROPOSED CLASSIFICATION OF WATER SUPPLY BOREHOLES IN IRELAND BASED ON TREATMENT REQUIREMENTS

David M. Ball Hydrogeologist

ABSTRACT

Irish Water want to classify their groundwater sources. They want to do this so that they can obtain an assessment of their sources, and determine the level of any future investment that they need for water treatment or new sources.. We have been working to devise a systematic way of classifying water supply boreholes within this context, so that hydrogeologists and groundwater engineers can do an assessment of Irish Water's groundwater assets and communicate the results in a systematic way to other professionals.

1. INTRODUCTION

The proposed classification in this paper arises from a commission by Malcolm Doak, Hydrogeologist – Asset Management in Irish Water. We have worked together collaboratively. It is anticipated that Irish Water will publish a document on this subject during the year. We are bringing the findings to this conference or 'common forum and community of practice' to provide an opportunity for comment, and because hydrogeologists and groundwater engineers may be asked to apply a methodology like this, in the near future.

A borehole or groundwater source classification could be seen as a passive process, which, when achieved, leads to a classification label for each borehole or source, that is fixed and unchangeable. Instead, the classification approach and methodology that has been developed for Irish Water is a process of assessment of the present state, but with a methodology to determine whether, and how a borehole's 'state', water quality and treatment requirement also could be changed and improved.

Boreholes require description and some form of descriptive classification, because the term 'borehole' means little or nothing. A borehole is a hole that has been excavated or bored into the subsurface by engine powered, or human powered, boring equipment. In hydrogeology, a borehole usually is a hole that is excavated below the 'water table' into the zone of saturation. There is no descriptive classification of boreholes that is accepted worldwide.

A borehole is simply a hole. It is a void; an empty space. Even the word borehole is not a universally used term. In South Asia the same hole is called a 'tubewell'. In many other English speaking countries it is called a 'borewell'.

Even experienced hydrogeologists in Ireland vary, and are inconsistent in, their use of a term to describe 'a hole in the ground from which water is obtained'. We call them 'water wells' when we are speaking loosely, and then, when we are being more specific, we could call it a 'high yielding, deep, water supply production borehole'.

It is not a surprise that engineers and other professionals in Irish Water are confused by our ways of describing or defining boreholes, nor they would want a system or nomenclature that provides greater clarity, consistency and their requirements.

Boreholes are constructed for different purposes, and sometimes they are classified by the purpose or objective; for example, an exploration borehole, a 'monitoring borehole' or a 'water supply borehole'. These names do not give any information about the construction dimensions of the hole or its success or failure. Therefore, boreholes are classified with additional sub divisions such as: ‘wide diameter borehole’, or ‘shallow borehole’, or ‘deep bedrock borehole’, or ‘water supply borehole – producing’, or ‘water supply borehole – abandoned’.

These classifications or descriptions are arbitrary, but for hydrogeologists working all over the world, this is useful to have a classification that can be adapted or redefined to fit with local conditions, customs or a specific project terminology.

Both exploration and production boreholes can be classified also by their yield and drawdown characteristics. This can be used as a proxy for the aquifer characteristics. This type of information can be used to compile aquifer classification maps.

Borehole classifications can be useful for different purposes. When Irish Water was set up in 2014, it began to determine the location and characteristics of the sources of the water supplies that had become its responsibility.

Irish Water wants to produce high quality drinking water. Therefore it wanted a system for classifying their sources in the context of the water treatment. Most water treatment issues, such as turbidity or pathogenic bacteria were well understood, but Irish Water were particularly concerned by the problem and risk of cryptosporidium in the water from their surface and groundwater sources.

Irish Water sought international guidance for ways of defining and classifying the risk of protozoa in water sources and the treatment levels required, and adopted the concept of a Cumulative Log Credit Approach. This is based on the additive barrier effect, on a log scale, of successive different treatment processes in the removal, or inactivation, of protozoans. The approach came from a USEPA document in 2006 called ‘National Primary Drinking Water Regulations: Long Term 2 Enhanced Surface Water Treatment Rule: Final Rule (USEPA 2006a)’. This USEPA document does not refer to groundwater sources, but it was adapted and used in the New Zealand Drinking Water Standards (2008).

From the latter document, Irish Water derived a table giving the ‘Log Credit treatment requirements for different surface water catchments and groundwater categories’. However, New Zealand criteria for determining the risks to, and requirements of, groundwater sources were difficult to apply to Irish groundwater sources. The New Zealand criteria used monitoring and water analysis parameters, borehole construction and aquifer characteristics that are either not used in, or are inapplicable to, Ireland. For example, in Ireland we do not use tritium, chlorofluorocarbon or sulphur hexafluoride to determine whether water from our boreholes is, say, less than one year old. We also do not have porous media bedrock aquifers or easily identified ‘confined’ aquifers. The rocks under much of New Zealand are younger and softer than the youngest bedrock below the Republic of Ireland.

Irish Water estimated in 2016 that over 700 of their individual sources were groundwater sources. Irish Water tried to classify these groundwater sources using a modified version of the New Zealand approach. Groundwater sources were ranked on a scale of 1 to 5, with a prefix of G before each number. GI is a low risk requiring little or no treatment and G5 is a high risk requiring many treatment processes. Surface water was ranked on a similar scale from 1 to 3 with an S prefix. S1 was equivalent to G3 and S3 was equivalent to G5 in terms of treatment processes needed to remove protozoans.

Irish Water did a quick scoping review of their groundwater sources and estimated that most of their sources were G3 or worse. Only one source was G1.

It was originally intended that this classification would be used either to plan and cost a large investment in water treatment plants for groundwater sources, or a programme of abandoning groundwater sources, and seek alternative new sources; possibly large surface water sources to supply regional schemes.

The difficulty of applying a New Zealand assessment method to Ireland, and the potential problems and costs, were realised 2017. A decision then was made to try to derive an appropriate new method of assessing groundwater sources in Ireland.

The classification proposed in this paper is an attempt to merge or bring together, the different characteristics of good and defective water supply boreholes with five levels of water treatment. We provide a classification spread sheet and a decision tree, and several examples of boreholes with design, construction and pumping characteristics that are likely require each of the five levels of treatment. Other examples of boreholes will be shown in the lecture.

2. PROPOSED CLASSIFICATION

Water treatment relates directly to the quality of the water pumped from the borehole, but water quality is often closely linked to the original borehole design and construction, and the current pump operation regime. Embedded in the classification methodology is the recognition that water quality is not fixed. It can vary during the pumping cycle, or with natural changes in recharge rates, water levels and agriculture. Also embedded is the recognition that water quality can be improved by changes in construction, pump position and operation of the pump.

Therefore, a water supply borehole might be classified initially, according to its present condition and water quality, but there is a recognition that a source could be given a higher classification with a less need for water treatment if the operation or construction is improved. For example, some defective boreholes can be reconstructed to proper standards, to avail of better quality water that requires less or no treatment, in a different, probably deeper, part of the aquifer.

The decision flow diagram in this paper gives an idea of how the characteristics of a water supply borehole, and the water it currently produces, can be assessed in the context of treatment, but also the context of improvement or rehabilitation.

Irish Water has accepted the standards and guidelines provided in the EPA Office of Environment Enforcement Drinking Water Advice Note 14 “Borehole Construction and Wellhead Protection”, published in September 2013, which includes the Institute of Geologists of Ireland’s ‘Water Well Guidelines’ produced in 2007. The water supply boreholes sited and constructed according to these documents are regarded by Irish Water as G1 boreholes.

Figure 1 shows a proposed classification of groundwater sources that is being proposed for use by Irish Water. It is put forward as a basis for hydrogeologists and engineers to assess individual sources. On the left of the table are columns relating to the type, design, specification, supervision of construction, construction, and availability of adequate records of construction geology and pumping tests. The entries in these columns are a way of assessing the quality of information about each source and the level of confidence in this information.

On the right of the table are two columns relating to water treatment. There are five levels of treatment.

- Level 1 is the addition of chlorine to the water. This is not a treatment to cure an inherent problem with the raw water, but more the addition of chlorine as a preservative to protect the water as it passes through the distribution system to the consumer.
- Level 2 is UV treatment to remove protozoa such as cryptosporidium and then the addition of chlorine.
- Level 3 is filtration to remove turbidity that would reduce the effectiveness of UV, followed by UV and the addition of chlorine
- Level 4 is Ozone treatment to remove colour or organics in solution followed by filtration, UV and chlorine.
- Level 5 is coagulation and flocculation to cope with a heavy sediment load, followed by

ozone to remove organics, filtration and finally ozone and chlorination.

Each increase in level of treatment builds an incremental layer of protection for the consumer particularly in the context of cryptosporidium, but the purpose of the table is to provide a systematic way of assessing the need for a particular level of treatment and the types of borehole or source that might require this level of treatment.

The central columns in the table provide criteria that assist in the assessment. These columns are asking the hydrogeologist or engineer questions about the source, the way it is pumped and evidence of water quality. Filling in the answer to the questions in the column headings means that the hydrogeologist or engineer is required to assess the quality of information and their confidence in it. The column headings are:

- Deep PVC or Steel Pump Chamber Casing? Yes or No
- Complete cement grout filled annulus around the pump chamber casing? Yes or No
- Correct pump position (in other words, is the pump intake within the pump chamber casing)? Yes or No
- Pumped correctly (in other words is the pump operated at or less than the sustainable yield, continuously or for long periods at a time, or is it pumped violently at a rate in excess of the sustainable yield and turned off and on frequently)? Yes or No
- Is there **credible** evidence of microbial contamination? Yes or No
- Is there a turbidity issue? Yes or No
- Is there colour and or a high level of colloidal or dissolved organic compounds in the water? Yes or No

The yellow high lit cells in the centre of the table are to draw attention to the fact that negative answers to these questions can be rectified or improved, if some aspect of the construction or operation of the source can be modified. For example the position of the pump can be raised up inside the pump chamber casing, and the pump can be operated gently for longer periods. This could cure a turbidity issue and mean that the source could be upgraded from requiring Level 3 treatment to just requiring Level 2 (ozone and chlorine) treatment.

The final column on the right briefly describes modifications or remedial actions.

As can be seen this classification table contains cryptic questions that require simple answers, yet providing a confident answer to each, requires information, assessment and analysis. The assessment and analysis requires skill and experience. It is not possible to provide a classification methodology that can be used with no prior training or experience.

The outcome of the classification is that groundwater sources requiring Level 1 treatment are classified or described as G1 sources. The prefix ‘G’ in Irish Water denotes a groundwater source.

3. G1 TO G5 BOREHOLE DIAGRAMS

A G1 borehole is not just a properly designed constructed and supervised borehole in accordance with EPA Drinking Water Advice Note 14 (2013), as shown in Figure 2. The classification in Figure 1 includes older boreholes which, by good fortune rather than design and construction, still require only a Level 1 treatment. Figure 3 shows such a borehole, where clay and transition zone debris has slumped around a pump chamber casing and prevented shallow, easily contaminated, water from flowing down the outside of the pump chamber casing and into the borehole. In other words a grout seal was not constructed by design, but occurred by good fortune arising from a conductor casing being mistakenly inserted to a depth that was too shallow.

Sometimes a borehole can be classified as G1 if the conductor casing is installed and grouted in below the transition zone and any upper or shallower zones yielding water. The conductor casing stops shallow water and also clay and other debris falling down the annulus around the pump chamber casing. It is not in accordance with modern standards, but fortunately, it is effective.

The classification therefore allows for older boreholes to be classified as G1 on the basis of credible evidence obtained during operation, and not just on the basis of an original modern design.

Figure 4 shows an example of a G2 borehole. The operational monitoring data shows that the water pumped from the borehole has continuous or periodic contamination by bacteria and there is a real risk of cryptosporidium oocysts in the raw water. In this example, shallow groundwater is the probable source of the microbiological contaminants. It is seeping under the steel conductor casing and the steel pump chamber casing, every time the pump is turned on. The pump is in the correct position, and the borehole is pumped gently. Therefore, this borehole does not have an issue of turbidity spikes at the start of pumping or persistent turbidity during pumping.

Figure 5 shows an example of a G3 borehole with both a microbiology problem and a turbidity issue. The borehole on this example, is being over pumped. There is no pump chamber casing. The pump is misguidedly placed at the bottom of the borehole (which is often, or usually the position chosen by pump suppliers). There is no grout sealing out the shallow water. When the oversized pump is turned on, the water level rapidly falls to near the pump intake. Water flows quickly along the productive conduits in the bedrock, and the turbulent flow picks up sediment from the floor of the conduits, and brings it into the borehole. The water from the conduits and from around the bottom of the casing, cascades down to the pump, which is also probably sitting in sediment at the bottom of the borehole. With the wrong sized pump, in the wrong position and pumped in the wrong way, it is inevitable that the water from this borehole will contain sediment. It may not be a lot of sediment, and it may just be at pump start up, but it will be sufficient to create a risk that UV treatment for cryptosporidia will be ineffective.

Once a borehole with these problems has been diagnosed, it is obvious that it would probably be possible to remediate the turbidity issue by changing the pump position and pumping the borehole gently for longer periods with a much lower drawdown. The sustainable yield from the borehole is not determined by the pump's power or the pump position but by the ability of water to flow along the conduits. A high drawdown, down to the pump intake, does not result in a higher yield. In fact it can result in a lower yield, by the drawdown in the 'aquifer' drying up the upper productive conduits. The correct position for the pump in this example would be above the level of the uppermost yielding conduit; in this case at 40-45 metres below ground level. If the new pumping arrangements are successful, then this G3 borehole could be re-classified as a G2 borehole.

Figure 6 shows an example of a G4 borehole, that has an issue with colour and organics, as well as microbiology and turbidity. The basic borehole and pump position is the same as the G3 borehole in Figure 5, but the borehole is drawing water from both a shallow transition zone under a peat bog and next to a stream, river or lake containing peaty or coloured water. The borehole drawing also shows a very limiting and ill-advised feature of many boreholes designed by drillers working without supervision in Ireland. It is a cheap thin-walled plastic sleeving (often called 'casing' or 'screen' by the drillers) installed by drillers to make sure that the borehole remains open to the full depth. Drillers are usually paid by hole depth, at so many euro per foot or metre for different diameters. Clients do not pay drillers to construct a proper water supply borehole, because they are not aware of the many factors involved in designing and constructing a proper water supply borehole, and it is still traditional to pay for depth. Sometimes the driller will cut irregular slots in the plastic sleeve with an angle grinder or hack saw. Sometimes, they do not do this, and all the water reaching the pump has to go down the annulus around the sleeve, and come up through the small 5 or 6 inch diameter open hole bottom of the sleeve pipe, partially blocked by the pump motor.

An important feature of all the borehole drawings (in Figures 3 to 7), is that every borehole has a concrete slab around the casing at the surface, and also a cover on the borehole. These borehole headworks prevent surface spillages and contaminants from going down the borehole. However, the drawings illustrate that the quality of the water from a borehole is really determined by the hidden construction of the borehole, and the pump position and the way it is pumped. In other words, the visible surface sealing of a borehole may make it look nice, and play a part in the quality of the borehole and the water pumped from it, but it is what goes on below the surface that is critical in the classification of a borehole.

Figure 6 shows the importance of borehole construction in relation to location and a particular overburden and setting. Figure 7 shows the same but a more extreme version. It shows both a borehole and a spring, where the setting and the catchment are more important. The high level of expensive treatment required for the water from these two G5 sources is determined by the fact that the raw water has all the quality characteristics of raw surface water.

The diagram in Figure 7 shows the catchment and flow system through the rock, as well as the borehole construction and pump position. It can be seen that a river or stream flows off a peaty moorland catchment on shale rock. The water will contain suspended sediment at high flow, and will be iron rich and organic rich particularly in low flow periods. This water disappears down a swallow hole at the boundary of the shales and limestone and makes its way rapidly along well-developed, shallow, wide conduits through the limestone to the spring. The borehole is merely intercepting some of this water en route from the swallow hole to the spring. The soil cover on the limestone is very thin or absent. The urine and faecal matter from the cattle or sheep grazing on the limestone is easily and rapidly washed down into the karst limestone cavities and conduits. Similarly, effluent from poor quality septic tanks for single houses or small villages is flushed down into the system. A borehole drawing upon both shallow and deep conduits in such a position will require Level 5 treatment, as if it was providing water from a river or lake.

Even though, on the face of it, a borehole like this should be abandoned as too expensive and difficult to treat, it is still possible to remediate such a source. The site does not need to be abandoned. If borehole diameters allow, it may be possible to retrofit a proper pump chamber casing with cement grout to exclude the upper shallow conduits, and leave open flow from the deep conduits. If retrofitting is impossible, it is still possible to drill a properly designed and constructed borehole to selectively draw upon the water from deep conduits that are often separated from the shallower conduits. A new properly constructed borehole or wellfield of boreholes would cost a fraction of the capital costs of a Level 5 treatment system, without even considering the long-term costs of operating a Level 5 treatment system.

4. DECISION TREE

An evidence based decision tree has been constructed in order to clarify and summarise the process of classifying groundwater sources. It is shown in Figure 8. The process starts in the top left corner with the collection of all existing information on the source, followed by an assessment of this information with professional assistance if necessary. This is probably the most important step.

The next is a question “is there sufficient credible raw water microbiology data and data on pumping, turbidity and colour?”. The emphasis is on credible data. Credible data needs to be collected in an appropriate manner and come from a credible source. This is the start, but is usual in hydrogeology to look at one data set and cross-reference it with the interpretation of one or more additional data sets, and build up a conceptual model of the source how it is constructed and pumped. When data sets seem to support each other in telling the same story, then it is reasonable to begin to have confidence in the data. This is the reason why it is necessary at the outset to call upon experienced professional advice.
If it is decided that there is insufficient credible information, then it is necessary to carry out additional systematic sampling, monitoring or measurements. There is no point in making a decision that has potential consequences for people’s health or capital investment costs without adequate credible information.

The rest of the decision tree is self explanatory. It is a series of questions with yes or no answers. These are in purple boxes. The prime questions are on the left hand side. A “Yes” answer leads down the page to the next question. A "No" answer leads across the page to a supplementary question. The four lower supplementary questions are the same, and in summary are "Can the borehole be reconstructed to mitigate or overcome the issue?"

If the answer is "No" then a red line leads across the page to either an action in a blue box to remediate the problem, or directly to a yellow box giving a groundwater source classification.

Taking a simple example: if there is "No" evidence of microbial contamination, then the supplementary question is "Are there periodic turbidity spikes at the start of, or during, pumping cycles?". If the answer is "No" than the straight red line leads to a G1 source classification.
The blue action boxes are:

- change the pump position or its operating regime
- reconstruct the existing source in accordance with EPA advice Note 14
- Site, design, design, construct and test a new source in accordance with EPA Advice Note 14.

The decision tree in Figure 8 leads from identifying a water quality problem to finding a hydrogeological solution. In other words the decision tree shows that the classification of a borehole or other groundwater source is not fixed. Boreholes and other sources can be improved. Improving a source is a significantly less expensive option than the cost of multiple layers of treatment required for, say, G3, G4 and G5 boreholes. The other alternatives are to accept the treatment requirements for the existing source, or abandon the source.

The cost of abandoning a source is not just the loss of a water supply, but involves a redundant site owned by Irish Water, and the well head infrastructure and distribution infrastructure connecting the site to the consumers. Therefore, it is always worthwhile considering whether a new properly constructed source with lower treatment requirements can be constructed on the site. Some sites are small, but I have successfully drilled new high quality boreholes within 3 metres of an existing defective source, and then decommissioned the defective source. It is not easy but it is achievable.

The proposed classification system, based on water treatment requirements, is more than a passive classification; something to be put in a file or a report. Instead, it is a foundation for planning and development. Such a classification and way of assessing water supply boreholes, and other groundwater sources, could be a proactive step forward to improve the Irish Water's cost effective use and development of our groundwater resources in Ireland.

I would like to acknowledge the contributions from Malcolm Doak and Henning Moe, and also the valuable comments and suggestions from Michael O'Hora, Head of Water Services in Laois County Council, and from Conor Ryle in Water Services Laois County Council.

Figure 1

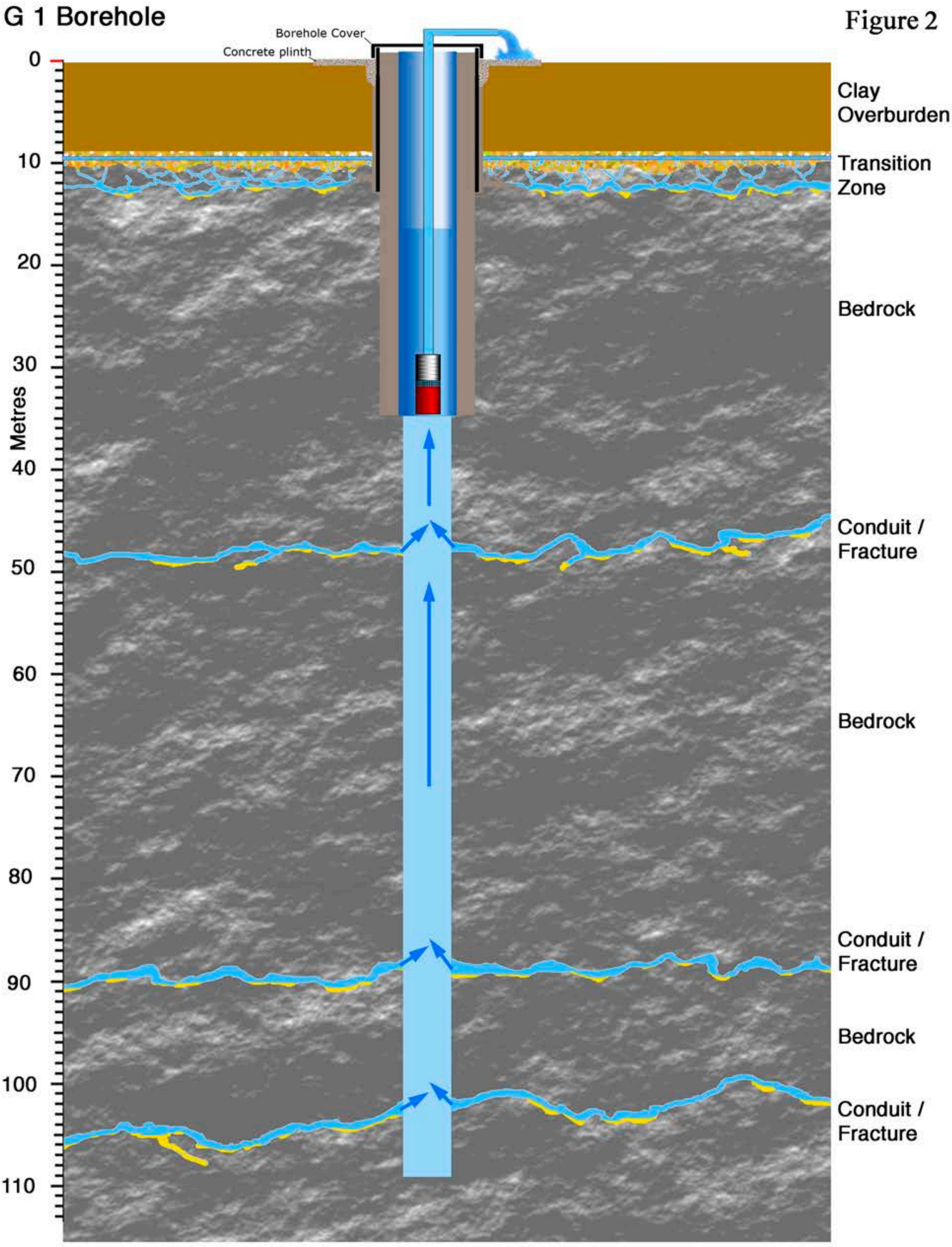
Description of Groundwater Sources

Type	Sited, designed and constructed in accordance with EPA Advice Note 14	* A Designed by:- B Specified by:- C Supervised by:- D Construction by:-	Adequate record of Design, Construction, geological log and pumping test results	Deep PVC or Steel pump chamber casing	Complete cement grout filled annulus around pump chamber casing	Correct Pump position	Pumped correctly	Credible Evidence of Microbial Contamination	Turbidity Issue	Colour and or high level of colloidal or dissolved organic compounds	Treatment Level Classification	Treatment Type (without any modification to the pump position, pump operating regime, or borehole construction)	Possible modifications or remedial actions to the borehole that should be considered in order to improve the Source Classification and hence reduce the treatment (number of treatment barriers) required
		1. Hydrogeologist or Groundwater Engineer 2. Civil Engineer 3. Driller 4. Civils Contractor											
Bedrock or sand and gravel Borehole	Yes	A, B, C = 1; D = 3	Yes	Yes	Yes	Yes	Yes	None	None	None	1	Chlorination to protect water quality in the distribution system	Irish Water Standard Construction and pumping arrangements
Sand and Gravel Spring or dug well	No	Probably none but sometimes A,B,C,D=1,2 or 4	Probably none	Not applicable	Not applicable	Not applicable	Yes	None	None	None	1	Chlorination to protect water quality in the distribution system	G1 because of catchment area and filtration by the aquifer material
Bedrock or sand and gravel Borehole	No	B = 1 or 2; A&D = 3	Yes	Yes	No	Yes	Yes	None	None	None	1	Chlorination to protect water quality in the distribution system	G1 status achieved by good fortune rather than by design and construction
Bedrock Borehole	No	B = 1 or 2; A&D = 3	May be available but may not be adequate or accurate	Yes	No	Yes	Yes	Yes	None	None	2	UV treatment to remove Cryptosporidium risk and Chlorination to protect water quality in the distribution system	May be possible to upgrade the Source classification to G1 by modifying the grout seal around the pump chamber casing
Bedrock Borehole	No	A&D = 3	May be available but may not be adequate or accurate	No	No	Yes	Yes	Yes	None	None	2	UV treatment to remove Cryptosporidium risk and Chlorination to protect water quality in the distribution system	May be possible to up grade the Source classification by modifying the pump chamber casing and grout seal
Bedrock Borehole	No	B = 1 or 2; A&D = 3	May be available but may not be adequate or accurate	No	No	No	No	Yes	Yes	None	3	Filtration (sand bed or pressure tank), then UV treatment to remove Cryptosporidium risk and finally Chlorination to protect water quality in the distribution system	May be possible to up grade the Source classification by modifying the position of the pump and changing the pumping regime and by modifying the pump chamber casing and grout seal
Bedrock Borehole, bedrock dug well or bedrock aquifer spring	No	A&D = 3 or 4	May not be available or may not be adequate or accurate	No	No	No	No	Yes	Yes	None	3	Filtration (sand bed or pressure tank), then UV treatment to remove Cryptosporidium risk and finally Chlorination to protect water quality in the distribution system	May be possible to up grade the Source classification by modifying the position of the pump and changing the pumping regime and by modifying the pump chamber casing and grout seal
Bedrock Borehole	No	B = 1 or 2; A&D = 3	May be available but may not be adequate or accurate	No	No	No	No	Yes	Yes	Yes	4	Ozone treatment to remove colour or organics, then Filtration (sand bed or pressure tank), then UV treatment to remove Cryptosporidium risk and finally Chlorination to protect water quality in the distribution system	May be possible to up grade the Source classification by modifying the position of the pump and changing the pumping regime and by modifying the pump chamber casing and grout seal
Bedrock Borehole, dug well or spring	No	A&D = 3 or 4	May not be available or may not be adequate or accurate	No	No	No	No	Yes	Yes	Yes	4	Ozone treatment to remove colour or organics, then Filtration (sand bed or pressure tank), then UV treatment to remove Cryptosporidium risk and finally Chlorination to protect water quality in the distribution system	May be possible to up grade the Source classification by modifying the position of the pump and changing the pumping regime and by modifying the pump chamber casing and grout seal
Bedrock borehole, dug well or spring drawing water from a bedrock catchment with minimal protective overburden cover and a shallow rapid flow groundwater system	No	B = 1 or 2; A&D = 3	May be available but may not be adequate or accurate	No	No	No	No	Yes	Yes Severe periodic or persistant sediment content	Yes	5	Coagulation and flocculation, Ozone treatment to remove colour or organics, then Filtration (sand bed or pressure tank), then UV treatment to remove Cryptosporidium risk and finally Chlorination to protect water quality in the distribution system	The main problem with these sources is the unprotected catchment area and rapid flow through the shallow groundwater system. However, it may be possible to re-drill the boreholes to draw upon a deep groundwater flow system and seal off the shallow system or drill new deep boreholes up gradient of existing springs or dug well chambers. Therefore, an existing site with a G5 source does not need to be written off or require a 5 level treatment barrier.
Bedrock borehole, dug well or spring drawing water from a bedrock catchment with minimal protective overburden cover and a shallow rapid flow groundwater system	No	A&D = 3 or 4	May not be available or may not be adequate or accurate	No	No	No	No	Yes	Yes Severe periodic or persistant sediment content	Yes	5	Coagulation and flocculation, Ozone treatment to remove colour or organics, then Filtration (sand bed or pressure tank), then UV treatment to remove Cryptosporidium risk and finally Chlorination to protect water quality in the distribution system	The main problem with these sources is the unprotected catchment area and rapid flow through the shallow groundwater system. However, it may be possible to re-drill the boreholes to draw upon a deep groundwater flow system and seal off the shallow system or drill new deep boreholes up gradient of existing springs or dug well chambers. Therefore, an existing site with a G5 source does not need to be written off or require a 5 level treatment barrier.

*Note: The (a) and (b) sub divisions of the G1, G2, G3, G4, and G5 classification are based on whether a source was designed or specified by a hydrogeologist/engineer or by a contractor, and therefore, whether it is likely that there is some record of a design or construction of the source that can be used to plan improvements or modifications to the source.

Factor that could be changed or reconstructed to improve the Groundwater Source Classification and hence reduce the Treatment Level

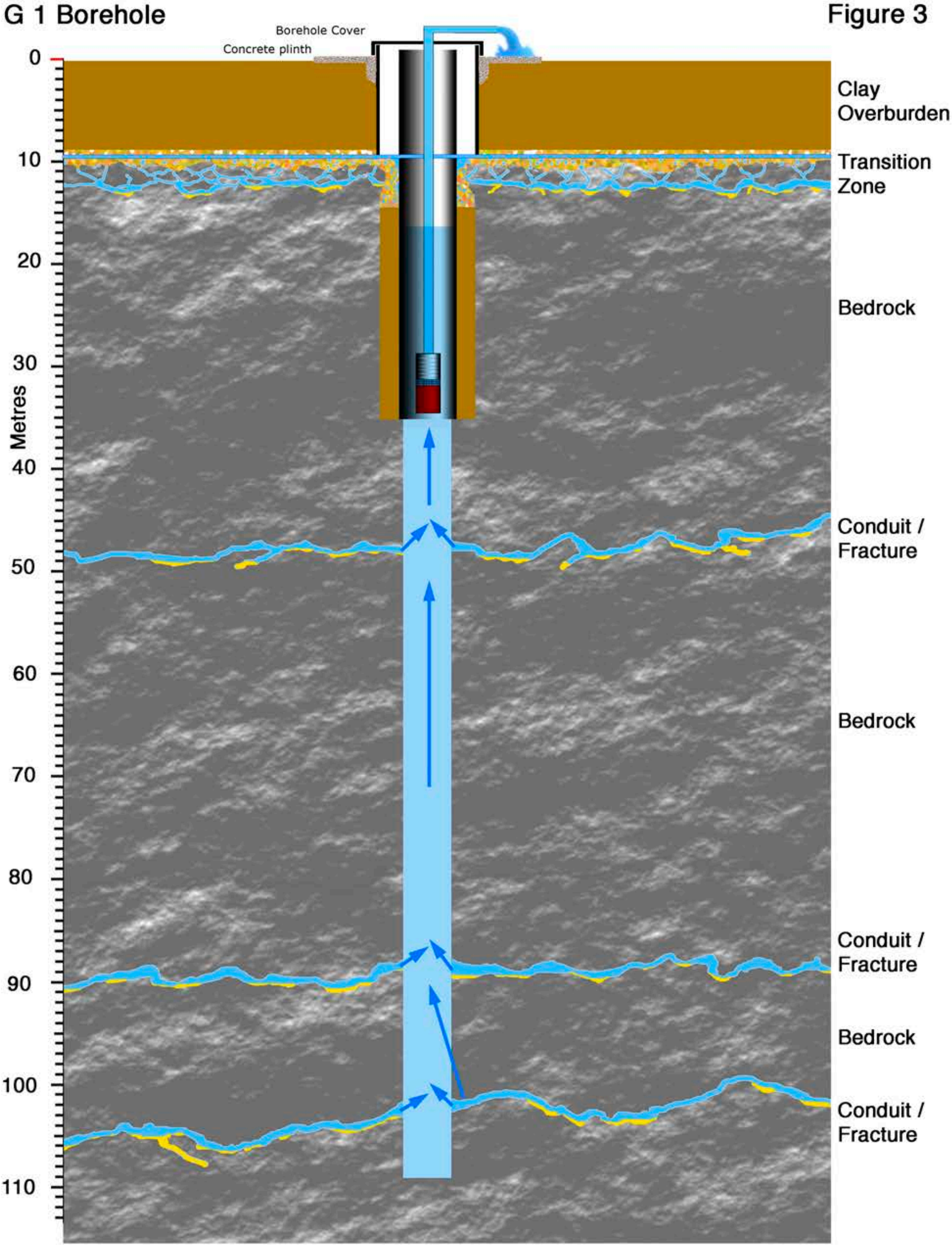
Figure 2



Borehole

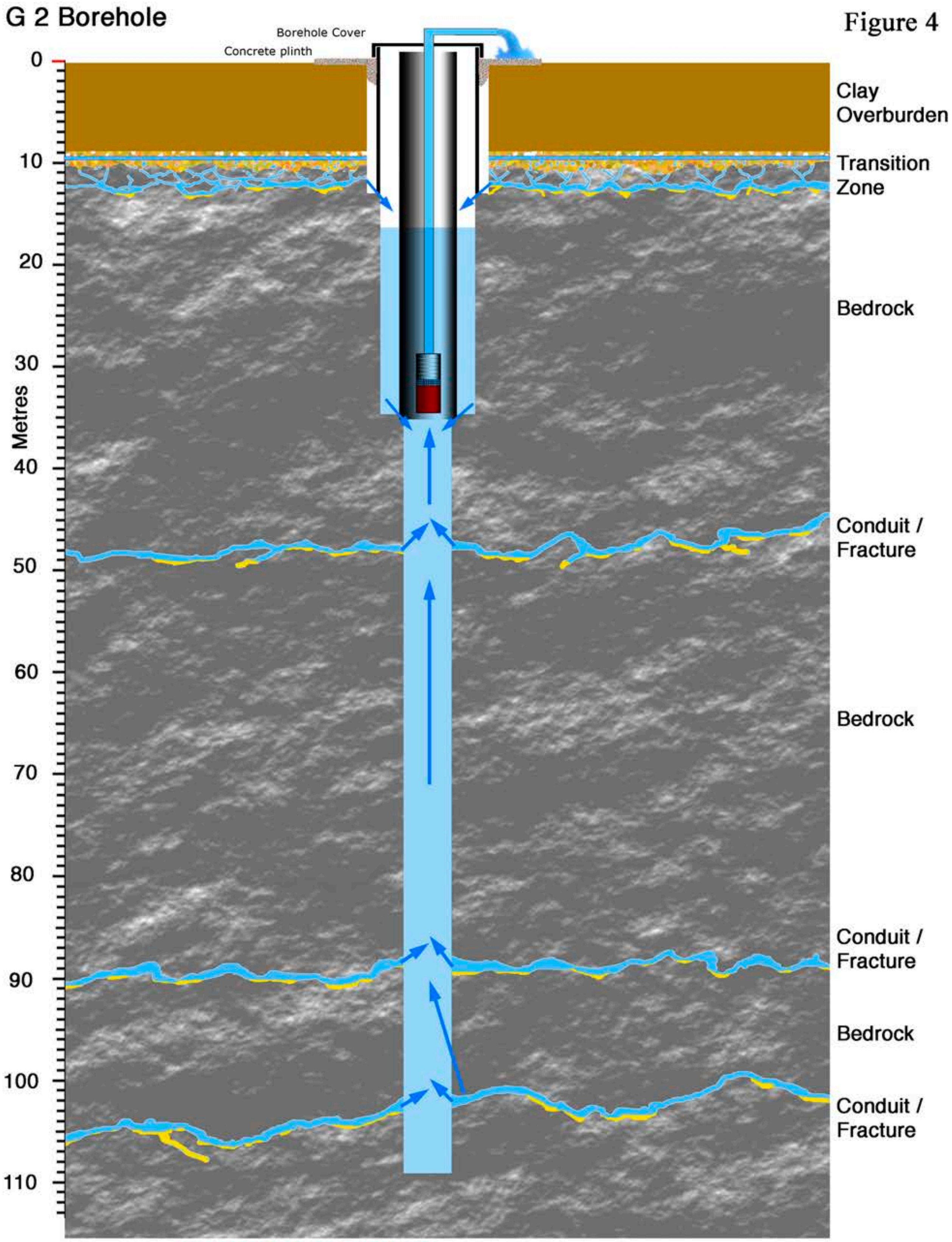
- Designed, supervised and directed by a hydrogeologist or groundwater engineer in accordance with EPA Advice Note 14 2013.
- PVC Pump chamber casing with a complete cement grout seal
- Pump in correct position inside pump chamber casing
- Water flows in and up from the deep groundwater system
- Shallow groundwater excluded by pump chamber casing and grout
- Pump operated continuously or for long pumping cycles
- Pump motor cooled by groundwater flowing up to the pump intake

G 1 Borehole Figure 3



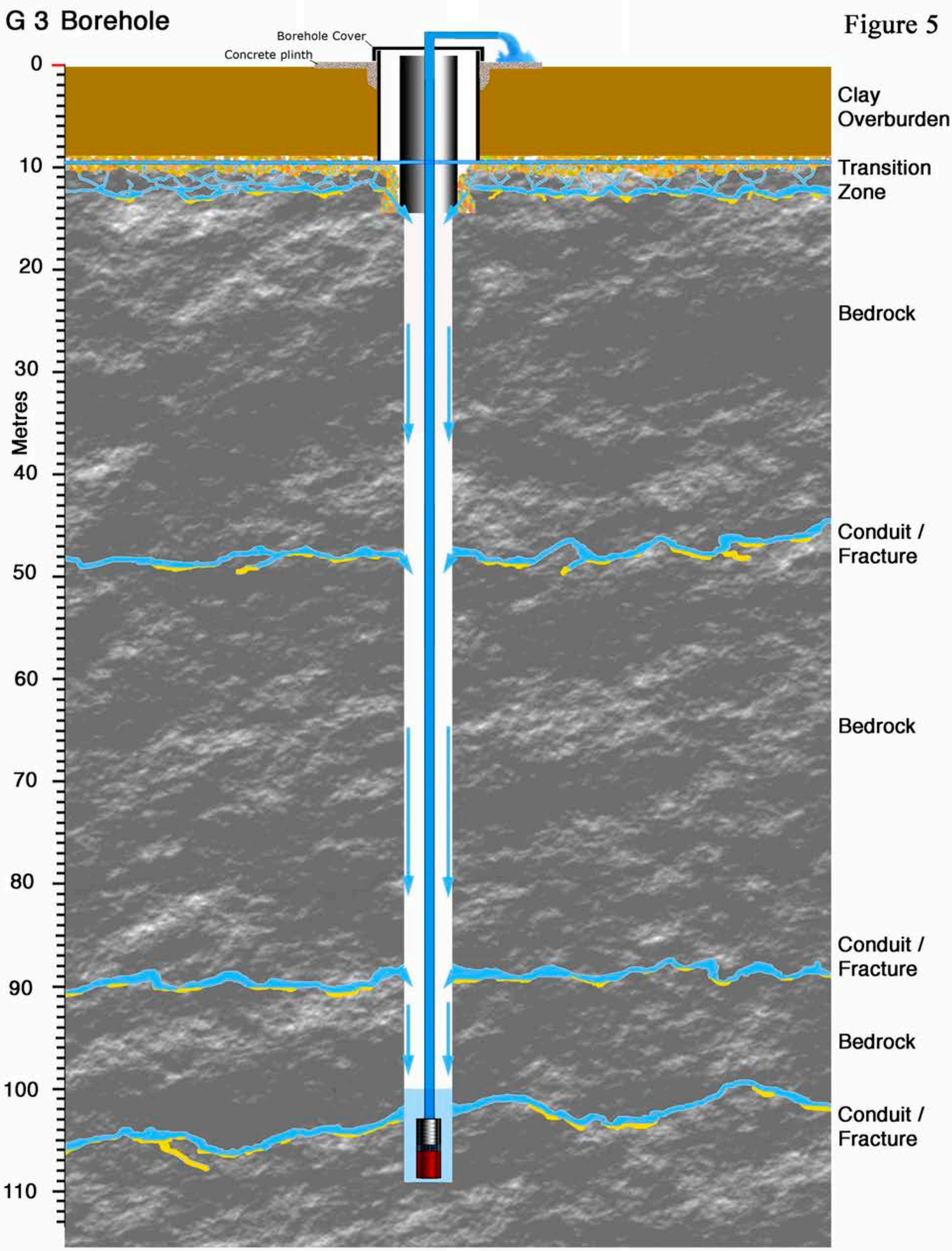
G 1 Borehole
Specified by an engineer probably before 2013 and designed by a driller
Steel Pump chamber casing with no cement grout seal around around either steel casing, but clay has slumped around the pump chamber casing.
Pump in correct position inside pump chamber casing
Water flows in and up from the deep groundwater system
Shallow groundwater fortunately excluded by the slumped clay seal
Pump operated continuously or for long pumping cycles
Pump motor cooled by groundwater flowing up to the pump intake

Figure 4



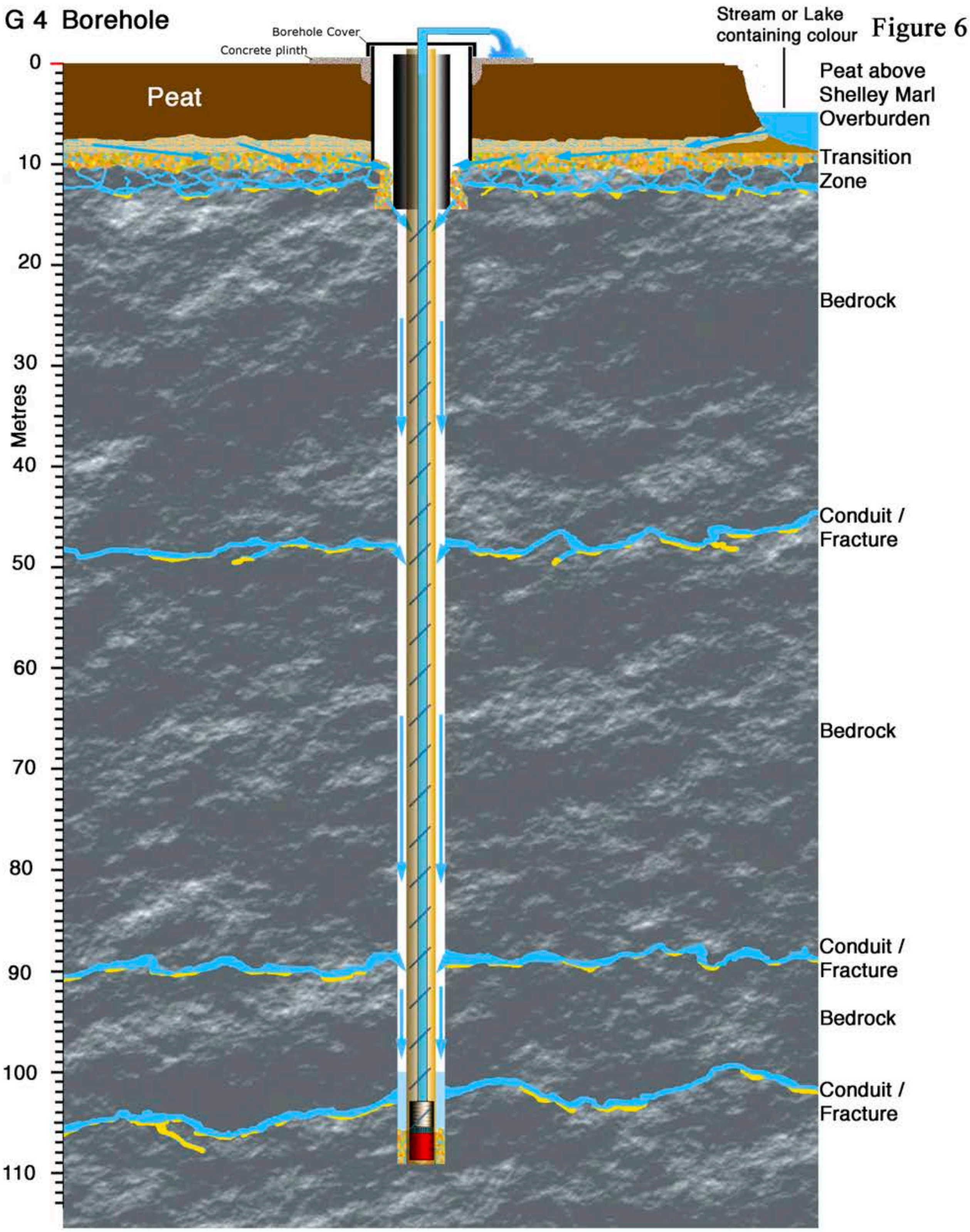
Borehole Microbiology problem

- Designed, supervised and directed by a hydrogeologist or groundwater engineer probably before 2013
- Steel Pump chamber casing but no cement grout seal around any casing
- Pump in correct position inside the pump chamber casing
- Water flows in and up from the deep groundwater system but
- Shallow groundwater flows into the hole under the steel casings
- Pump operated continuously or for long pumping cycles
- Pump motor cooled by groundwater flowing up to the pump intake



Borehole Microbiology problem and Turbidity spikes

- Specified by an engineer or hydrogeologist (perhaps pre-2007) and designed on site by the driller without supervision or direction by a hydrogeologist
- No pump chamber casing and No cement grout
- Therefore water flows in from both shallow and deep levels
- Pump at the bottom of the borehole. • Pump motor sitting in sand and clay
- Pumped intermittently at a rate exceeding the sustainable yield
- Rapid drawdown during pumping to a deep level just above the pump
- Sand and clay pulled in from conduits everytime the pump turns on
- Turbidity spike at start of each pump cycle, or a chronic turbidity issue

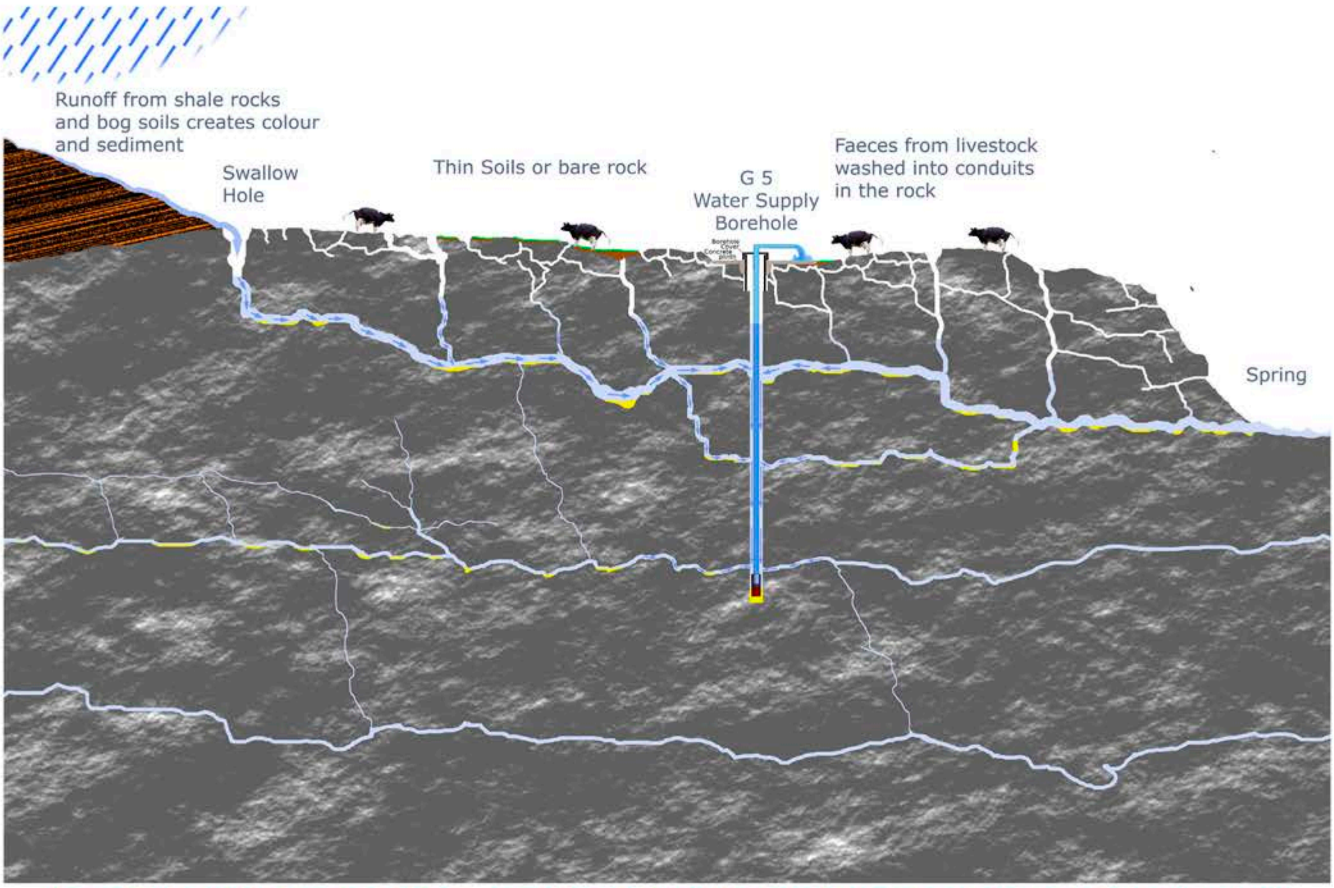


Borehole Microbiology problem, Turbidity spikes and Colour

- Designed by a driller without supervision or direction by a hydrogeologist
- No pump chamber casing and No cement grout
- Therefore water flows in from both shallow and deep levels
- Lined with cheap plastic ducting with occasional saw-cut slots
- Pump at the bottom of the borehole. • Pump motor sitting in sand and clay
- Pumped intermittently at a rate exceeding the sustainable yield
- Rapid drawdown during pumping to a deep level just above the pump
- Sand and clay pulled in from conduits everytime the pump turns on
- Turbidity spike at start of each pump cycle, or a chronic turbidity issue and
- Coloured water coming in from either peat catchment or adjacent surface water

G5 Borehole

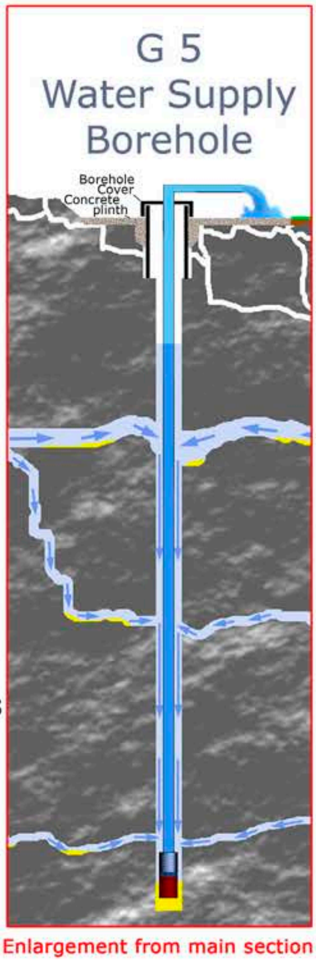
Figure 7



Severe Microbiology problem, continual turbidity problem and organic colour issues

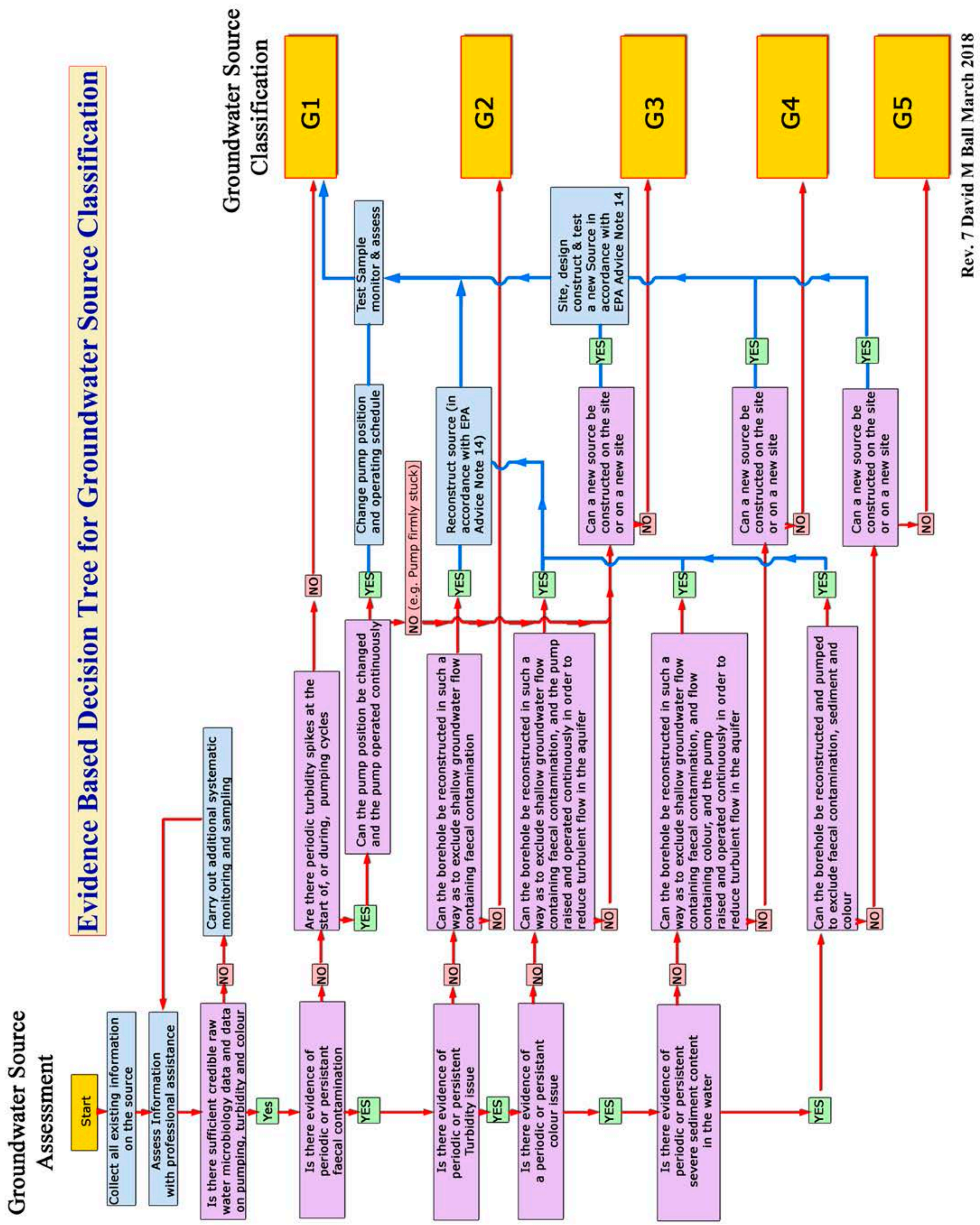
Borehole

- The problems with this borehole are a combination of site and catchment, as well as design, construction and pump position
- Location chosen probably by a 'water diviner' or someone without an understanding of the catchment vulnerability.
- Groundwater catchment has little soil cover, and is fed by rapid recharge through caves and shafts in the limestone, and sinking streams or rivers flowing off peaty hillsides.
- In effect the groundwater flow system has all the negative characteristics of a surface water system
- Designed and constructed by a driller, without supervision or direction by a hydrogeologist or groundwater engineer.
- There is no pump chamber casing
- There is no grout seal
- There is no attempt to seal off the shallow 'underground river' containing bacteria, sediment and water coloured with organic compounds.
- The pump is at the bottom of the borehole and the pump motor is sitting in sand and clay.
- The motor is likely to overheat.
- The pump is operated intermittently at a high rate which causes water to flow rapidly into the borehole from the caves, bringing sand with it.
- The pumped water is continually turbid and coloured
- The pumped water has spikes of very high microbiological content shortly after each rainfall event.
- Trying to operate a water treatment plant under these circumstances is very difficult.



Enlargement from main section

Figure 8


Evidence Based Decision Tree for Groundwater Source Classification
Groundwater Source Assessment
Groundwater Source Classification
Start
Collect all existing information on the source
Assess Information with professional assistance
Is there sufficient credible raw water microbiology data and data on pumping, turbidity and colour
Yes
NO
Carry out additional systematic monitoring and sampling
Is there evidence of periodic or persistant faecal contamination
YES
NO
Are there periodic turbidity spikes at the start of, or during, pumping cycles
YES
NO
Can the pump position be changed and the pump operated continuously
YES
NO (e.g. Pump firmly stuck)
Change pump position and operating schedule
Test Sample monitor & assess
Is there evidence of periodic or persistent Turbidity issue
YES
NO
Can the borehole be reconstructed in such a way as to exclude shallow groundwater flow containing faecal contamination
YES
NO
Reconstruct source (in accordance with EPA Advice Note 14)
Is there evidence of a periodic or persistant colour issue
YES
NO
Can the borehole be reconstructed in such a way as to exclude shallow groundwater flow containing faecal contamination, and the pump raised and operated continuously in order to reduce turbulent flow in the aquifer
YES
NO
Can a new source be constructed on the site or on a new site
YES
NO
Site, design construct & test a new Source in accordance with EPA Advice Note 14
Is there evidence of periodic or persistent severe sediment content in the water
YES
NO
Can the borehole be reconstructed in such a way as to exclude shallow groundwater flow containing faecal contamination, and flow containing colour, and the pump raised and operated continuously in order to reduce turbulent flow in the aquifer
YES
NO
Can a new source be constructed on the site or on a new site
YES
NO
Can the borehole be reconstructed and pumped to exclude faecal contamination, sediment and colour
YES
NO
Can a new source be constructed on the site or on a new site
YES
NO
G1
G2
G3
G4
G5
Rev. 7 David M Ball March 2018

SITE VISIT

THE TULLAMORE WELLFIELD (NORTH) ARDAN WELLFIELD
FIELD GUIDE & NOTES TO A GROUNDWATER COMMUNITY OF PRACTICE

Malcolm Doak PGeo, SiLC, EurGeol. Hydrogeologist, Asset Planning.

IRISH WATER
Colvill House, 24-26 Talbot Street
Dublin 1

1. INTRODUCTION

AECOM Limited and Jennings O'Donovan & Partners Limited were jointly commissioned by Irish Water (William McKnight) to provide technical support in respect of the enhancement of the Tullamore Water Supply scheme in County Offaly.

CCTV, geophysical logging and pump testing occurred at the two wellfields, at Ardan, the subject site (currently two boreholes at 3MLD) and at Clonaslee (six boreholes at 1.7MLD) south of Tullamore, to assess the potential for increasing the volume of available water to feed the Tullamore area water supply.

Following assessments of the reports and engagement with Hydrogeologists in both IW and AECOM it was established further exploration work would occur at Ardan, to determine sustainable yield from this one wellfield and its limestone (gravels overlying) aquifer. In three to five years time a decision will be made on the Clonaslee wellfield and sandstone aquifer (Devonian thick flaggy sandstone, thin siltstone).

The Fieldtrip is focussing on the two Ardan Boreholes, the trial well drilled in 2017, and plans for a new Production Well to be drilled in May 2018. The discussion will also review on-site the ongoing G1 to G5 borehole classification scheme being proposed to the community of practice, of which an early draft is discussed at the conference proper by the eminent Hydrogeologist, Mr David Ball. The geophysical and CCTV records for the two Ardan Boreholes in the Appendix, will serve as material for consideration while on-site. The forty or so participants will need to wear PPE and sign a register before entry onto site. More details will be advised at the conference regarding Irish Water access instructions.

Figure 1. IW Intranet Q2 2017. Groundwater emerging from a spring, stakeholder interaction…

Figure 2. Location of the wellfield

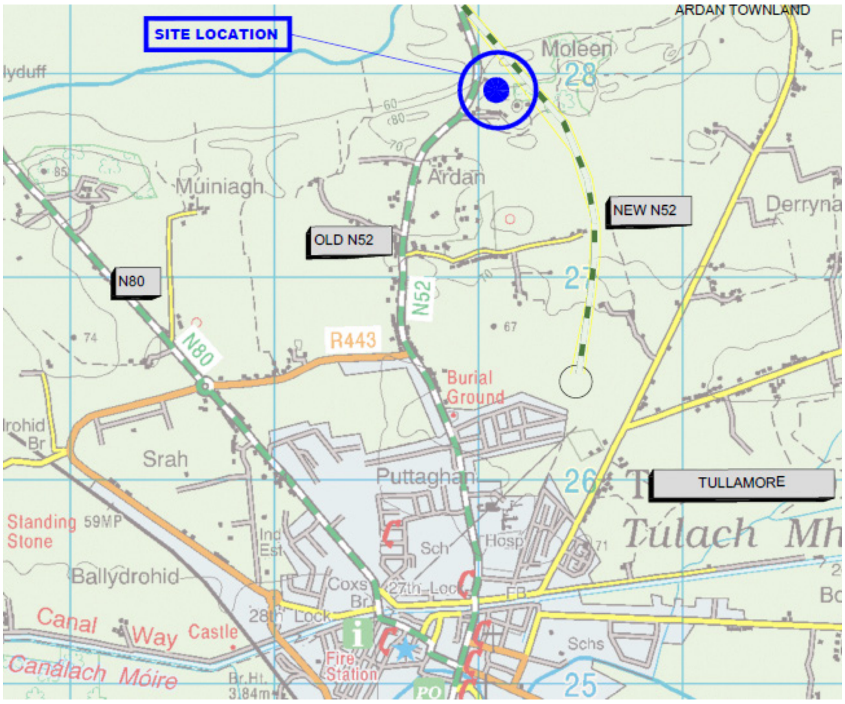


Figure 3. Wellfield (Green) and Proposed Extension (Blue)

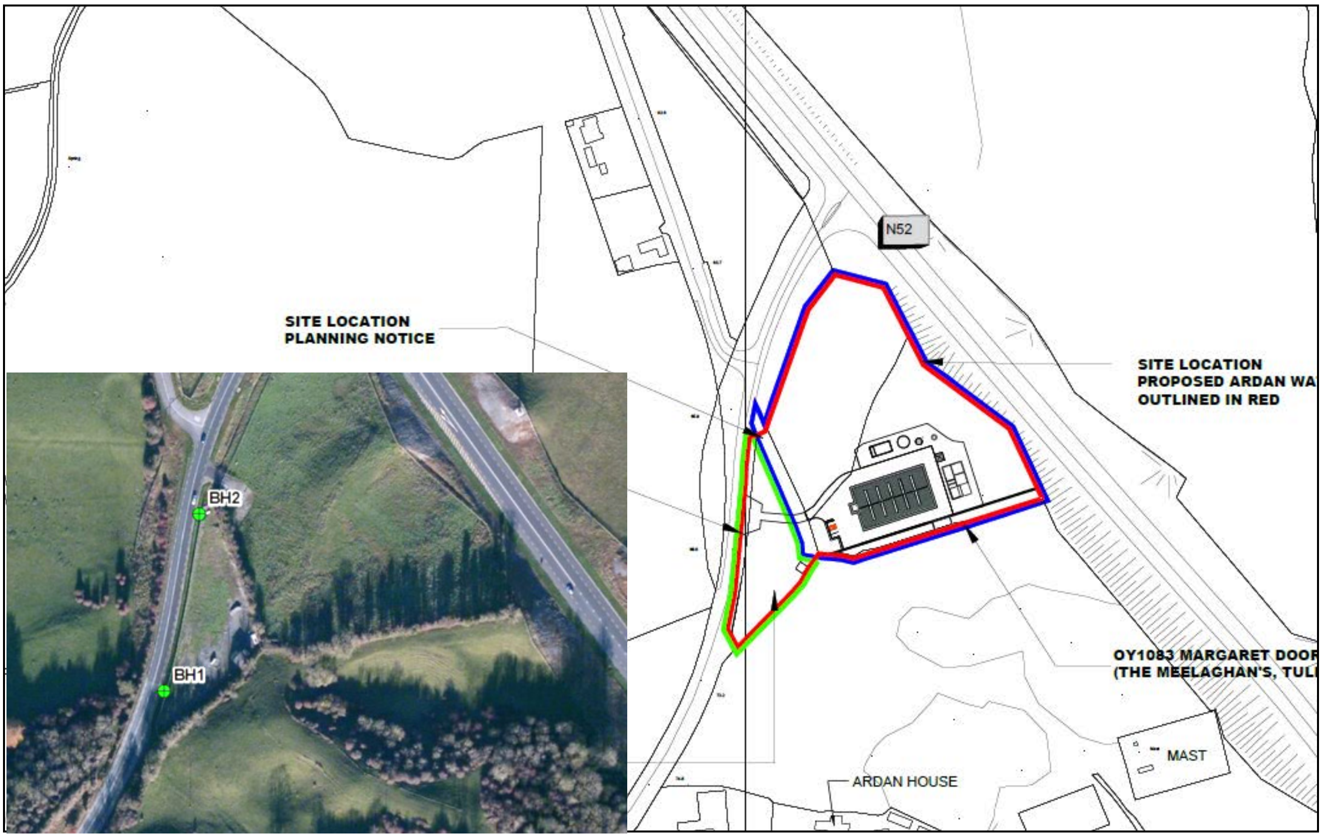
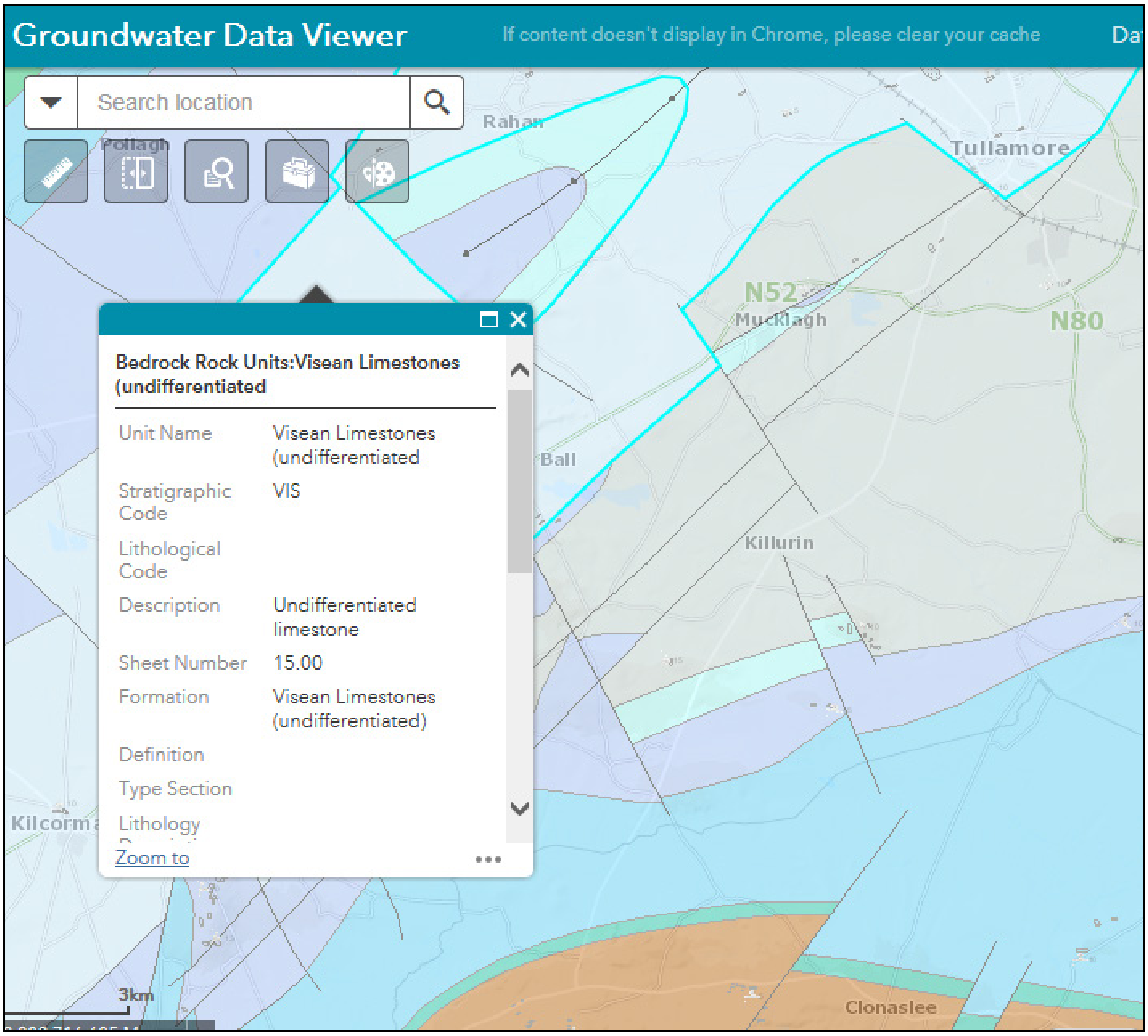


Figure 4. Two wellfields for Tullamore. Clonaslee in the Devonian south, and at Ardan at Tullamore north in the Visean Limestones.



In February 2017, Meehan Drilling were appointed by Irish Water to undertake the investigation works at Ardan.

2. PRELIMINARY REPORT AT ARDAN WELLFIELD 2017

Ardan Borehole BH1

The works at the Ardan BH1 site were conducted between the 4th and 6th of April 2017. Details of Ardan BH1 were recorded by Meehan Ltd. Ardan BH2, located approximately 50m away, was pumping during the course of the three day period.

Ardan Borehole BH2

The works at the Ardan BH2 site were conducted between the 10th and 12th of April 2017. Ardan BH1 was pumping during the course of the three day period.

An overall summary of the findings is presented in the Table below:

Borehole	Depth (m)	Diameter (mm)	RWL (mbs)	Pump depth (mbs)	Pump type
Ardan Well Field					
Ardan BH1	103.6	320	11.7	55.4	8" diameter Grundfos pump with 6" Franklin motor. 4" diameter rising main.
Ardan BH2	32.3+	207 (0 – 21.76m) 154 (21.76 to base)	8.11	19.6	Grundfos SP30-8 with Grundfos 7.5kW motor. 3" rising main.
Ardan BH3	46.3	204	13.9	No pump installed. Borehole not in supply.	

	Yield (m^3/hour)	PWL (mbs)	Comments
Ardan BH1	59.2	14	Open hole from 24.2m. Abundant fracturing. Main inflow from below 74m.
Ardan BH2	32.9	10.7	Borehole depth uncertain. Not possible to survey below 32.3m due to zero visibility - possible blockage or collapse.
Ardan BH3	90	28.7	Test pump (April/May 2017)

3. CLASSIFYING OUR BOREHOLES TO TREATMENT

In New Zealand, the classification of a borehole water as secure is key to determining less treatment.

The concept of the NZ borehole categorisation is quite simple: the dirtier the water, the greater the amount of treatment needed. Secure bore water is considered to be free from microbiological (bacterial and protozoal) contamination.

NZ guidance introduces the terminology of barriers; between the source and the consumer's property, various elements of a water supply act as barriers to the entry of contaminants. Each barrier contributes to the safety of the supply, but it is generally recognised that the greatest protection to water quality and public health is achieved by ensuring that four fundamental barriers are in place. These four barriers must achieve the following:

1. prevention of contaminants entering the raw water of the supply
2. removal of particles from the water
3. inactivation of micro-organisms in the water
4. maintenance of the quality of the water during distribution

A secure bore water has met the first three barriers with respect to microbiological contamination. In the absence of dissolved chemicals of public health significance, prevention of contaminants entering the water after it is abstracted from the ground is then the only concern.

At Irish Water, for the IRC2 review in 2015, the 550 IW borehole assets were categorised using a NZ type approach by the water engineering team. Figure 5 outlines the five categories of groundwater abstraction (G1 to G5) which Irish Water used for the IRC2 review.

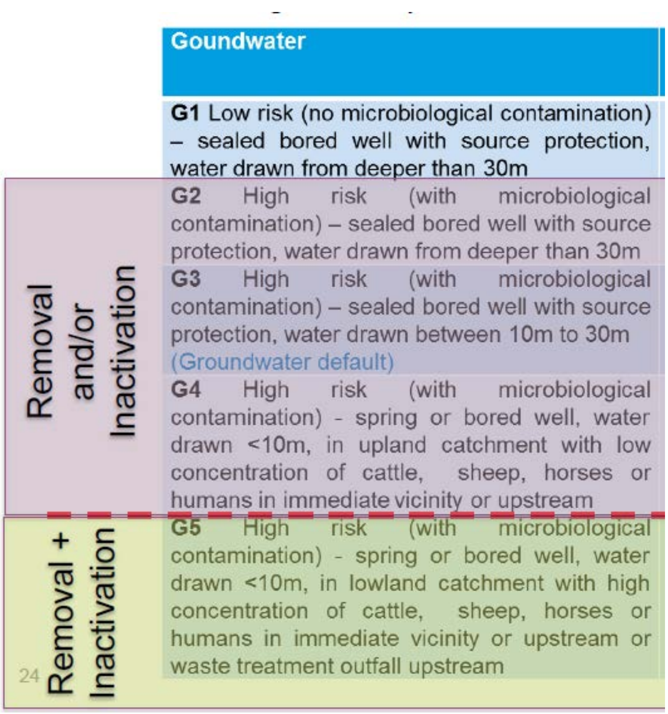


FIGURE 5. IRC2 Borehole Categories

A G1 type log credit 1 low risk borehole (a concrete sealed borehole and the depth to watertable at more than 30m, with a ZOC protection plan) permits IW to design singly for disinfection with chlorination. A G5 type log credit 5 high risk borehole/spring requires IW to design for four barriers of treatment, including alum/PAC coagulation with sedimentation/DAF plus rapid gravity sand filtration (3 log) plus UV and/or ozone to earn another 1 log.

The preliminary review is IW hold a large inventory of G3 (420) and G4 (77) boreholes. There are few, if any, boreholes in Ireland which have a G1 type finish/construction, apart from up to 20 G1 boreholes in Co. Laois.

4. DRILLING OUR BOREHOLES BETTER

The GSI and EPA, and the Institute of Geologists of Ireland (IGI), have developed more practical guidelines on water well drilling, which will help us improve the drilling of new production wells. The IGI guidelines assert steel casing and concrete annulus should be installed to at least 2 metres below the depth at which the pump will be set, and the pump intake should be in the un-slotted casing above the well screen section. Moreover, the IGI determine boreholes should also be pumped gently and for long periods. Frequent stopping and starting of a pump and, in particular, pumping at high rates above the long term sustainable pumping rate, causes rapid oscillations in the water level in the borehole and turbulent flow into the hole from the aquifer. This stress on the borehole, and turbulence in the aquifer supplying the borehole, can lead to suspended sediment in the water.

The EPA Note 14, has published their view of a secure borehole.

In current work with David Ball, it is considered to re-work the NZ approach we undertook for the IRC2 in 2015.

The EPA Note 14 borehole we consider can be called G1. Both borehole finishes are presented below for consideration:

Figure 6. EPA Note 14 Standard Borehole as a Production Well

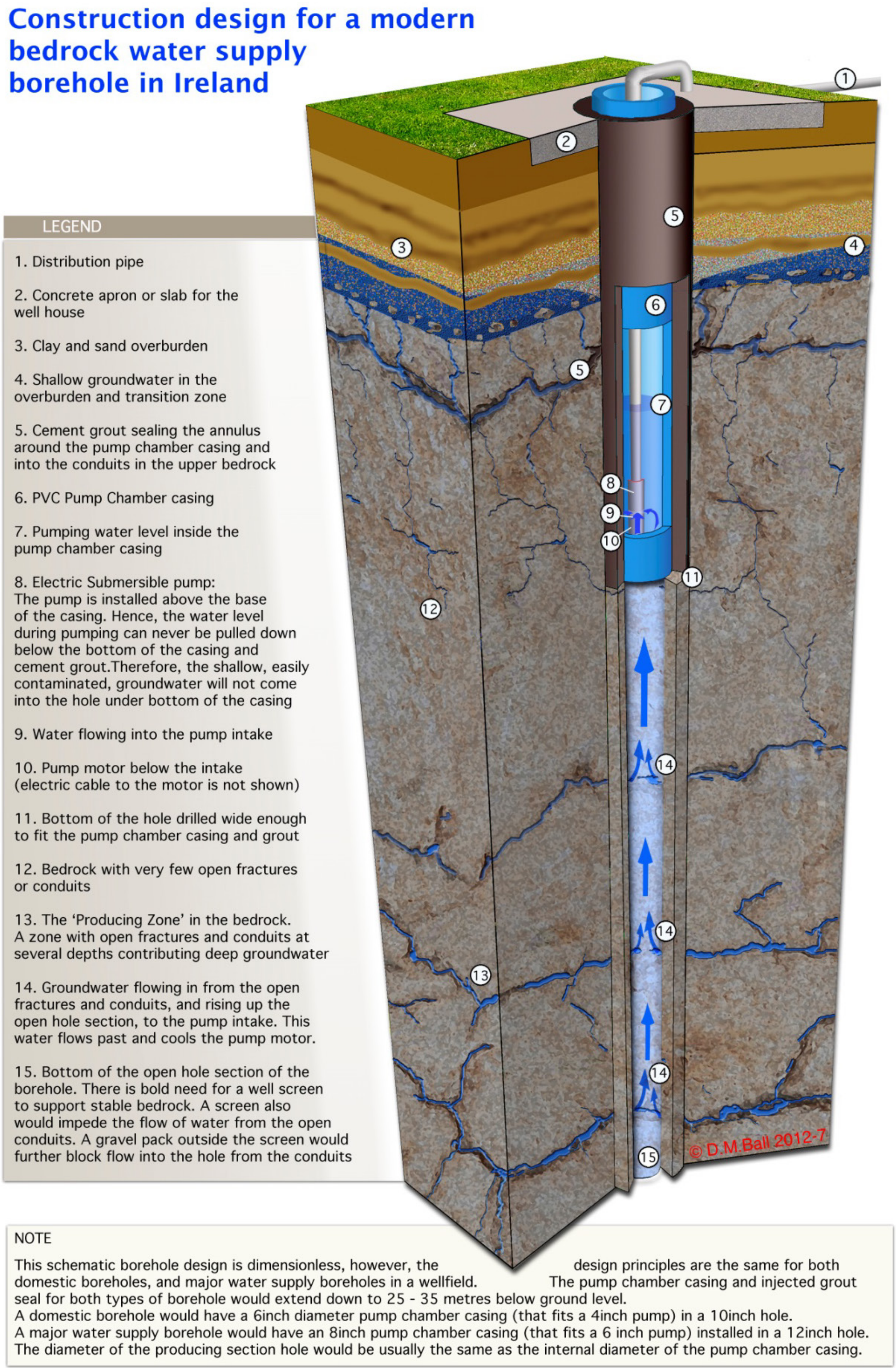
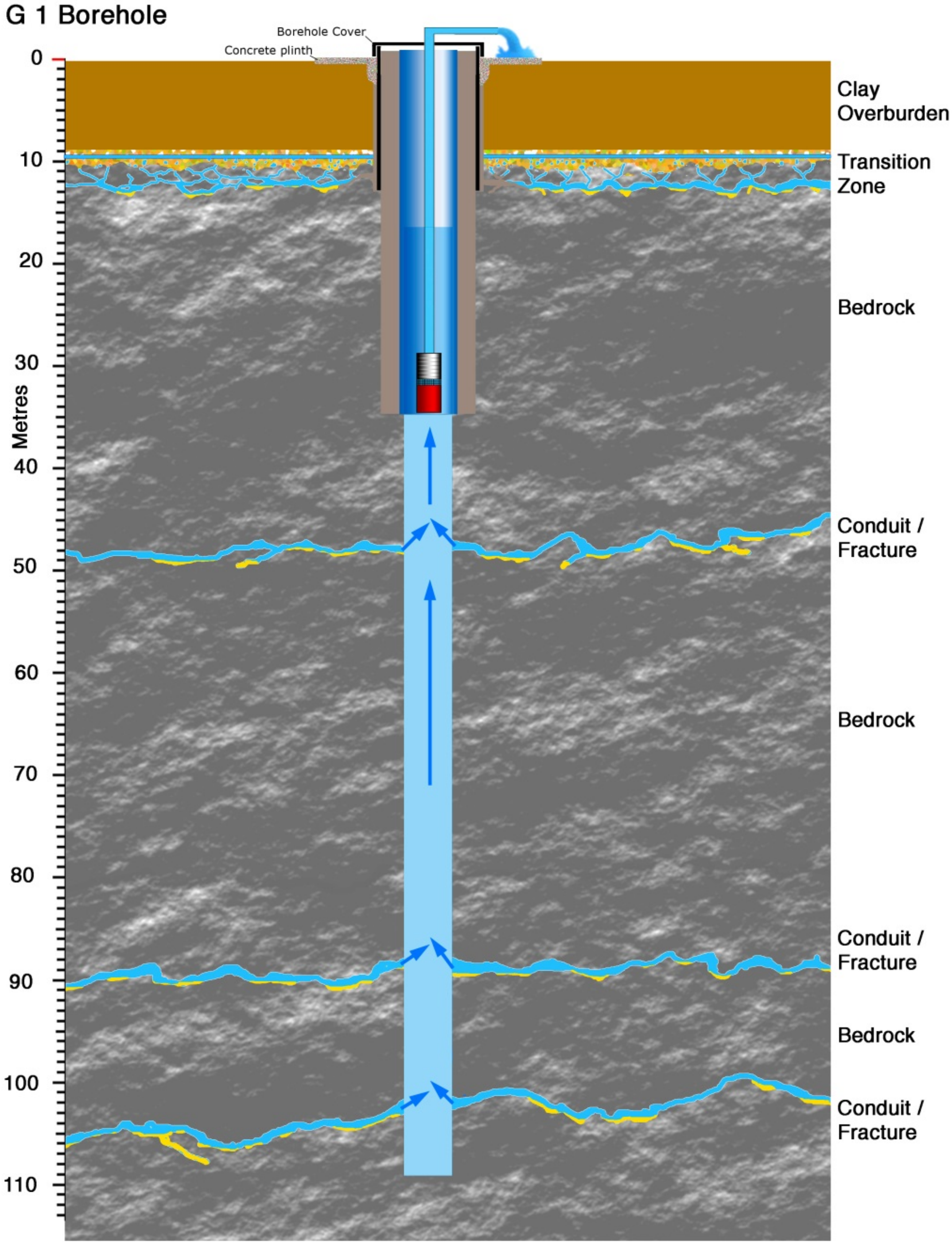


Figure 7. IW G1 type Borehole Construction, based on EPA Note 14 Standard Borehole



Borehole

- Designed, supervised and directed by a hydrogeologist or groundwater engineer in accordance with EPA Advice Note 14 2013.
- PVC Pump chamber casing with a complete cement grout seal
- Pump in correct position inside pump chamber casing
- Water flows in and up from the deep groundwater system
- Shallow groundwater excluded by pump chamber casing and grout
- Pump operated continuously or for long pumping cycles
- Pump motor cooled by groundwater flowing up to the pump intake

REFERENCES

AECOM (2017). *Clonaslee and Ardan Phase 2 Works - Borehole Inspections.* Darragh Reilly, Philip Smart (Hydrogeology). Victoria Square, Birmingham, B2 4AJ, England.

APPENDIX

EUROPEAN GEOPHYSICAL SERVICES

REPORT ON THE VIDEO SURVEY

AND

GEOPHYSICAL LOGGING

OF

BOREHOLE 1

At ARDEN,

Co. OFFALY, IRELAND

Prepared For:

MEEHAN DRILLING

Meehan Drilling Ltd
Collonbeg Farm
Collon
Co. Louth
Ireland

MAY 2017/MEEH1603_ArdenBH1_rpt/IRE

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5.0 RESULTS

PHOTOGRAPHS FROM THE CCTV SURVEY

Arden Borehole 1 **Date: 05th April 2017**

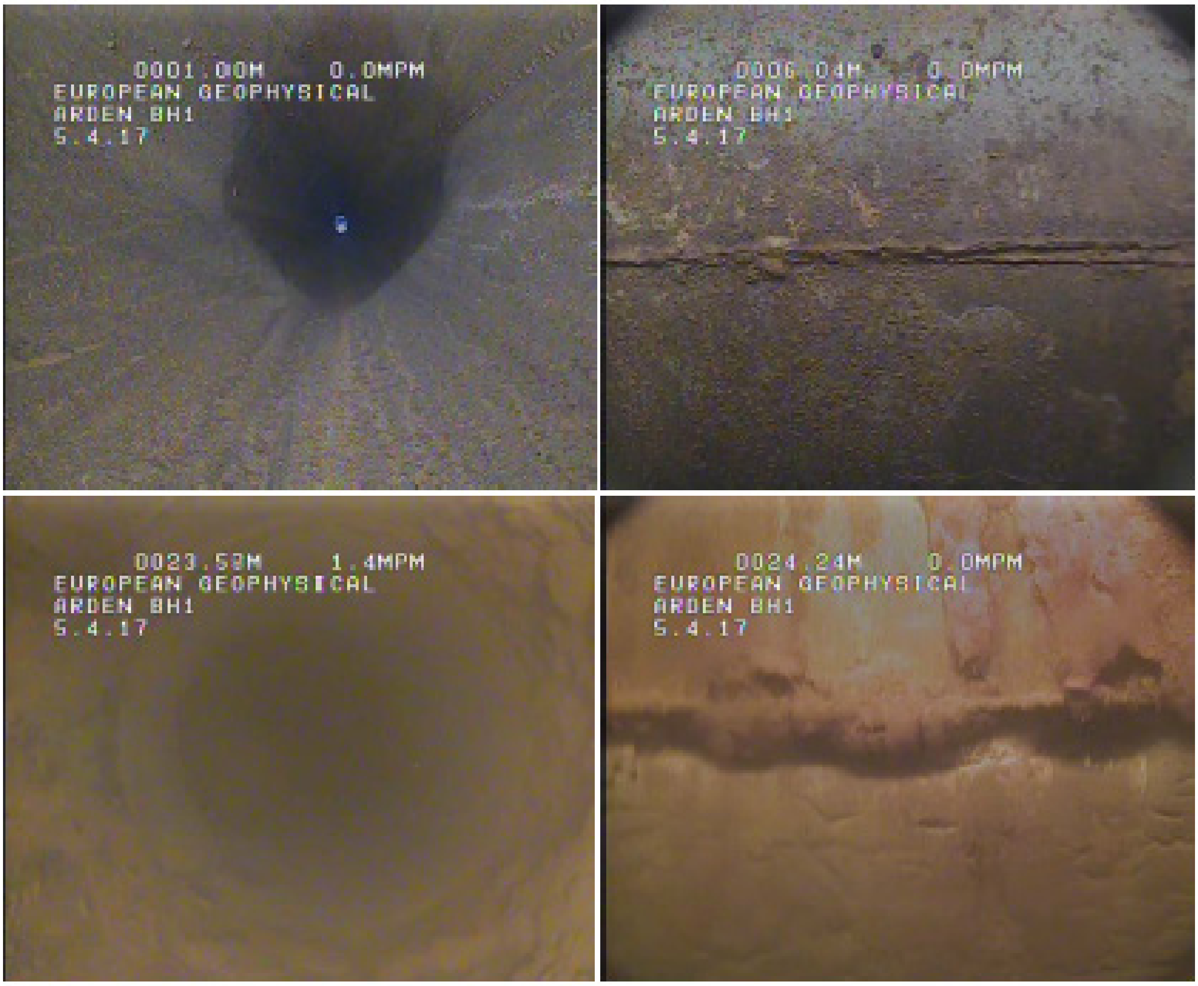

Figure 5.2

0.0m	Down-hole image showing overall condition of plain lining.
6.04m	Light corrosion associated with lining join.
23.58m	Base of lining visible below. Increased surface encrustation.
24.24m	Base of lining.

5.0 RESULTS

PHOTOGRAPHS FROM THE CCTV SURVEY

Arden Borehole 1 **Date: 05th April 2017**

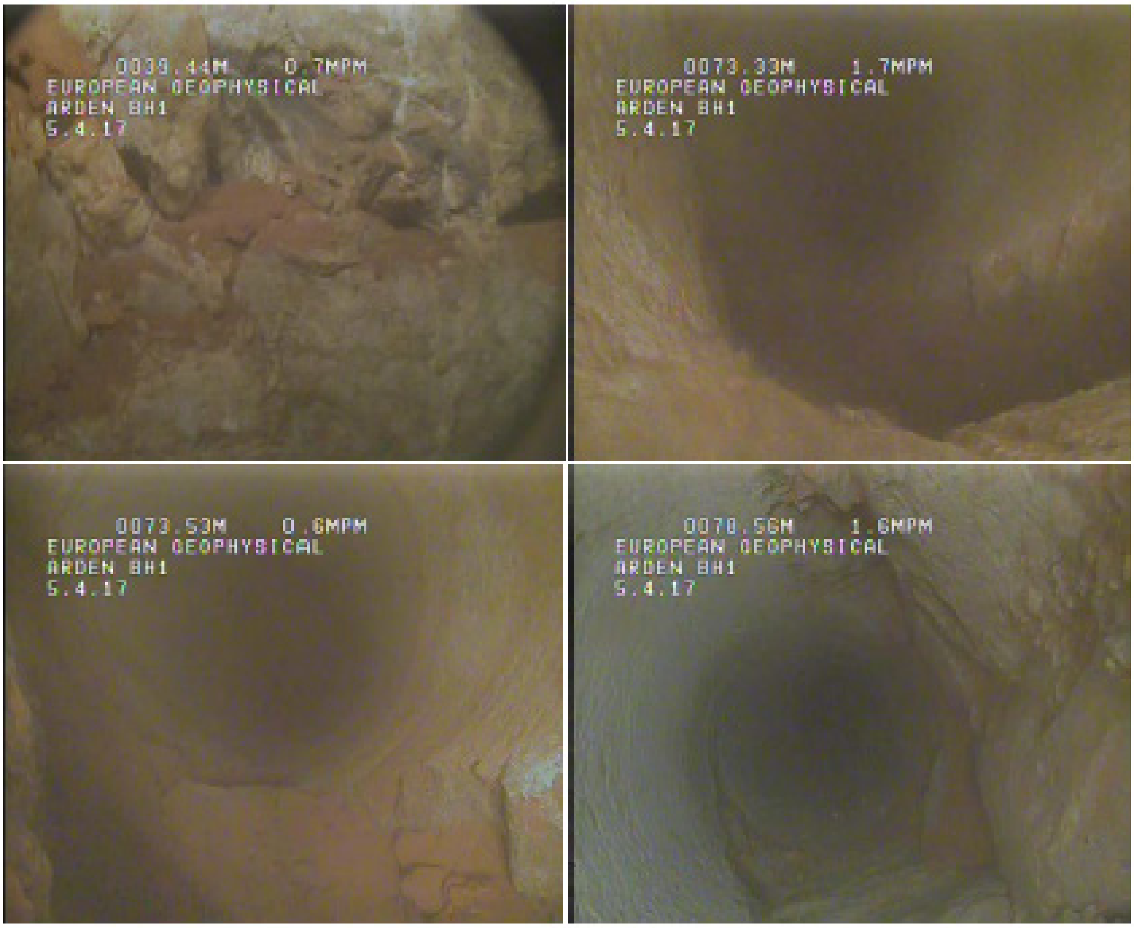

Figure 5.3

39.44m	Thin fracture with sediment accumulation.
73.33m	Large fissure below.
73.53m	Sediment accumulation on fissure base.
78.56m	Sub-vertical fissure. Increased fluid clarity.

5.0 RESULTS

PHOTOGRAPHS FROM THE CCTV SURVEY

Arden Borehole 1 **Date: 05th April 2017**

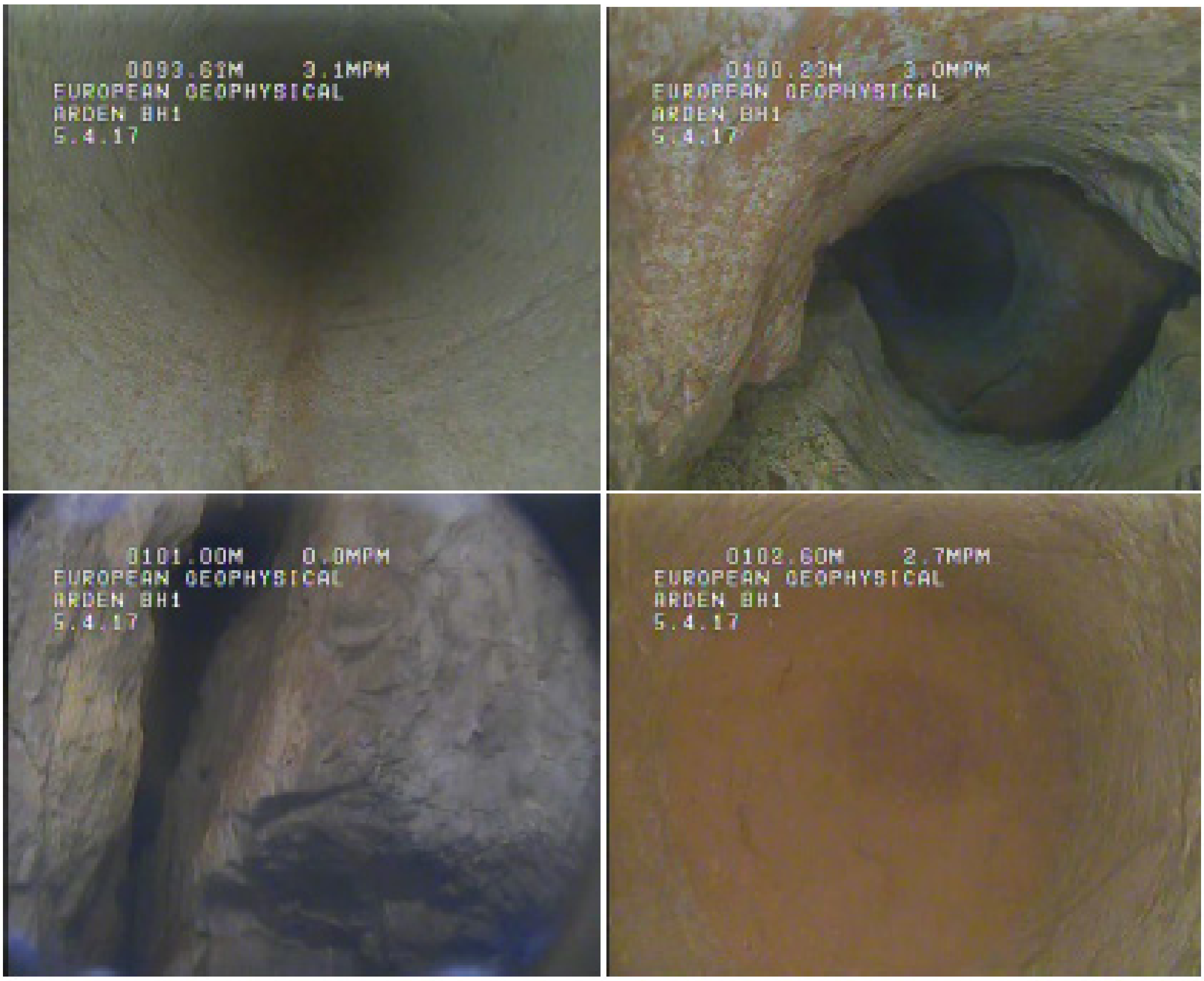

Figure 5.4

93.61m	Competent limestone formation.
100.23m	Large sub-vertical fissure.
101.0m	Large sub-vertical fissure.
102.60m	Base of borehole.

6.0 CONCLUSIONS

6.1 The final visible depth of the borehole was 103.20m.

6.2 The well was lined with 320mm i.d. plain steel lining between 0m – 24.2m.

6.3 The plain lining was in a reasonable visible condition with light surface corrosion, increasing below approximately 23.0m.

6.4 Joins within the lining appeared to be corroded but showed no signs of leaking or failure.

6.5 The unlined borehole was measured at approximately 315mm i.d throughout.

6.6 The unlined borehole consisted of massively bedded competent limestone and occasional marl bands.

6.7 Several fissures were present within the borehole, most notably at 72.6m, 73.7m and 100.6m.

6.8 Fine grained brown sediment was present in accumulations on protrusions throughout the unlined borehole.

6.9 The rest water level was 11.7m and was of initially poor clarity, improving below the fissure at 73.7m..

6.10 Vertical fluid movement was suspected between approximately 73.7m and 100.6m.

6.11 Fluid electrical conductivity decreased from 750µS/cm at the water level to 720µS/cm at 74m and below.

EUROPEAN GEOPHYSICAL SERVICES

REPORT ON THE VIDEO SURVEY

AND

GEOPHYSICAL LOGGING

OF

BOREHOLE 2

At ARDEN,

Co. OFFALY, IRELAND

Prepared For:

MEEHAN DRILLING

Meehan Drilling Ltd
Collonbeg Farm
Collon
Co. Louth
Ireland

MAY 2017/MEEH1603_ArdenBH2_rpt

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3.0 BOREHOLE DETAILS

Figure 3.3 Arden Borehole 2 with logging tripod setup over borehole.

Figure 3.4 View of top of Borehole 2 within above ground steel chamber.

5.0 RESULTS

PHOTOGRAPHS FROM THE CCTV SURVEY

Arden Borehole 2 **Date: 11th April 2017**

Figure 5.2

1.0m	Downhole view showing overall condition of plain lining.
3.58m	Join in plain lining.
8.08m	Water level. Light flaking on lining.
9.63m	Join in plain lining

5.0 RESULTS

PHOTOGRAPHS FROM THE CCTV SURVEY

Arden Borehole 2 **Date: 11th April 2017**

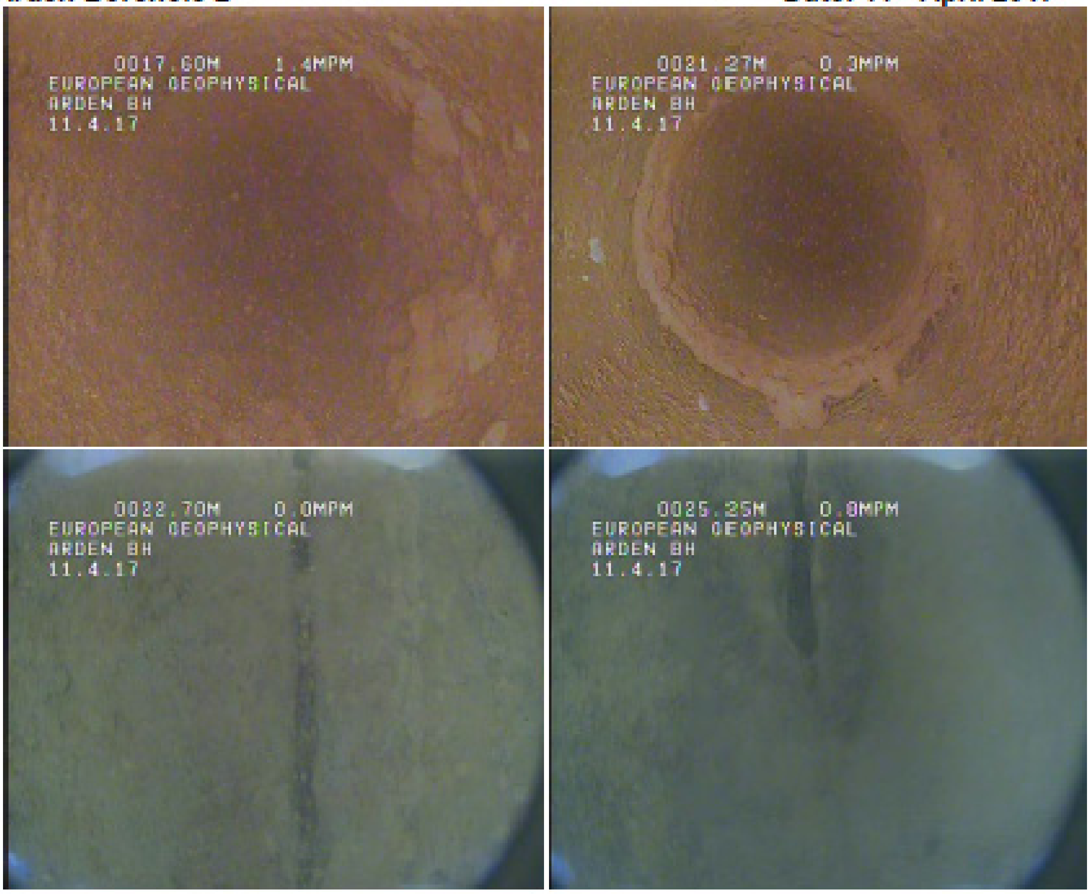


Figure 5.3

17.60m	Increased surface encrustation on plain lining.
21.27m	Dropset lining visible below.
22.70m	Vertical slot in lining.
25.25m	Vertical slot. Fluid clarity quickly reduced below this point.

6.0 CONCLUSIONS

6.1 The final visible depth of the borehole was 30.48m where zero visibility was encountered. Logging tools could not pass the assumed base at 32.3m.

6.2 The well was lined with 207mm i.d. plain steel lining between 0m – 21.76m. Below this, the borehole was lined with 154mm i.d. vertical slotted plain steel. An outer string of 254mm i.d. casing was also observed, extending from 0m to an unknown depth.

6.3 The plain lining was in a reasonable visible condition with initially light surface corrosion, increasing with depth.

6.4 The slotted lining had reasonable surface corrosion and increasingly thick sediment deposit.

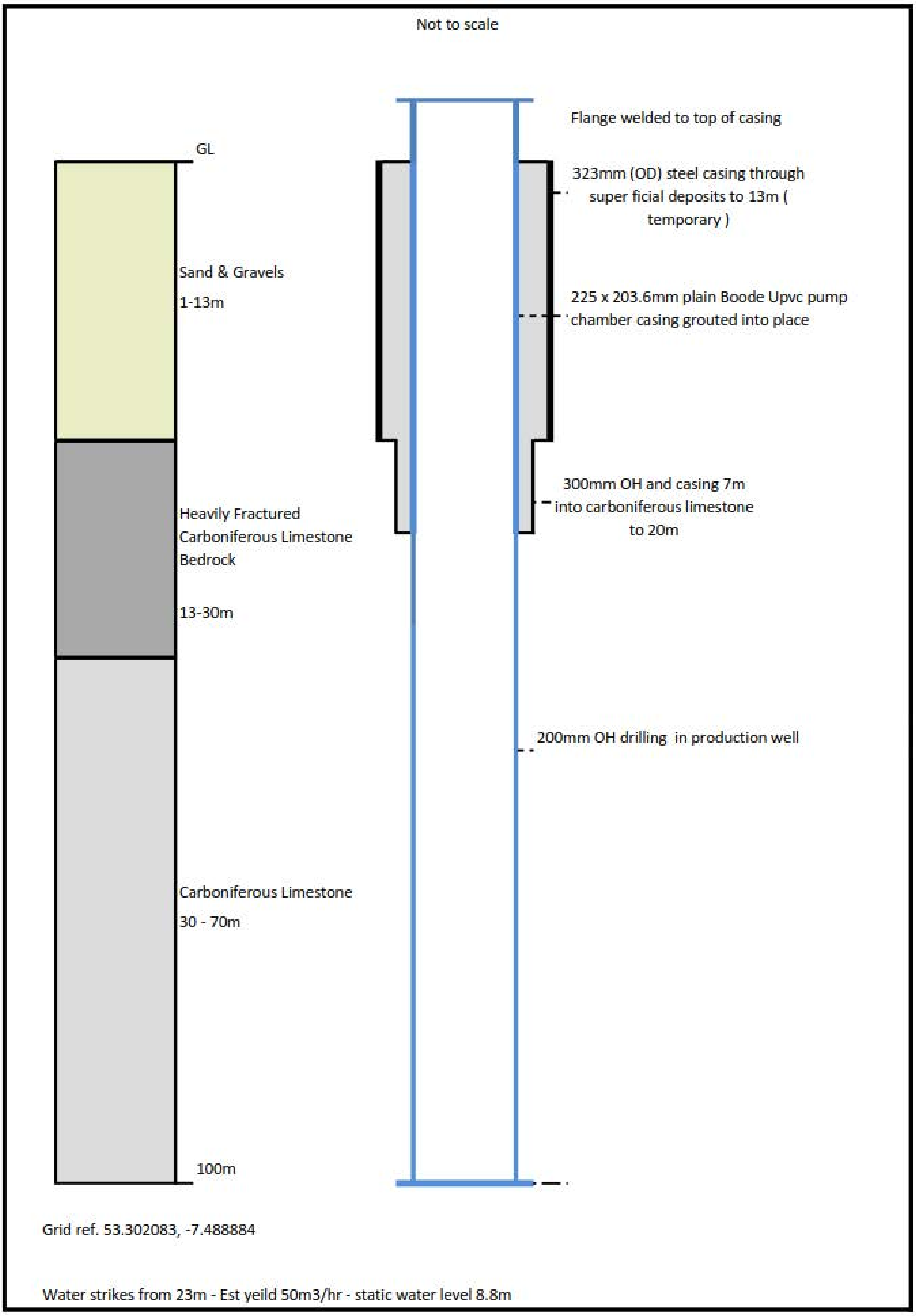
6.5 Joins within the lining appeared to be corroded but showed no signs of leaking or failure.

6.6 Low natural gamma counts indicated clean limestone formation to be present throughout.

6.7 The rest water level was measured at 8.08m, and was initially of reasonable clarity, though this reduced, particularly where the passing camera dislodged sediment within the slotted lining.

6.8 No definitive flow regime was identified. A possible fluid horizon was suggested at 29m, though this may have been induced by the recent removal of the pump.

6.9 Fluid electrical conductivity varied little throughout the fluid column, remaining at approximately 800µS/cm.



Meehan Drilling LTD Collonbeg farm, Collonbeg, Co louth.	Client: AECOM Irish Water Drilling date: 26-09-17	Project: Arden BH4 Trial well	Drawing title: As Constructed Borehole Log WW5273

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