Irish Groundwater Newsletter

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Issue 55 of the Groundwater newsletter includes the customary diversity of topics but with an emphasis on various aspects of groundwater quality. Henning Moe brings some sober science to the fraught and controversial topic of fracking in a hydrogeological context, in his evaluation of two Carboniferous basins in Ireland. An article on Cryptosporidium and Giardia by Paul Hynds and Jean O'Dwyer, completes a trio of contributions on microorganisms in groundwater; the first two, by Paul, appearing in issues 51 and 53 of this Newsletter.

Jean and Paul also contribute an article documenting the results of an investigation in NW Munster into groundwater as a source and pathway for antibiotic-resistant infections. Roisin Dowd Smith and Shailen Flock present the findings of a study on nitrate contamination of groundwater at GWS groundwater sources in Laois and Wexford. From the water management perspective, Matthew Craig summarises the draft second-cycle River Basin Management Plan for Ireland with particular reference to the status of groundwater bodies.

As ever, karst hydrogeology features: Shane Carey describes recent work in karst areas of Ireland using LiDAR images while Bunce and Drew unpick some of the complexities of karst groundwater systems in the central Burren.

This issue includes the annual review of Institutional research into groundwater in Ireland and concludes with hydrogeological news from a variety of sources.

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Cover photo: Groundwater : surface water relationships in River Fergus [David Drew]

Potential impacts of fracking[1] on water resources in two case study areas

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Fracking: investigating the potential hydrogeological effects in two areas of Ireland.

Risks of impact on groundwater, surface water and related aquatic ecosystems from Unconventional Gas Exploration & Extraction (UGEE) activity, including fracking, were assessed[3] in the two case study areas shown in Figure 1: the Northwest Carboniferous Basin (NCB) in the Ireland/Northern Ireland border region, and the Clare Shale Basin (CB) near the River Shannon estuary. The assessment was conducted as part of a joint research programme (JRP)[4] funded by the Environmental Protection Agency (EPA), the Department of Communications, Energy and Natural Resources (DCENR), and the Northern Ireland Environment Agency (NIEA). The assessment, which is specific to the two case study areas, was carried out to assist relevant government bodies in making informed decisions about any potential future licensing and management of UGEE projects on the island of Ireland.

Risk Factors

Impacts of fracking on water resources are documented in international literature, and whilst the science of impact identification and assessment is still evolving, the weight of evidence points to the principal risk factors being:

- Accidental or deliberate spills, leaks and discharges of fluids which are used in or generated by the UGEE activity, both at individual well pads and across wider areas where multiple sites are involved; and
- Stray gas migration of natural gas constituents via natural or man-made pathways, the latter typically resulting from poor well construction practices and/or the fracking operation.

Risks of impact at any given location are largely determined by case- and site-specific conditions, including hydrogeology. Risks can be assessed by applying the Source-Pathway-Receptor model of environmental risk assessment which underpins most water resources protection initiatives on the island of Ireland. Potential modes of impact are summarised in Figure 2.

Source: Potential sources of UGEE-related contamination are many. Most relate to UGEE operations at the ground surface, whilst those perceived to be of greater concern relate to fracking operations in the deeper subsurface environment. Surface sources are represented by spills, leaks and discharges of operational and waste fluids (e.g. fuel, chemicals, and flowback waters[5] from the fracking operation) to streams, drains or ground. Potential underground sources are associated with fracking, which can mobilise and result in the migration of: a) naturally occurring gas constituents; b) drilling fluids and chemicals (as well as their decomposition or transformation products); and c) chemical constituents in bedrock formations, including hydrocarbons, saline formation waters and naturally occurring radioactive materials (NORMs).

[1]High-volume, high-pressure hydraulic fracturing of vertical or horizontal wells in low-permeability bed-rock formations.
[2]Study co-authored with Pat Barrett, Dr Laura Foley, Lorraine Gaston, Oriol Ciurana and Dr Roger Olsen.
[3]CDM Smith, 2016a.
[4]http://www.epa.ie/researchandeducation/research/researchpillars/water/ugee%20research/
[5]CDM Smith, 2016b.

Figure 1: Location of case study areas (Northwest Carboniferous Basin (NCB) top; Clare Shale Basin (CB) bottom)

Pathway: Potential pathways are of both natural and man-made origins. Subsoil and bedrock characteristics determine the presence and scale of natural pathways. These are conceptually well understood in the shallow subsurface environments (to approximately 200 m depth) in both case study areas, but are poorly understood and quantified in the deeper subsurface environment. The presence of natural, open fracture networks at depth is the principal *inherent* risk factor associated with fracking operations. Man-made pathways can be created during drilling and well construction activity, and by the fracture stimulation that results from the fracking operation. Mostly, international experience points to poor or inadequate well construction practices as a contributing cause of impact on shallow water resources and receptors. This includes use of poor quality construction materials, inadequate cementation and/or welding of steel casing, and the improper abandonment of test wells. Flawed or failed installation procedures, which tend to be of an unintended or accidental nature, are also cited.

Receptor: Potential water-based receptors of UGEE-related contamination in the two case study areas would be: a) the available water resources represented by lakes, streams and aquifers; b) associated water supplies (abstractions); c) registered protected areas; and d) groundwater-dependent terrestrial ecosystems. These are broadly mapped, and many of the features, notably water supply sources, were ground-truthed during the JRP.

UGEE projects require water supply for several purposes, including drilling operations, well construction, fracking, sanitation and equipment washing. The amount of water needed is case-specific, as a function of the hydraulic properties of the geological formations, the depths and lengths of drilling to be undertaken, and the targets set by the exploration companies. The highest water use requirements are associated with the fracking operation. In Europe, reported demands generally range between approximately 5,000 and 15,000 m^3 per well. The maximum daily water demand at a given well is defined by the number of fracking stages and the volumes of water needed for each stage. The duration of peak demand is typically short, on the order of 3-4 days (per stage). UGEE activity is rarely confined to single locations, and if several UGEE activities are carried out at multiple sites concurrently, the total daily water demand can become large and impacts of abstractions can become cumulative.

As a cost-saving measure, exploration companies would normally try to source water locally. Available sources of supply are rainwater, lakes and reservoirs, streams and rivers, and groundwater (in bedrock aquifers). The capacity to supply water for fracking operations in any given area would ultimately be conditioned by how and where the development would proceed, both spatially and temporally. Accordingly, UGEE-related abstraction plans should include detailed planning, with a clear timeline of demands and with the participation of relevant stakeholders and regulatory bodies.

Summary of Northwest Carboniferous Basin (NCB) Characteristics

The NCB is a geologically complex sedimentary basin. The rocks, comprising shale, sandstone and limestone formations, are extensively faulted and are intruded by volcanic dykes. Regional NE-SW trending strike-slip faults extend through the entire stratigraphic sequence. These are accompanied by smaller conjugate sets of normal and reverse faults. As a result, geological formations are juxtaposed against one another at numerous locations.

Unconventional gas exploration in the NCB would be targeted in the Bundoran Shale Formation (BSF). Horizontal hydraulic fracturing would require the initial vertical drilling and construction of boreholes to depths between 700 and 1,300 m below ground surface. In the main target area near Lough Allen, the "vertical separation distance" between the BSF and principal shallow receptors ranges between 250 and 570 m (average 426 m), as recorded in 10 past gas exploration wells. The range reflects spatial variations in the thickness and structure of the intervening Mullaghmore Sandstone and Benbulben Shale Formations.

The main potential receptors of contamination would be surface waters and shallow bedrock aquifers, mainly (but not exclusively) the karstified Dartry Limestone Formation (DLF). In this hydrogeological environment, there is considerable hydraulic interaction between groundwater and surface water, and receptors would be susceptible to both surface and underground sources of contamination.

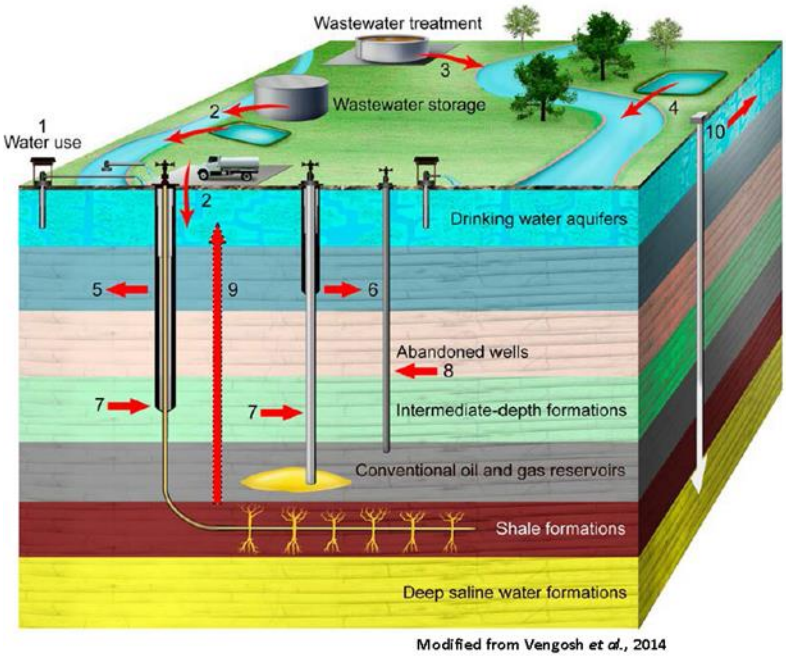
Potential hydrogeological connections between the BSF and shallow receptors are inferred rather than proven. Such connections would exist where open fracture networks are present in the deeper intervening formations (e.g. Benbulben Shale Formation). Although geological structures and fracture patterns at the ground surface are well mapped and described in literature, the presence and patterns of natural, open fracture networks at depth are not conclusively demonstrated or characterised. Their presence is inferred from acoustic televiewer images of past, deep gas exploration boreholes in the Mullaghmore Sandstone, and from records of saline formation waters, ranging from brackish to brine, in prior gas-tested wells to more than 2,000 m depth.

Such open fractures would represent potential pathways of naturally occurring gases, including methane, from hydraulic fracturing operations. It is not yet understood whether the reported saline formation waters in deep sandstone formations are 'fossil' or part of active (even if slow-moving) groundwater flow systems. Existing data do not provide a sufficient database from which conclusive interpretations of deep hydrogeological conditions can be made.

Summary of Clare Shale Basin (CB) Characteristics

Prospective unconventional gas exploration in the CB would be targeted in the Clare Shale Formation (CSF). Horizontal hydraulic fracturing would likely require the drilling of wells to 800–1,200 m depth, mostly towards the Shannon Estuary and Loop Head peninsula. Away from these areas, the CSF thins and is structurally too shallow to be considered a viable source rock or target for UGEE.

The bedrock formations above the CSF are characterised by significant lithological heterogeneity, comprising sandstone and siltstone units, interlayered with shale and mudstone units. There does not appear to be a regionally continuous caprock that would effectively separate the CSF from shallow receptors. Accordingly, and conceptually, potential UGEE-related migration of natural gas



Schematic illustration (not to scale) of possible modes of water impacts associated with UGEE:

1. Over-abstraction of water from streams, lakes or shallow aquifers – higher risks of impacts during low flow conditions.
2. Contamination of surface water or groundwater from leaks and spills of waste materials and wastewater storage near drilling.
3. Disposal of inadequately treated wastewater to local streams, lakes or groundwater.
4. Leaks to waterways and/or groundwater from storage ponds.
5. Shallow aquifer contamination by stray gas that originated from the target shale gas formation through leaking well casing. The stray gas contamination can potentially be followed by salt and chemical contamination from hydraulic fracturing fluids and/or formation waters.
6. Shallow aquifer contamination by stray gas through leaking of past gas exploration wells (e.g. via casings), see also Figure 45.
7. Shallow aquifer contamination by stray gas that originated from intermediate geological formations through annulus leaking of past gas exploration wells (possible in NCB especially).
8. Shallow aquifer contamination through abandoned other wells (via annular spaces (no cases known in NCB or CB).
9. Flow of gas (and saline water, although unlikely) from deep formations to shallow aquifers via natural pathways; and
10. Shallow aquifer contamination through leaking of injection wells (possible but unlikely future scenario).

Figure 2: Potential modes of impact (reproduced with permission).

and other constituents might be less constrained than in the NCB. The potential for contaminant migration will likely be determined by the presence of through-cutting faults rather than stratigraphic or lithological controls. Despite the relative and apparent absence of faults on existing geological maps, bedrock formations have undergone structural deformation and are fractured to some extent. The extensive cover of till, the lack of outcrops across most of the study area, and the repetitive nature of the sedimentary rock succession in the CB all imply that structural complexities may simply be masked. The presence of deeper fractures are noted by reports of fresh water strikes to c. 600 m depth in one hydrocarbon exploration well drilled in the early 1960s.

Addressing Risk Factors

In the deeper formations, saline formation and flowback waters are dense and would not be prone to upward migration unless other driving forces, e.g. thermal gradients, overcome density effects. Gases, including methane, behave differently, and the potential for upward migration is greater. Ultimately, the migration of gases, liquids and fluids would be case- and site-specific, depending on the chemicals that are used, the natural head gradients that are present (e.g. between formations), the pathways and flow mechanisms that are present, the vertical separation distance between the UGEE target formations and shallow receptors, and the interactions with the geological media through which contaminants would be transported.

Whereas surface contamination can be mitigated against with proper planning, enforcement and monitoring under existing laws and regulations, subsurface contamination is more difficult to detect and control, mainly due to the inherent uncertainty about hydrogeological conditions in the deep subsurface environment. Accordingly, risk mitigation for fracking would require prior hydrogeological characterisation and baseline monitoring of the physical–chemical systems involved, at appropriate scales, and employing best practice methods that build on international experiences. Because the risks are case- and location-specific, the nature and scale of related investigations would be judged against the nature and scale of planned UGEE activity. Firm plans for UGEE activity in the case study areas do not yet exist, hence, addressing risk can only be discussed in general and conceptual terms.

The protection of groundwater resources in Ireland and Northern Ireland is presently guided by vulnerability maps and related response matrices. These tend to be focussed on 'shallow' groundwater resources and their susceptibility to surface pollutants. They do not address the risks of contamination that can result from deep fracking, even if principles of contaminant migration are similar in both the shallow and deep environments. Both Ireland and Northern Ireland classify all rock formations as usable groundwater resources (aquifers), irrespective of type, and there are no fixed depth limits which define when groundwater ceases to be a usable water resource.

Questions about deeper hydrogeological conditions can only be addressed through detailed hydrogeological investigation. Such studies would most likely be specified and supervised in context of a future UGEE licensing process. Deep hydrogeological characterisation would involve drilling, geophysical logging, hydraulic testing, sampling and monitoring of new (deep) wells, to depths of 1,000 m or more. Such study would focus on characterising the bedrock formations that separate UGEE target formations from shallow water resources, and characterising the nature and origins of deep formation waters (e.g. in the deep sandstone formations).

A sub-regional approach to deep hydrogeological characterisation would provide valuable data, but the ensuing statements about risk can always be challenged in the context of one location over another, and this approach would not necessarily produce the answers that are needed at the location-specific scale of an individual UGEE operation. Location-specific characterisation is, therefore, necessary, and the onus for this would be placed on the exploration companies, under terms and conditions which would be established, supervised and enforced by regulators.

Baseline Environmental Monitoring

Prior baseline monitoring is a requirement of planning for UGEE activity, as embodied in the European Parliament resolution on the "Environmental impacts of shale gas and shale oil extraction activities" [2011/2308(INI)]. Accordingly, sub-regional baseline monitoring networks were designed for both case study areas, for potential future implementation.

Following a review of best practice guidelines in international literature, a precautionary approach was adopted which: a) is comprehensive in scope and extent; b) would be capable of distinguishing impacts of UGEE-related activity from general environmental pressures; and c) would also be able to describe potential cumulative impacts across catchments. The resulting monitoring networks[6] are receptor-focussed, and are guided by conceptual hydrogeological models that define known or interpreted Source–Pathway–Receptor relationships. The monitoring networks encompass groundwater, surface water, aquatic ecosystems, as well as stream sediments. International best practice requires that groundwater samples are analysed for a wide range of analytical parameters, including dissolved gases in water (e.g. methane), stable isotopes of gas constituents, and NORMs.

Specifications are included on methods and potential new infrastructure that would be needed for implementation. For example, to be able to distinguish UGEE impacts from other environmental pressures, the application of chemical 'fingerprint' techniques are required.

In the context of UGEE, systematic or routine baseline monitoring for natural gas constituents has not been undertaken in Ireland or Northern

[6]CDM Smith, 2016a.

Ireland. An appropriate and recommended starting point for baseline monitoring would be to adopt and adapt the techniques and methods of the British Geological Survey (BGS) in England and Wales[7].

Baseline monitoring is a longer-term commitment and the resulting datasets would inform about natural trends as well as potential UGEE impact. To be cost-effective, there are opportunities to integrate the recommended baseline monitoring programmes with existing monitoring initiatives (e.g. WFD monitoring) by State agencies and public bodies in both Ireland and Northern Ireland.

Conclusions

The potential presence of natural, open fracture networks at depth, in the formations between UGEE targets and near-surface receptors, is the inferred principal inherent risk factor associated with fracking in the two Irish case study areas. Man-made pathways created during drilling and well construction activity, as well as fracture stimulation (across intervening formations), represent the other major risk factor.

Although shale (clay-rich) lithologies would impede vertical movement of water and contaminants, the presence of open fracture networks and deeper groundwater flow components are considered to be possible in both case study areas. This was also recognized by the one of the exploration companies in the NCB who, in the context of recommendations for future horizontal hydraulic fracturing, reported that "Natural fracture systems are expected to be prevalent although their specific intensity variations and trends are not yet understood".

The existing knowledge-base about deep hydrogeological conditions is insufficient to make conclusive statements about risks of impact from fracking operations. Risks are identified and acknowledged, but are presently not quantifiable. Additional studies with field investigations are needed. Implementation of baseline monitoring would subsequently also be required, both sub-regionally and locally at individual UGEE sites.

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Vengosh, A., Jackson, R.B., Warner, N. et al., 2014. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. Environmental Science & Technology 48: 8334–8348.

[7]CDM Smith is indebted to the BGS for allowing the project team to participate in the sampling for dissolved methane gas in groundwater in England.

Overview of the WFD Draft River Basin Management Plan 2018-2021

Matthew Craig, Environmental Protection Agency

Some of the text included in this article has been reproduced from a recent article in the WFD Spring 2017 Catchments Newsletter, with the permission of the author: **Ken Jordan**, Department of Housing, Planning, Community and Local Government

WFD: the status of groundwater bodies in Ireland and the second-cycle River Basin management plan.

The overarching aim of the Water Framework Directive is to achieve at least good status for all water bodies. It aims to do so by ensuring effective water management based on river basins and catchments. Whilst this requires Government to devise and implement plans and programmes, it also requires all agencies and actors to work together, and the further development of a wider public engagement in water policy and water management.

A central element of the Directive is the requirement for member states to produce River Basin Management Plans. These plans must, amongst other things, assess the environmental pressures causing water bodies to be at risk of not meeting the objectives of the Directive, for example, pressures causing water bodies to be at less than good status. Based on this assessment a programme of measures must be developed to address the significant pressures on such water bodies.

The Directive prescribes 6 yearly planning cycles. Ireland's first cycle plan covered the period 2009-2015, and a draft second cycle River Basin Management Plan has recently been published by the Department of Housing, Planning, Community and Local Government for public consultation. The full draft plan and details on how to engage in the consultation process are available online, until the end of August 2017.

As required, this draft plan provides an assessment of the pressures on the water environment in Ireland, and the proposed programme of measures to be implemented in the period to 2021. The plan identifies prioritised objectives, including meeting our EU obligations, preventing deterioration of water bodies, and achieving protected area and high status water body objectives. Based on these significant pressures and the prioritised objectives, proposed measures are set out for each of the identified significant pressures including agriculture, waste water, hydromorphology, forestry and peat extraction. Proposed implementation structures, and planned actions for communication and public engagement are also set out.

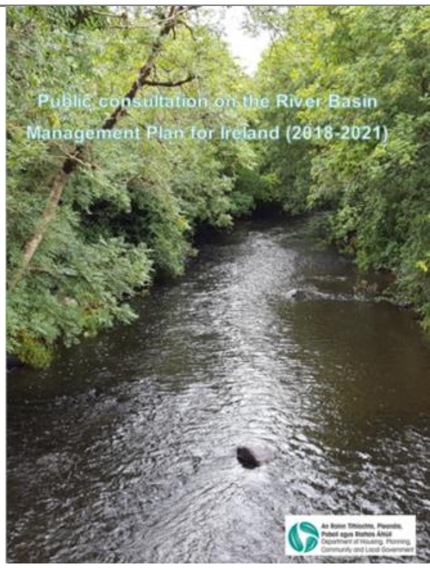

Figure 1: draft river basin management plan

Key Water Body Issues

For the purposes of the Water Framework Directive all waters have been grouped into

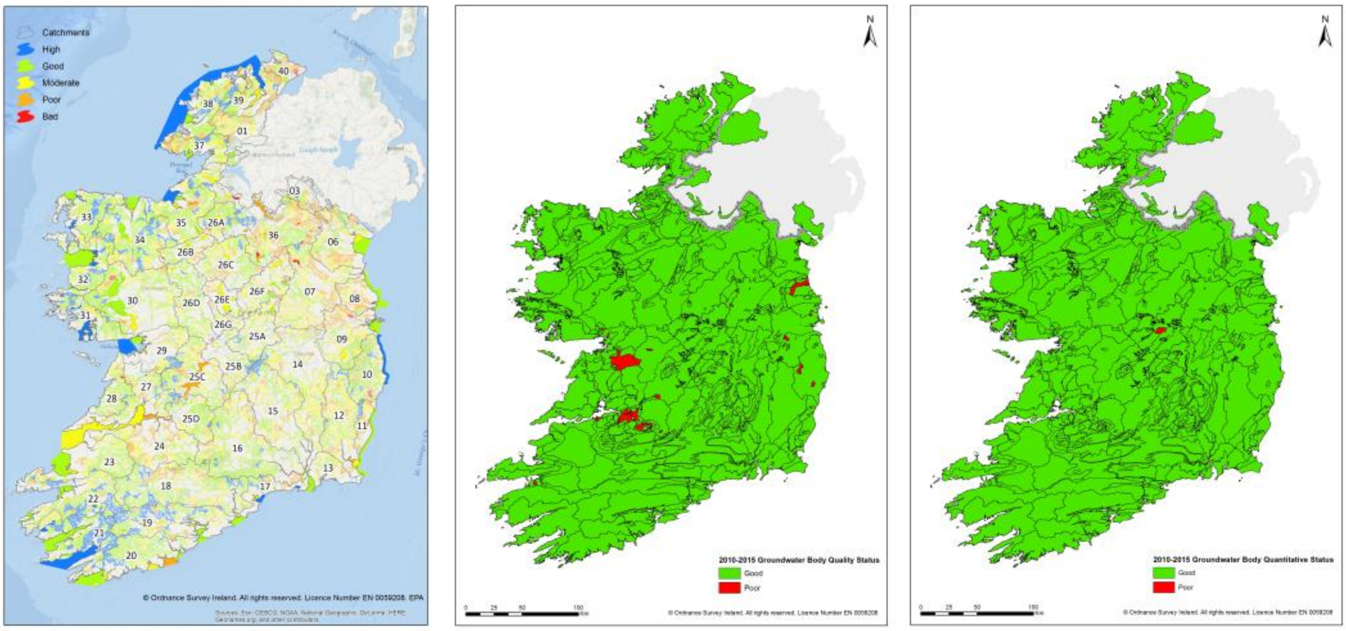

Figure 2: Maps of Surface Water, Groundwater Chemical and Groundwater Quantitative Status

types and individual management units called water bodies. These include 513 groundwater bodies, 3,192 rivers, 812 lakes, 194 transitional (estuarine) and 110 coastal water bodies. 34 water bodies are deemed to be heavily modified and there are 11 artificial (canal) water bodies.

WFD classification for groundwater consists of quantitative status and chemical status. Each groundwater body is assigned either good or poor quantitative and chemical status.

WFD classification for surface water consists of ecological status and chemical status classification. The quality elements relevant in assessing ecological status for surface waters relate to the biological, chemical and physical condition of water bodies. Surface water bodies are assigned to one of five ecological status classes (high, good, moderate, poor or bad), with the status assigned being determined by the status of the poorest quality element. Chemical status has a pass-fail outcome, relating to the presence of priority hazardous pollutants at concentrations above the relevant standard. Heavily modified and artificial water bodies are assessed in terms of the water bodies' ecological potential i.e. what the potential ecological condition could be in light of the modification.

Full details of status assessments are available on the EPA catchments website and are summarised in Figures 2 and 3.

Nationally a small proportion of surface water bodies of water bodies appear to have deteriorated in status since the last status assessment in 2009. However, the national picture masks the fact that significant numbers of water bodies (approximately 900) have improved or dis-improved since 2009, with the dis-improvement thought to be mainly due to increased phosphorus concentrations and/or siltation in rivers in areas with poorly drained soils.

The outlook for groundwater is more positive, with 468 (91%) of the 513 groundwater bodies meeting their good chemical and good quantitative status objectives in 2010-2015, accounting for 99% by area. Of the 45 poor status groundwater bodies; 44 were due to failures to meet the chemical status and 1 was due to failures to meet the quantitative status objective. These poor status ground water bodies are generally small and the significant pressures typically relate to largely historic

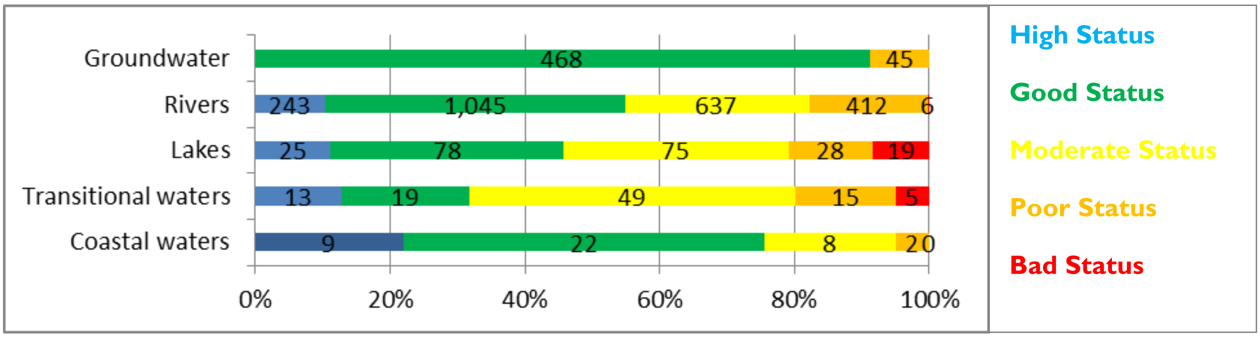

Figure 3: National Overview of Water Body Status

contamination from point sources including mines, landfills and industry.

Thirty three of the 44 poor chemical status groundwater bodies have been designated as being at poor status because of widespread historical contamination from mining activities and industrial development i.e. where the pollution extent is having a significant impact at a groundwater body scale.

The major change in groundwater body status relates to those groundwater bodies that had been failing due to phosphate contribution to surface waters and are now achieving good status. In the previous WFD cycle, 95 poor status groundwater bodies, primarily in the karstified limestone groundwater bodies to the west of the Shannon, were failing to meet their chemical status objective due to the contribution of phosphate in groundwater to surface water bodies impacted by nutrient enrichment. The revised assessment identifies that nine of the 513 groundwater bodies are at poor chemical status for phosphate contribution to surface water bodies that were failing to meet their status objective as a result of nutrient enrichment. Whilst this infers significant improvement in groundwater quality, in reality it reflects a modest improvement because the river and lake catchments in the karstified limestone areas to the west of the Shannon still have limited capacity to receive additional nutrients before an ecological impact becomes apparent.

The other key change for groundwater is that 33 groundwater bodies failed the general chemical test in relation to historic pollution associated with mining, industrial licenced facilities and waste licenced facilities. This represents an increase in number of groundwater bodies failing due to these pressures when compared to the eight poor status groundwater bodies identified in the previous WFD cycle, but this increase is due to improved information and the development of technical assessment approaches rather than there being an actual deterioration in water quality since 2009.

Our understanding of groundwater dependent terrestrial ecosystems (GWDTE) is still not sufficient to ascertain if the quality and quantity of groundwater that supports the wetland habitat is causing impacts on the ecology of these wetlands. Ecological and/or chemical impacts are apparent at two turloughs (phosphorus) and one raised bog (historical drainage) which has resulted in the associated groundwater bodies failing their status objective. Further assessment is required at a number of other GWDTE to determine if regional pressures on the groundwater body are the cause of ecological impacts at these wetlands.

Measures and Next Steps

The types of measures outlined in the draft plan fall into two broad categories. Firstly, those high level measures to be implemented by national authorities, for example, ensuring effective waste water treatment is in place and ensuring appropriate application of EU regulations in sectors such as agriculture and forestry. It is envisaged such plans and programmes will result in significant progress during the second cycle in terms of managing pressures on the water environment.

Secondly, there are supporting measures, which are required where these high level measures have been implemented, but are not sufficient to ensure good water quality in specific areas. The draft plan envisages that local authorities will lead in terms of decision making and managing implementation of these supporting measures, supported by the expertise and evidence base of the EPA. However, the plan also recognises the need for stakeholders including local authorities, public authorities, non-governmental organisations and communities to cooperate and work together to achieve common goals. The recently established Local Authority Waters and Communities Office will have a vital role in making such co-operation a reality on the ground – as will the continued work of the EPA in developing networks and engagement on water quality issues.

For groundwater the historic pollution associated with mining, industrial licenced facilities and waste licenced facilities will need to be addressed via the associated licence or responsible authorities for the pressure. In many instances it may not be technically feasible to attenuate the pollution to a satisfactory level by 2027, and lower objectives and extended timelines may need to be sought for these groundwater bodies. Where groundwater is a significant contributor to surface water bodies failing to meet their status objective, a holistic approach is required to specifically identify catchment wide measures to address the issue, which may include controls to limit nutrients entering surface water via groundwater.

Whilst the status classification represent the current or recent condition of our water bodies, the risk characterisation process looks forward to determine if a water body is at risk of not meeting its objectives (i.e. good status or high status) in the future, by taking account of the current condition, water quality trends and recently implemented or planned measures. Currently 1,945 water bodies are classified as not at risk of failing their status objective, 1,515 are classified as at risk, with the remaining 1,372 requiring further investigation to verify the risk during the next WFD cycle. Allowing a focus on the future condition of our water bodies, enables pro-active measures to be initiated as part of planning and development; thereby limiting the risk of causing deterioration in status.

Governance, Public Consultation and Engagement

One of the key changes since the first WFD cycle is that Ireland has moved away from the seven river basins model to a single river basin district approach. This facilitates the development of national context with regard to evaluating progress and decision making, but regional and local concerns and activities are now addressed by the establishment of the Local Authority Waters and Communities Offices. The existing national authorities retain responsibility for implementation of national programmes, with regional structures driving the implementation of supporting measures.

The Department of Housing, Planning, Community and Local Government has already undertaken significant consultation with stakeholders including environmental organisations in terms of developing this draft plan and the proposed programme of measures. Further engagement with stakeholders will be central to developing the final plan. The current public consultation on the draft plan provides an opportunity for wider engagement on water management issues, and that individuals, community groups and schools can engage with the plan and inform how the plan can be improved, and how we can better facilitate their engagement in the implementation of this plan and the objective of improving the water environment.

Water tracing in the Carron depression and River Fergus valley, Burren, Co Clare

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Karst: complex groundwater flow systems in the Burren.

Introduction

This article describes and discusses water tracing that has been carried out in the Carron enclosed depression and the upper valley of the River Fergus between 2011 and 2017. Although the tracings are chiefly of local interest in the overall context of Burren hydrogeology, the results obtained and the problems encountered in the study, do have a wider relevance to karst hydrogeology investigations in Ireland.

Particular issues that arose in this work include:

- The importance of multi-tracing where groundwater flow patterns are stage dependent
- Determining whether or not a negative result at a sampling site is valid
- Whether or not 'overlapping' karst groundwater flow systems can exist with a shallow groundwater system draining to a wholly different outlet to a deeper flow system beneath it.

At 9km² the Carron enclosed depression is the largest of several closed depressions that are found on the eastern side of the Burren (Figure 1). It contains two turloughs (0.4km² and 0.3 km²) with the lowest point being at the Castletown sink at 110m OD, perched c.70m above the regional water table. It was first described by Sweeting (1953) who reported that "water was believed to flow south to the River Fergus" where a number of springs are located 7km away at an altitude of c.28m OD. There have been several failed and poorly-reported attempts to test Sweeting's hypothesis. One positive trace was reported by Tratman (1968) to the Fergus River Cave springs in 36-48 hours.

The River Fergus sinks underground at An Clab at the limestone-shale boundary and reappears (it was presumed) at Poulnaboe spring 1km to the east. The largest spring in the Fergus valley is at Elmvale 1.5km downstream from Poulnaboe and on the southern side of the river; this spring was presumed to drain much of the south-central Burren. If the water from the sink in the Carron enclosed depression were to rise here it would imply that the conduit would have to pass beneath the river Fergus at shallow depth without interacting with the river water.

To date (including the recently defined WFD catchment boundary), it has been assumed that the catchment boundary between groundwater flowing north to Galway Bay and groundwater flowing south into the River Fergus and hence the River Shannon estuary lay close to the northern scarp of the Burren. The geological structure of the Burren plateau is such that southward groundwater flow, down the dip of the strata (albeit rising through the stratigraphy from the Aillwee member to the top of the limestone succession) seems more probable than northward flow which would require the water to flow up-dip and to pass vertically through a number of 'barriers' to groundwater movement (clay wayboards and chert-rich hori-

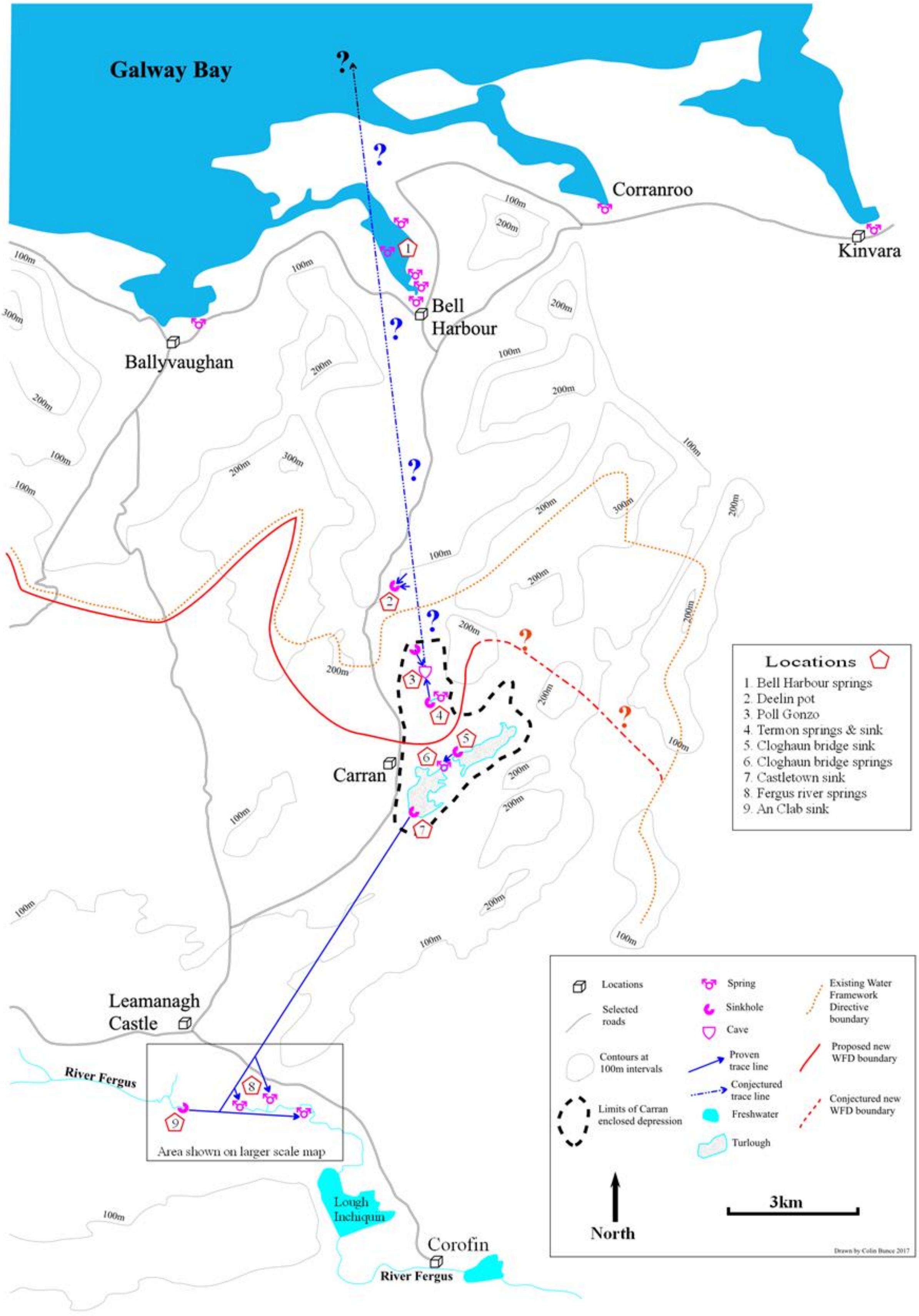

Figure 1: Hydrogeology of the area of the central Burren between Galway Bay and the valley of the River Fergus.

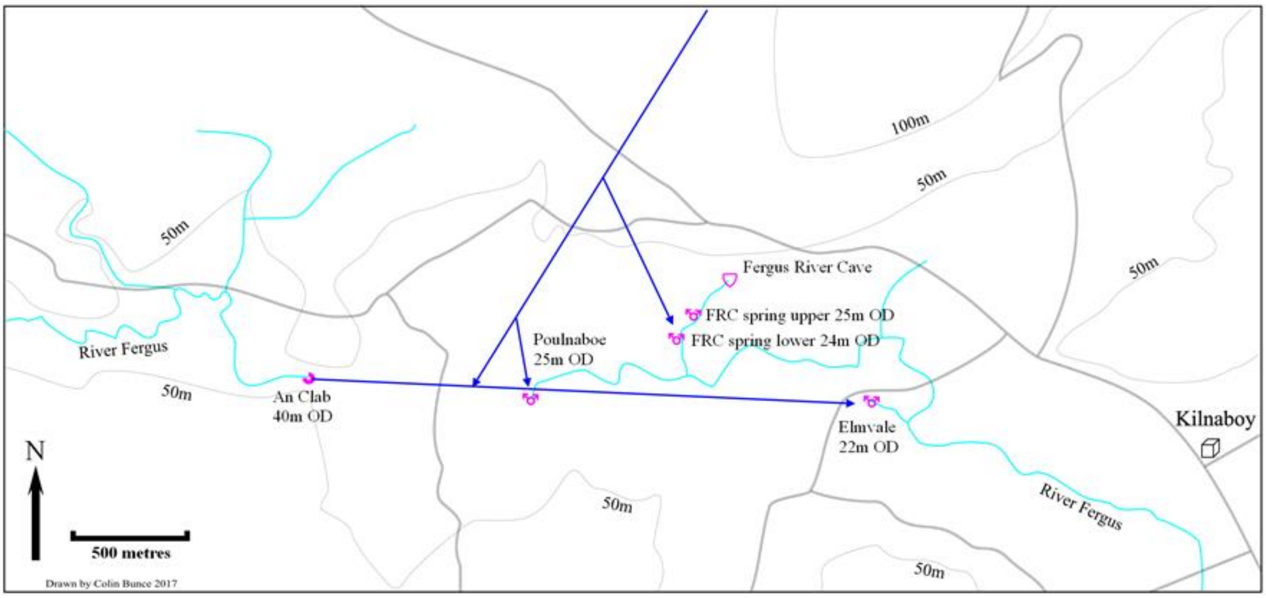

Figure 2 Groundwater: surface water relationships and water tracings in the upper course of the River Fergus.

zons) en-route to outlets in Galway Bay.

In 2009 a significant new cave, Poll Gonzo (Bunce, 2010), was discovered 1.5 km north of Carron where a large stream with estimated discharges of 30-100 l/s, has been followed downwards over a short horizontal distance to and a depth of 90m to 30m OD. This is very close to the level of the Fergus springs, making them an unlikely destination. The other possibility was drainage north to the marine and inter-tidal springs on the south side of Galway bay at Ballyvaughan, Bell Harbour and Corranroo – respectively 9.4, 8-9 and 10.7km distant from Poll Gonzo.

Another question was where the water in Poll Gonzo came from, and this led to an examination of the internal hydrology of the depression and the location of a number of previously unknown semi-permanent springs and sinks (Drew and Bunce, 2016) with the requirement for more tracing.

The water tracing

The results of the tracings that were undertaken are summarised in Table 1 and depicted graphically in Figures 1 and 2.

Summary and analysis

Drainage to the River Fergus

- The upper turlough at Carron drains underground to the lower turlough springs at Cloghaun bridge.
- Water from Castletown sink in the lower turlough drains south to the River Fergus springs, reaching Poulnaboe spring, c.20 hours sooner than Elmvale spring which is a shorter distance from the tracer input site.
- Maximum dye concentrations were very similar at all three springs.
- The flow rate was c.50m/hour to all outlets. This is in marked contrast to the flow rate of <170m/h that would have been required if the Tratman (1968) tracing from Carron to the River Fergus springs, under similar low flow conditions, is valid.
- Poulnaboe spring is the initial outlet for the water sinking at Castletown sink except under very low water conditions, with some (most?) of the flow continuing underground to Elmvale by an immature route of limited capacity. Possibly Elmvale is capturing the flow to Poulnaboe. It is known that outflow

Table 1. Summary of water tracings carried out from the Carron enclosed depression area, 2011-2016.
NUIG = Galway university, CCC = Clare Caving Club, DD = David Drew, CB = Colin Bunce, RS = Robin Sheen. Fl = fluorescein, Rh = rhodamine, OB = Optical brightener

Tracer input location	Traced by	Date	Tracer & amount	Sites monitored	Results	Flow rates
Poll Gonzo	NUIG	2011	Fl 5kg	4 intertidal/ submarine springs in Bellharbour Bay and Corranroo	All negative	N/A
Termon sink	CCC	6/2011	OB 5 l	Poll Gonzo (main stream)	Positive (on cotton wool)	N/A
Poll Gonzo	DD/ CCC	6/2015	Rh 20 l	5 x Fergus springs 7 intertidal/ submarine springs 4 boreholes in Turlough valley	All negative	N/A
Sink 150m NNW of Poll Gonzo	CB	3/2017	Fl 50gm	Gonzo north stream	Positive (on charcoal)	N/A
Cloghaun bridge sink	RS	2013 (?)	FL ?	Lower turlough springs	All negative	N/A
Cloghaun bridge sink	CCC	12/2014	OB	3 springs in Carran lower turlough and Poll Gonzo	All negative	N/A
Cloghaun bridge sink	DD/ CCC	6/2015	OB 8 l	5 x Fergus springs Poll Gonzo 7 intertidal/ submarine springs 4 boreholes in Turlough valley	All negative	N/A
Cloghaun bridge sink	DD/ CCC	4/2016	Fl 5 l	3 springs in Carran lower turlough	Positive at Cloghaun bridge spring	N/A
An Clab	DD	6/2014	Fl 5 l	Poulnaboe (no flow) Buntober Cross bridge Elmvale	Positive at Elmvale	**50-75m/hr**
Castletown sink	DD/ CCC	6/2015	Fl 20 l	5 x Fergus springs Poll Gonzo 7 intertidal/ submarine springs 4 boreholes in Turlough valley	Positive at: **1st** Poulnaboe (7,340m, 120hrs) **2nd** Elmvale (6,700m, 140hrs) **3rd** Fergus springs (180hrs)	First trace at Poulnaboe after 120 hrs, persisted for >7 days, peak at 150 hours. **c.60m/hr** First trace at Elmvale after 140 hrs, persisted for 16 days (22 days after input), peak at c.200 hours **c.45m/hr**
2 sinks ENE of Deelin pot	CB	3 / 2017	Fl 50gm	Deelin Pot inlet	Both positive (on charcoal)	**< 50m/hr**

from Poulnaboe commonly exceeds inflow from the An Clab water implying that Poulnaboe spring receives water from a wider area of the Burren than just the Carron area.

- There is an underground route of limited capacity between An Clab and Elmvale, presumably passing beneath Poulnaboe spring.
- It is not necessary for groundwater from the Carran area to pass at shallow depth beneath the River Fergus to reach the Elmvale spring


Figure 3 (left): Poll Deelin Pot, discovered in 2016, is a palaeokarst shaft oriented along a number of north-south orientated calcite veins. The shaft was filled with glacial sands and gravels which are being slowly excavated by post glacial streams. These streams enter the pot from a north-northeasterly (up-dip) direction from enlarged bedding planes within the epikarst on at least 2 levels. The water then drops vertically into the pothole to follow the palaeokarst flow path to the north, presumably to outlets in Galway Bay.

Figure 4 (right): Shallow groundwater flow in the bedding, perched above a clay wayboard, dropping vertically along a north-south vein to flow north to outlets in Galway Bay

(always a hydrogeological improbability) as there is a subterranean route between Poulnaboe and Elmvale.

Drainage to Galway Bay

- Poll Gonzo water does not flow to the River Fergus but probably flows north to the Galway Bay springs. This groundwater flow to the north emerges from the Black Head Formation (or even stratigraphically lower) having passed through the wayboards of the Aillwee and the Maumcaha massive limestone en-route
- One possible pathway for this would be utilising mineral veins for the vertical drop. A 2km wide suite of silica rich veins with a strong north-south orientation passes through Carron have been mapped by the Geological Survey of Ireland, and can be clearly seen in Poll Gonzo. Some of these veins have a sponge-work texture and the added presence of sulphide mineralization might enhance flow path development.
- The quantity of tracers used, the occurrence of flushing due to heavy rain and the long sampling period mean that the negative result is probably valid and that the water must discharge at sea at some depth below sea level.

A revised conceptual model for the hydrogeology of the central Burren

- The tracing implies that watershed between groundwater draining north to Galway Bay and south to the Fergus-Shannon system must lie <3km south of its currently designated location and that approximately 20km^2 of the Burren plateau drains north to Galway bay rather than south to the River Fergus catchment as previously thought.
- This is supported by the fact that the amount of water entering and leaving the Carran depression (estimated at <50 l/s) suggests that it does not have an extensive catchment outside of the depression.
- It may be that sub-basins within the Carran enclosed depression route groundwater flows in differing directions
- Numerous 'epikarst' springs to the north and

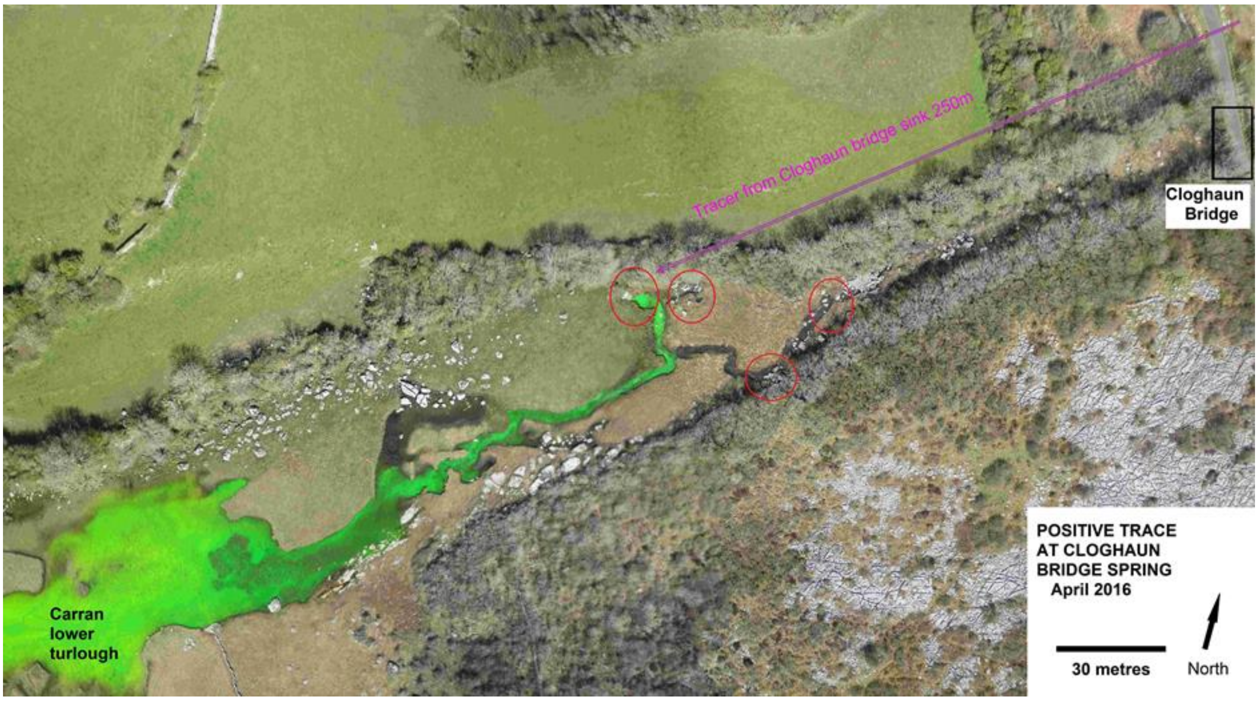

Figure 5. A drone photograph showing the unambiguously positive trace (at the fourth attempt) from the upper to the lower Carran turloughs. Aerial imagery acquired and supplied by Peter Kinghan and John Kelly of SLR consulting

east of the Carran depression (as elsewhere in the Burren) seem to direct shallow groundwater flow south and south-westward (down-dip) but this water then descends via veins (such as in Poll Gonzo and Deelin Pot) and then flows northwards (Figures 3 and 4) Thus, an upper groundwater flow system draining southward is underlain by a north –draining groundwater system (the same water). Perhaps this is not uncommon in karst groundwater flow systems?

Problems arising

Of the nine tracings described in this article only four gave unambiguously positive results. One tracing over a distance of c.500m from the upper to the lower Carron turlough, gave negative results on three occasions before the third tracing turned the spring very green (Figure 5). It is unusual for a particular tracing to be repeated four or more times, yet in this instance it was necessary to obtain the 'truth'. Unsuitable tracer/ inadequate sampling or analysis/effects of different groundwater conditions? Water tracing Irish referendum style.

The tracings from Poll Gonzo were consistently negative and because of the factors outlined earlier, it is tempting to consider these to be 'genuine' negative results i.e. the tracer does not go to the sampled sites. However, this is essentially a subjective interpretation.

Water tracing in karst is an inexact science!

Acknowledgements

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Karst from the skies

Shane Carey, Geological Survey Ireland

Karst: the value of LiDAR datasets in karst hydrogeological investigations.

Introduction

LiDAR has proven to be hugely beneficial to the Groundwater Section of Geological Survey Ireland (GSI) in terms of picking out potential karst features, modelling water flows from turloughs and, in certain cases, helping to fine-tune geological maps. This article describes the basic principles of how LiDAR works, areas surveyed by GSI and karst feature mapping form LiDAR. It also touches on how geological mapping can be aided through the use of LiDAR, as well as how GSI quality control (QC) and quality assess (QA) LiDAR data. It also highlights the benefits of organisational collaboration in such projects.

LiDAR stands for Light Detection And Ranging – a remote sensing method that uses light to measure distances to the Earth (Figure 1). As technology continues to develop, capturing higher resolution large datasets from various platforms is becoming increasingly common. Remotely sensed data is captured from satellites, aircrafts and most recently from UAV (Unmanned Aerial Vehicle) technology. Availability of such datasets assists geological mapping. Large datasets can provide interesting new challenges too. Handling “Big Data” requires more sophisticated databases and models to store, query and use the data.

LiDAR and how it works

A laser pulse is emitted from a remote platform (e.g. satellite or aircraft) and a detector records the time it takes for that pulse to bounce back (Figure 1). Bounce backs are classified into returns. Pulses that bounce off tree canopies and buildings are returned first and hence are classified as first returns. Fourth and fifth returns are also captured by the instrument and these returns are classified as last returns and it is these returns that are used to create a Digital Terrain model.

Survey areas and statistics

GSI captured LiDAR data in parts of Cork, Kerry, Galway and Roscommon in 2015 and 2016. Table 1 outlines the size of the blocks captured. Parts of Sligo, Leitrim and Mayo are scheduled for 2017.

LiDAR datasets are stored in an industry-standard binary file format known as LAS. This is the standard way of storing 3-dimensional point cloud data. Even storing data in this way, files can become very large, very quickly. For example, the Roscommon LiDAR block comprises of an area of 131km^2 and has just over half a billion data points (Figure 2). The area is divided in 1km^2 grids. The LAS file for each 1km^2 grid

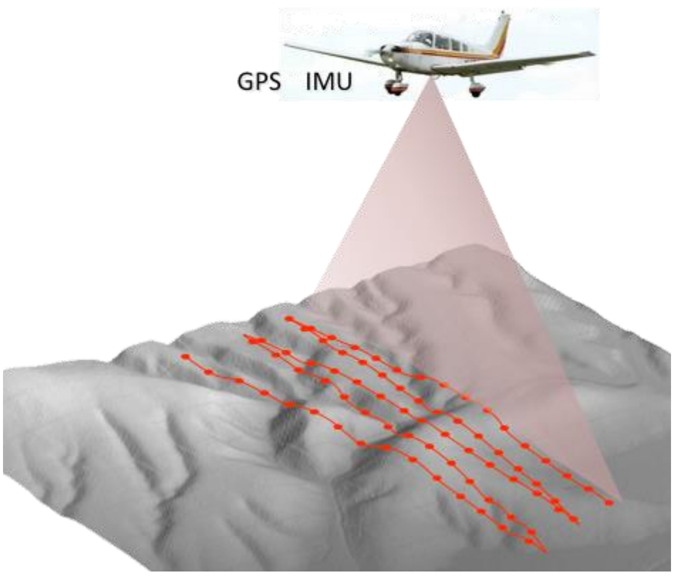

Figure 1 LiDAR collection. Image credit.

Articles

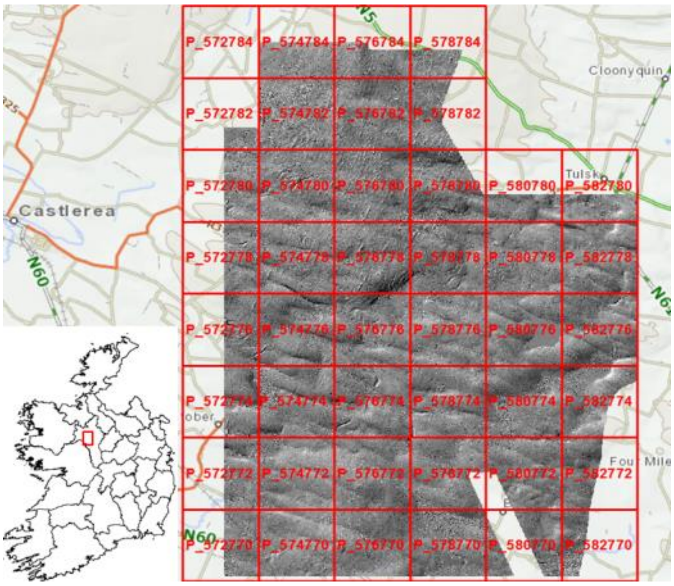

Figure 2 Roscommon survey block

Table 1 Survey areas

County	Area (km^2)
Cork	267
Kerry	60
Roscommon	131
Galway	261

square is half a gigabite in size.

Karst feature mapping and 3-D modelling

Prior to capturing LiDAR data, karst feature mapping was undertaken by utilising 6-inch maps, aerial photography, local knowledge and intense fieldwork campaigns. LiDAR now provides a "bird's eye view" of an area, meaning that a hydrogeologist can pick out karst features more readily during the desk study phase, which reduces fieldwork time.

Not only does LiDAR estimate the surface topography, it also provides information, such as intensity values from the reflected surface which help to pick out vegetation and water in a given dataset. Products such as hillshade (Figure 4), slope, aspect, drainage networks can also be derived from the Lidar datasets. The data allows 3D analysis of karst features to be undertaken, giving greater insight into these karst features.

Geological mapping

LiDAR has aided geological mapping in North Cork which is exemplified in Figure 5. The image shows a series of depressions in the processed LiDAR data, the current, interpreted geological boundary between sandstone to the left and pure limestone to the right and mapped sinking streams. Field mapping confirmed that the LiDAR depressions were swallow holes and dolines. By comparing the karst features identified by the LiDAR data, the geologist was able to cor-

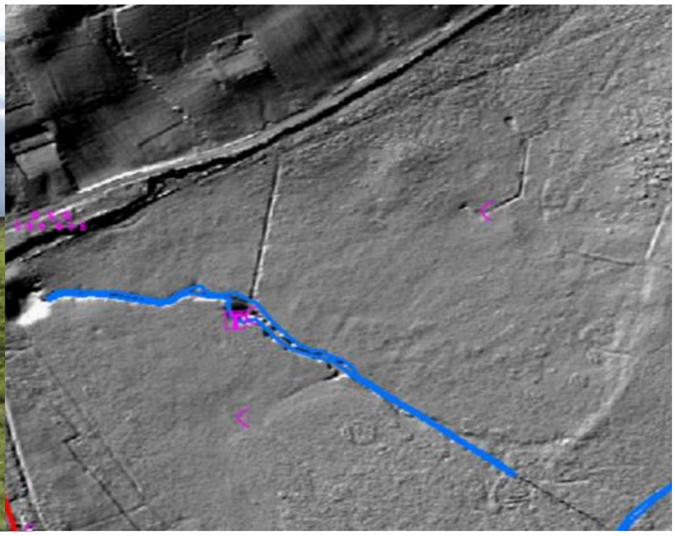

Figure 3 (left) Karstic landscape near Castleplunket, Roscommon; Figure 4 (right) Hillshade dataset of a LiDAR dataset in Castleplunket, Roscommon. Karst features and sinking streams are overlaid.

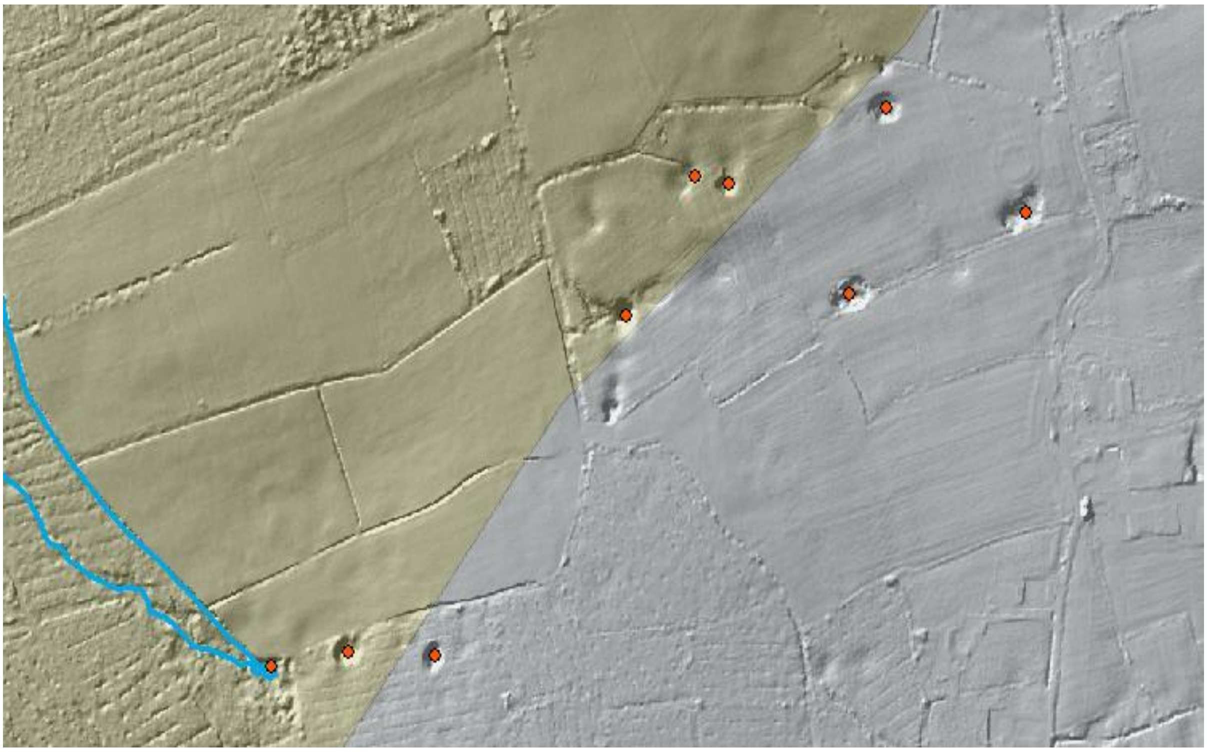

Figure 5 LiDAR collection has allowed GSI geologists to update the boundary between sandstone and limestone in North Cork

rect and update the boundary between the sandstone and limestone on the 1:100,000 bedrock map.

Data QA/QC: Open Source tools

When acquiring LiDAR data, it is important to assess the data for:

- Scan angle;
- Point density;
- Point spacing;
- Swath overlap.

While there is propriety software available to undertake this type of work, there are many excellent open source tools available also. To date, LiDAR data for this project has been quality assured and quality controlled using open source tools.

Data Availability

The data is likely to become available by the end of summer 2017.

Collaborations

This LiDAR acquisition project was successfully carried out in collaborative partnership with Coillte. The project reinforces the benefits of working together where there is a transfer of knowledge and skills between organisations. GSI and Coillte have recently cemented their successful working relationship through the signing of a Memorandum of Understanding (Figure 6).

Figure 6 Signing of the MoU between GSI and Coillte. Left to right are Liam Malone (Coillte), Bill Stanley (Coillte), Koen Verbruggen (GSI) and Monica Lee (GSI)

Waterborne Pathogens and Disease: Protozoa

Paul Hynds, Dublin Institute for Technology and **Jean O'Dwyer,** University of Limerick

Micro-organisms in groundwater: Protozoa

Introduction

This, the last in a series of three articles, provides a review of protozoa (microbial parasites) as groundwater pathogens, with an emphasis on Irish water wells. The most frequently encountered protozoa (Cryptosporidium spp., and Giardia spp.) are outlined, along with their potential sources, pathways, and potential human health effects.

Protozoa (from the Greek proton, meaning "first", and zoa, meaning "animals") are a sub-kingdom of microorganisms (Alcamo & Warner, 2009). Most are free-living, some of which can cause disease, whereas others are obligate parasites (i.e. cannot reproduce outside host) (Haas et al., 2014). They form structures called cysts, oocysts or spores (depending on the life cycle of the organism) which are resistant to adverse conditions such as high temperatures and disinfection (Karanis et al., 2007). The species most frequently transmitted through waterborne pathways are summarized in Table 1. Pathogenic (i.e. infectious) protozoa are primarily excreted in the faeces or urine of an infected human or animal host, and transmitted during the infectious (oo)cyst stage via the faecal-oral route (Haas et al., 2014). Both Cryptosporidium spp. and Giardia lamblia became notifiable in Ireland on January 1st, 2004, following amendments to the Infectious Diseases Act (SI 707).

Cryptosporidium spp.

Cryptosporidium spp. are coccidian protozoan parasites belonging to the phylum Apicomplexa (Barer & Wright, 1990). There are currently 21 recognised species, including two of particular importance in the context of human infection; C. parvum and C. hominus. C. parvum is the species primarily responsible for clinical illness in humans and animals (Hrudey & Hrudey, 2004), with the first case of human infection recorded in 1976 (Marshall et al., 1997). Cryptosporidium oocysts are present in the faeces of infected hosts, immediately infectious upon excretion and capable of survival in the environment for considerable periods (Robertson & Gjerde, 2006). Gray (2004) suggests that Cryptosporidium outbreaks are frequently associated with water treatment not effectively eradicating the parasite; for example, chlorination at levels used in water treatment is ineffective

Table 1: Water borne protozoa (from Marshall et al)

Protozoa	Resistant stage (size, µm)	Illness or disease
Entamoeba histolytica	Cyst (10-20)	Diarrhoea, abscesses
Naegleria fowleri	Cyst (7-15)	Primary meningoencephalitis
Giardia lamblia	Cyst (8-15)	Diarrhoea
Balantidium coli	Cyst (45-65)	Diarrhoea
Cryptosporidium spp.	Oocyst (3-8)	Diarrhoea
Toxoplasma gondii	Oocyst (10-12)	Congenital infection
Cyclospora	Oocyst (8-10)	Diarrhoea

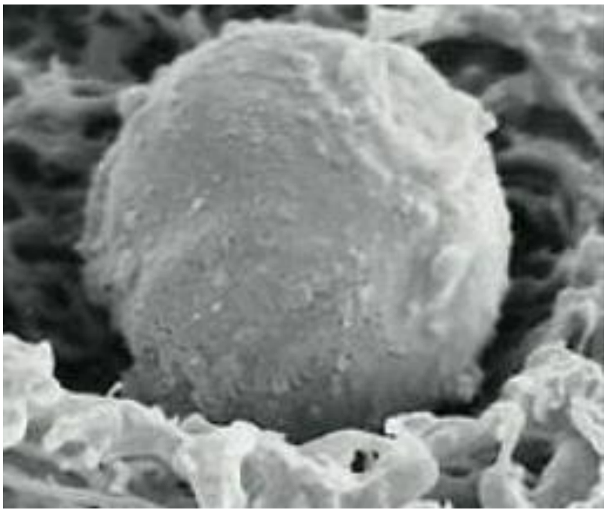

Figure 1: Scanning electron micrograph (SEM) of *Cryptosporidium spp*. Protozoa. Image source.

against oocysts, with concentrations as high as 16,000 µg l^{-1} required to ensure removal.

Waterborne cryptosporidiosis outbreaks have occurred in Northern Ireland (Glaberman et al., 2002) and the Republic of Ireland (McDonald et al., 2011). Willocks et al (1998) have reported on 345 confirmed cases of cryptosporidiosis in North Thames during spring 1997. A case control study indicated that the outbreak was associated with drinking unboiled tap water that originated from a deep chalk borehole. More recently, approximately 40% of cryptosporidiosis cases reported in Ireland in 2015 used a groundwater supply; groundwater currently supplies 22% of domestic households in the Republic of Ireland (Brabazon et al., 2015). In Canada, the cryptosporidiosis disease burden is relatively low (1.82 cases/100,000 people per year), however, the number of predicted cases of Cryptosporidium is roughly 9 and 14 times greater in private wells and small groundwater supplies, respectively (Murphy et al., 2016). The first reported outbreak of cryptosporidiosis (26 confirmed cases) in Ireland strongly associated with drinking water occurred in April 2002 in the midlands (Hanly, 2003), with the water source in this case being a spring-fed lake (Lough Owel). In 2005 an outbreak associated with the Carlow town water supply resulted in 31 confirmed cases between February-May 2005, with private groundwater suspected as a primary risk factor (Coffey et al., 2007). During the period 2004-2015, an average of 455 confirmed cases per annum of cryptosporidiosis have occurred in Ireland (Min 294; Max 608), equating to a national incidence rate of approximately 10/100,000. In 2015, approximately 49% of confirmed cases occurred in children <4 years, reflecting the higher level of susceptibility among children.

Two annual cryptosporidiosis peaks are typically observed in Ireland, the first during early spring with a second, typically lower peak occurring in mid-autumn. Numerous potential reasons have been cited, including agricultural cycles (farming activities such as slurry and muck spreading, lambing and calving), increased outdoor activities (e.g., swimming during the summer recreational water season and camping) and high rainfall periods (Brabazon et al., 2015). Previous studies of environmental water samples have often indicated an association between rainfall and Cryptosporidium spp. (Clapham & Franklin, 1998).

Giardia lamblia

Giardia lamblia is a flagellated protozoan belonging to the family Hexamitidae, is recognised as a significant global cause of mild to severe gastroenteritis, and is found in a wide range of animals, existing in the free-living trophozoite form (Gray, 2004). Cysts can survive for long periods in groundwater environments, particularly at cold temperatures during the winter months (2-3 months at <10°C; up to 1 month at 21°C) (Teunis & Havelaar, 2002). Transmission pathways are similar to Cryptosporidium; however, Giardia is more widespread, with most surface water containing Giardia cysts (Coffey et al., 2007). Ingestion of waterborne Giardia cysts causes giardiasis, which is the most common protozoan gastrointestinal infection worldwide (Haas et al., 2014). Symptomatic illness is characterized by acute diarrhoea, upper or mid-epigastric cramping,

Figure 1: Scanning electron micrograph (SEM) of *Giardia lamblia* protozoa. Image source.

bloating and flatulence, with patients usually reporting malaise and nausea (like cryptosporidiosis). The prolonged duration of diarrhoea, frequently continuing for 2-4 weeks is a typical feature (Ashbolt, 2004).

During the period 1980-1985, Giardia was positively confirmed as the causative organism in 52% of waterborne disease outbreaks in the US. One large outbreak occurred at a Colorado ski resort, when sewage contamination of a groundwater supply resulted in 123 people contracting symptomatic infection (Akin & Jakubowski. 1986). Between 2004 and 2015, an average of 66 cases of giardiasis were reported per annum in Ireland (Min 44; Max 145), resulting in an approximate incidence rate of 1.5/100,000 (Brabazon et al., 2015). It is not known how many of these cases were water related, however in 2015, three outbreaks were of suspected waterborne transmission and a marked seasonality in the onset of giardiasis occurs between early summer and early autumn

Laboratory Analysis

The current standards for detecting Cryptosporidium spp. and Giardia spp. in water are USEPA Method 1622 and USEPA Method 1623, respectively. Both methods comprise three steps: 1) filtration of 10-1000L of water, 2) (oo)cyst concentration using an antibody based immune-magnetic separation procedure, and 3) detection using immune-fluorescence and contrast microscopy to enumerate total (oo)cysts. Flow cytometry may also be used for enumeration; however, these techniques cannot be used to determine the species of the (oo)cysts; moreover, they cannot be used to assess organism viability (i.e. live or dead cells). For species identification and genotyping of waterborne protozoa, several molecular tools are available and currently in use, including (q)PCR, fluorescence in-situ hybridization (FISH) and sequence typing. More recently, multiplex PCR and microarray technologies have been utilized to develop multi-pathogen detection assays, which have the potential to simultaneously detect multiple waterborne pathogens in one sample. Limitations of these techniques include the necessary collection and filtration of very large water samples, the necessity for highly trained laboratory personnel and expensive equipment, while some techniques such as flow cytometry are associated with only moderate recovery rates (i.e. as little as 50% of (oo)cysts positively identified).

Faecal Indicator Organisms (FIOs) and Protozoa

The primary limitation associated with faecal indicators, with respect to protozoan presence, is that they are subject to comparatively rapid die-off due to environmental stresses. As previously mentioned, both Cryptosporidium spp. and G. lamblia are characterized by high environmental resistance, particularly in subsurface aquatic environments, thus limiting the value of FIOs as a measure for indicating protozoan contamination (Hynds et al., 2014). However, previous studies have examined the concurrence between FIOs and protozoa in the aquatic environment, with some success. For example, Hogan et al. (2012) reported that the detection of high levels of Cryptosporidium spp. and G. lamblia coincided with detection of E. coli concentrations >400 MPN (most probable number) in coastal wetlands. Likewise, Clapham & Franklin (1998) found the incidence of Cryptosporidium spp. in private groundwater supplies in the UK to be significantly correlated with faecal streptococci (r = 0.6783, p = 0.001), while Hynds et al. (2014) report a similar association (r = 0.886, p = 0.026) in US and Canadian groundwater during the period 1990-2013. Clostridium perfringens are the traditional organism for indicating protozoan contamination, as they are more resistant to environmental stress than coliforms and generally persist longer in the environment (they may survive longer than (oo)cysts). However, a concrete relationship between C. perfringens and protozoan contamination has yet to be conclusively proven.

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Articles

Out of sight, out of mind?
Groundwater as a source and pathway for antibiotic-resistant infection in the Republic of Ireland

Jean O'Dwyer, University of Limerick and **Paul Hynds,** Dublin Institute for Technology

Antibiotic-resistant infection: the significance of groundwater.

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 (Figure 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 to 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.

Through Darwinian Evolution, micro-organisms adapt to changes in their environment in order to survive; this process is governed by myriad

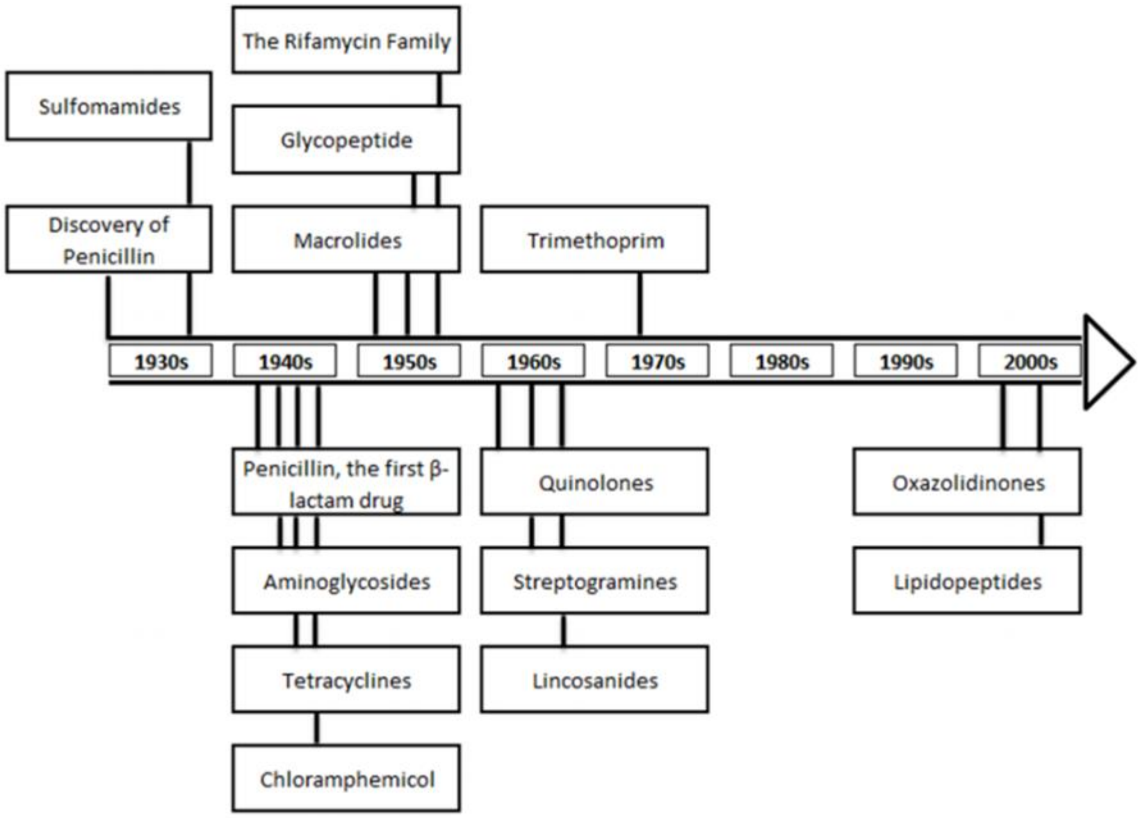

Figure 1 Timeline of new antibiotic classes. The timeline illustrates when the major antibiotics were developed during the past 70 years. During the 1950s new antibiotics peaked, this is known as the golden era, this is when most of the antibiotics that we used today were discovered. The lean years followed from about 1960; this was a low point in antibiotic discovery and development.

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 [1-3]. 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 (Figure 2).

The region is geologically diverse and is variously

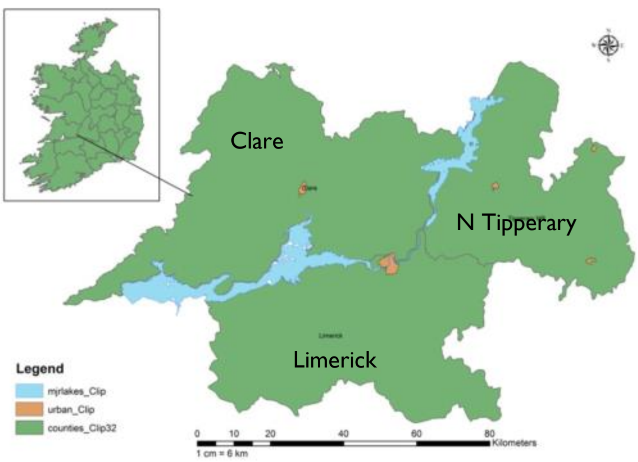

Figure 2: Map of the research area consisting of counties: Clare, Limerick and North Tipperary and forms the Mid-Western Health Board of Ireland

Articles

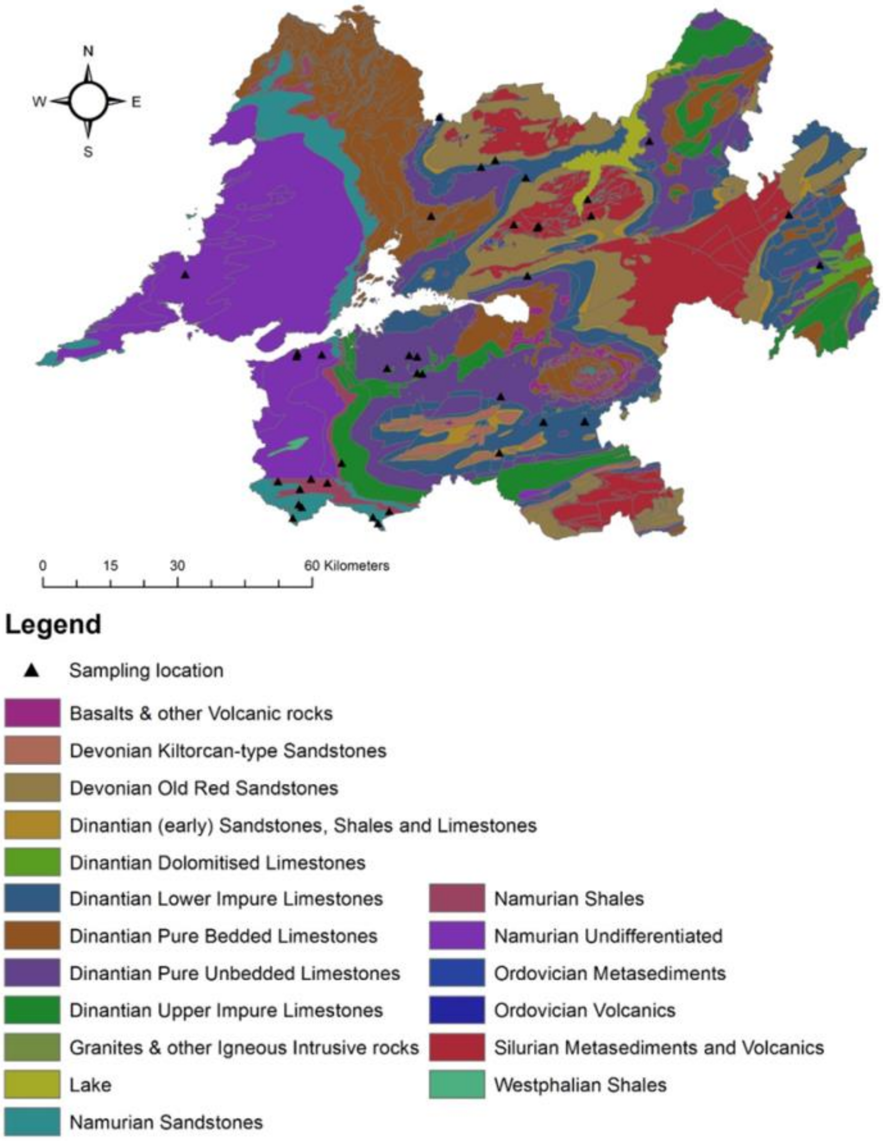

Figure 3: Geographic distribution of the sample sites overlain on the geological attributes of the area.

underlain by bedded and un-bedded Dinantian limestone and Devonian sandstone derived bedrocks, in addition to volcanics and shale deposits (Figure 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.

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" (Figure 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).

Methodology:

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 (< 5 years and > 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 >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 unmetabolized 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 <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 ≤3 years were prescribed ≥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.

Figure 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.

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 hydrological 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 uncharacterised 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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Articles

Investigations of Nitrate in two Group Water Schemes

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Early Career Hydrogeologists' Network

Group Water Schemes: nitrate contamination.

Introduction

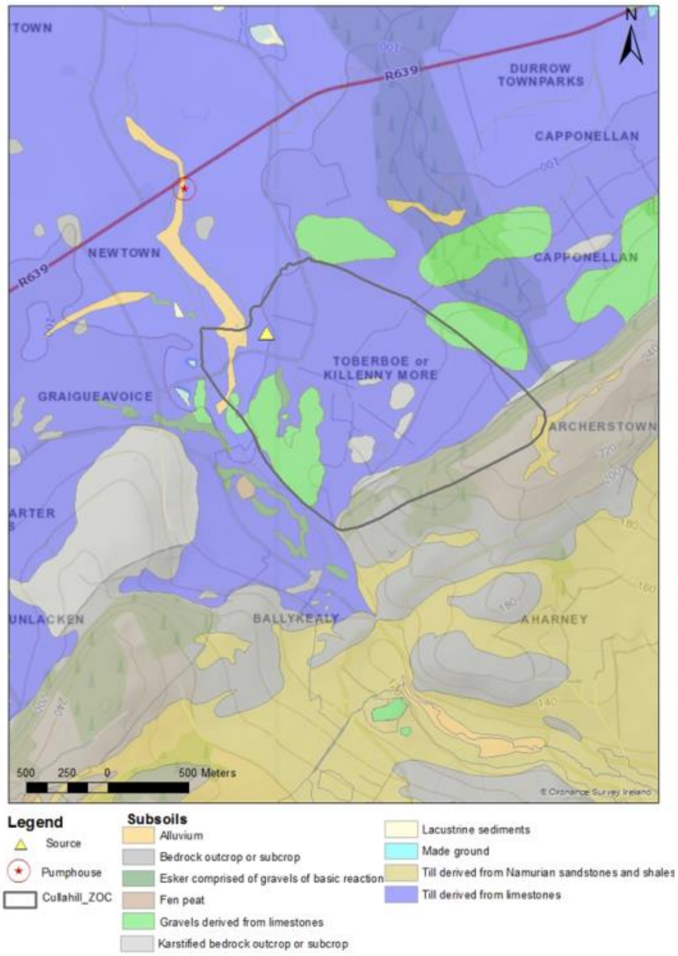
Research projects on nitrate contamination in two Group Water Schemes (GWS) in Cullahill Co. Laois and Kilanerin, Co. Wexford were completed as part of the Master's programme in Environmental Science in Trinity College Dublin (TCD) (Dowd Smith, 2016; Flock, 2016). These research projects were carried out in conjunction with TCD, Geological Survey Ireland and the National Federation of Group Water Schemes (NFGWS). They were three-month research studies from May-September 2016, which built on previous work on these water supplies by Meehan et al. (2010) and Ibbotson et al. (2015). During these projects, extensive field-mapping, compilation of existing data, and water sampling was performed, as well as interviewing the local landowners. Water samples were collected from both groundwater and surface water sources across the Zone of Contribution (ZOC) of both catchments and chemical analysis and statistical analysis were performed. A wide range of cations and anions were examined and additional analyses of contaminant source markers were carried out by other researchers from TCD and NUIG, including tests for sweeteners, sterols and stanols, and fluorescent whitening compounds, and Microbial Source Tracking (MST) (see Acknowledgements for details).

Cullahill GWS

The Toberboe spring supplies water to the Cullahill GWS. This spring was developed in 1938 and is the main spring in the catchment. The spring water emerges from gravels and sands and collects in a 0.3m thick concrete chamber that is dug into the subsoil. This chamber is approximately 4m in width and 2m deep (Meehan et al. 2010). The water from this chamber can then be pumped to the pump house, which is 950m to the north-northwest, or flow downslope by gravity, depending on the time of year and whether there is an overflow. Chlorination as well as UV treatment take place in the pump house to treat the water before it is pumped to the reservoir at Graigueavoice. This reservoir can store two days' supply. A tap is also available in the pump house to access raw water for microbial or chemical analysis. The spring is used to supply 250m3 of water per day to the Cullahill group water supply scheme (Meehan et al. 2016). This GWS has approximately 100 connections, both domestic and non-domestic. The water quality in the area is classified as hard to very hard, with a calcium-bicarbonate chemical signature. These values are characteristic of an area where groundwater is coming from a limestone bedrock aquifer.

Since the beginning of 2014, there has been an issue of elevated nitrate levels in the drinking water coming from the spring. Nitrate levels have stayed consistently above the groundwater threshold value of 37.5mg/L (SI No.9 of 2010), with a record peak of 72.2mg/L, recorded on the 29/01/2016.

The catchment is underlain primarily by Carboniferous limestone, characteristic of the Irish midlands. The water at the Toberboe Spring therefore comes from a karst limestone bedrock aquifer (composed of the Ballyadams for-



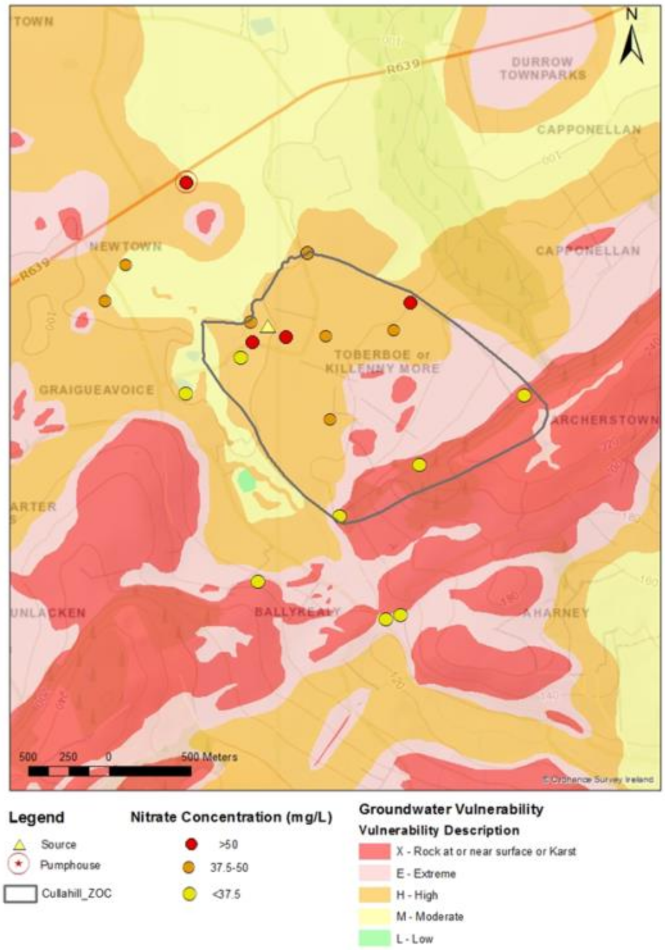


Figure 1 (left): Map showing the different types of subsoil in the ZOC and Figure 2 (right): Map showing the Cullahill groundwater vulnerability in the ZOC, along with the different sampling points

mation and classified by the Geological Survey of Ireland as Rkd – regionally important karstified aquifer dominated by diffuse flow). The ZOC is made up of different subsoils, as can be seen in Figure 1. These subsoils have different permeability and varying degrees of thickness, giving rise to variable groundwater vulnerability, which is predominantly extreme to high (Figure 2). In addition to diffuse entry of contaminants through thin or permeable subsoils, there is also a risk of contaminant entry by point recharge: limestone aquifers are particularly vulnerable to an array of different human impacts due to the presence of karst features such as swallow holes and sinking streams. Mapping of karst features in the ZOC of Toberboe located a swallow hole 4.5 km south-east of the spring which takes intermittent flow from the siltstone at the southern edge of the ZOC, and one sinking stream was also found to the north of the spring. This sinking stream is likely to play a role in the transportation of contaminants to the aquifer.

From the chemical analyses, varying degrees of groundwater contamination exist. The detection of *E. coli* in the raw water at the Toberboe spring indicates that either human or animal waste is entering the spring. The detection of bacterial DNA from human hosts in the Toberboe spring, together with very low concentrations of an artificial sweetener, indicates that there are traces of septic tank discharge in the ZOC. However, bacterial DNA from bovine hosts was present in the Toberboe spring water also.

Analysis of nitrate in wells across the ZOC did not show the expected relationship of increasing nitrate with increasing groundwater vulnerability. The highest concentrations were found in areas of high vulnerability, whereas the lowest nitrate concentrations were found in areas of X-extreme vulnerability at the southern edge of the ZOC, as can be seen from Figure 2. It is thought that this spatial distribution reflects variations in land use, with more intensive agriculture in the high vulnerability areas. Therefore, in this ZOC, where the soils are generally freely draining, it would appear that source factors are more important than pathway factors in controlling groundwater nitrate concentrations.

From discussion with the landowners in the catchment, information relating to the landspreading and livestock density was obtained. This information, along with Teagasc standard conversion factors for fertilisers and livestock, were employed to calculate the nitrogen (N) input from agriculture to the soil in the ZOC. There are 17 houses in the ZOC, each of which has a septic tank. By taking this information into account along with published values from previous septic tank research (Gill and Mockler, 2016), the maximum input of N that can be released from septic tanks was calculated for the catchment. Performing these N balance calculations indicated that agriculture has the potential to have a far greater contribution to N inputs than septic tanks. N inputs from agriculture in the ZOC were estimated as 62, 513 kg N/yr. Studies elsewhere suggest that in freely draining soils 10 -20% of agricultural N inputs may be leached. So taking a conservative estimate of agricultural N leaching losses of 6,250 kg N/yr, this can be compared with the maximum amount of nitrogen that can be released from septic tanks of 154 kg N/yr. Thus even assuming that 100% of septic tank N is lost to groundwater, agricultural N losses are estimated to be at least 40 times greater. An alternative approach of estimating N inputs to the ZOC from nitrate concentration at the springs and from estimated mean spring flow gave an approximate load of N discharging from the spring of 7,702 kg N/yr i.e. of the same order of magnitude as the estimated agricultural N leaching losses. This load corresponds to leaching losses of approximately 38.5 kg N per hectare per year.

The study ultimately found that the highly vulnerable nature of the catchment, coupled with intensive farming, has led to the contamination of the drinking water being supplied to the Cullahill GWS.

Kilanerin GWS

The water supply for the Kilanerin Group Water Scheme comes from the Pond Road Well, which has consistently high nitrate concentrations above the threshold value of 37.5 mg/L NO-3 (S.I. No. 9 of 2010; Ibbotson *et al.*, 2015). The highest recorded value of nitrate in this well was 51.95 mg/L NO-3 in 2013, which is also above the drinking water standard of 50 mg/L NO-3 (98/83/EC). This borehole is located in the southeast of Ireland in Co. Wexford about

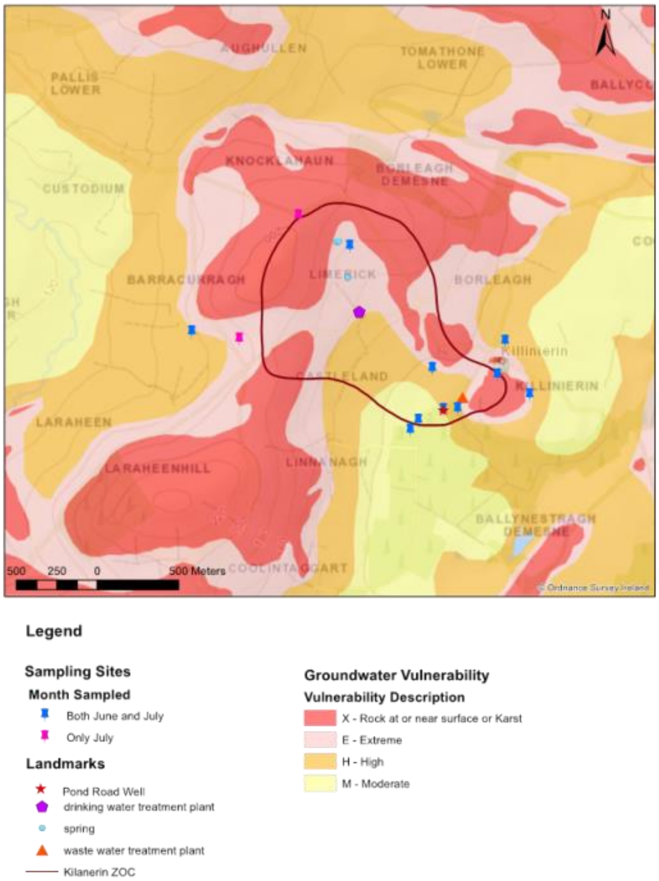


Figure 3: Groundwater Vulnerability Map for the Kilanerin ZOC

Figure 4: Photograph of section with large transition zone in Kilanerin, Co. Wexford. Crowbar for scale. Photo source: Shailen Flock

500m south of Kilanerin Village. The village is surrounded by upland areas to the north, west, and south, which define the catchment area or ZOC for the Pond Road Well. The land in this catchment slopes eastwards towards the Inch River and its tributaries making up the Inch River Catchment. The immediate area around the Kilanerin groundwater borehole is surrounded by forested and boggy land, while the ZOC is dominated by agriculture, mainly dairying. In addition to diffuse agricultural sources of nitrate from fertiliser and grazing animals, potential point sources in the ZOC include septic tanks, slurry pits, and slatted units. There is also a wastewater treatment plant near the well, which could potentially contribute to the nitrate contamination.

The majority of the ZOC for the Pond Road Well consists of well drained acid brown earth soils, although the area immediately surrounding the Pond Road Well has glacial till overlain by poorly drained gley soil (Ibbotson *et al.*, 2015). The Pond Road Well is located in an area of moderate subsoil permeability and high groundwater vulnerability. However, the majority of the ZOC's subsoil permeability is marked as N/A due to the very shallow subsoil (<3 m) in the region, and the groundwater vulnerability in the majority of the ZOC is extreme (E and X), seen in Figure 3. The freely draining soil and shallow subsoil allow for quick transportation of water down to the bedrock. This makes the groundwater highly vulnerable to contaminants such as nitrate.

There are two rock formations at this site: dark grey slate and minor grey pale sandstone (Kilmacrea Formation), and green and grey slate with thin siltstone (Ballylane Formation) (Ibbotson *et al.*, 2015). These two formations are separated by a geologic fault just north of the Pond Road Well. The groundwater flow at this location is controlled by both the topography, and the amount of fracturing in the rock units. Most of the groundwater flow in this region is thought to occur within the top 15-30 m of the bedrock aquifer. Observations of sections down to bedrock in Kilanerin demonstrated the presence of a transition zone with weathered and fractured bedrock directly below the subsoil, shown in Figure 4. The transition zone in the Kilanerin region could cause nitrate to move into the groundwater relatively fast with no opportunity for denitrification.

Information was collected on fertiliser usage and type, quantity of livestock, and landspreading through interviews with the local farmers who have dairy farms in the ZOC for Kilanerin. These data, along with Teagasc conversion standards for fertilisers and livestock, were employed to calculate nitrogen input from agriculture to the soil in the ZOC. The estimate of septic tank nitrogen input was calculated based on the quantity of septic tanks in the area and published values from previous septic tank research (Gill and Mockler, 2016). The estimated nitrogen input from farms had a much larger magnitude than that from the septic tanks. It was calculated that septic tanks yield a maximum of 500 kg N/yr into the ZOC, assuming no nitrogen attenuation in the percolation area. Nitrogen inputs to the farmland were estimated as 42,224 kg N/yr, and taking a conservative estimate (for this vulnerable, freely draining situation) that only 10% of the agricultural N is leached (4,222 kg), this input is still eight times greater than that from septic tanks. Only limited nitrogen concentration data, and no flow data, are available from the WWTP outlet, but observations of flow and nitrogen concentrations in the receiving stream suggest that percolating contaminated stream water is unlikely to be a significant source of N in the borehole. The N inputs indicate that agricultural practices are likely to be contributing more to the nitrogen pollution in the Pond Road Well than septic tanks and the WWTP. This is also supported by the findings of the statistical analysis of all groundwater monitoring points within the ZOC, which revealed that nitrate was significantly correlated to the number of farms within 300m up- gradient and 100m down-gradient of each water sampling location. Nitrate was also significantly correlated with both livestock density and inorganic fertilizer input from the farm closest to the sampling site. However, nitrate was not significantly correlated with the number of septic tanks or septic tank age.

The chemical analysis points to both sewage and agricultural practices as sources for pollution in the Pond Road Well ZOC. One artificial sweetener was present in the Pond Road Well on one occasion at a very low concentration, while the MST data show the presence of very low quantities of bacterial DNA of both human and bovine origin. Therefore there are indications that human waste from either septic systems or the WWTP could contribute to nitrate pollution in the groundwater, although the nitrogen input calculations suggest that the dominant source is more likely to be agricultural. Further investigation would be needed to quantify the exact inputs from both diffuse and point sources.

Future Work

Additional research work on chemical indicators of contaminant sources in these two GWS supplies is being carried out by Damien Mooney (TCD) as part of a PhD project on agrochemicals in Irish groundwater: the occurrence of anthelmintics, anti-coccidials and pyrethroid insecticides (which are the most widely used veterinary drugs in Irish agricultural production) is currently under investigation.

The National Federation of Group Water Schemes is currently evaluating possible future approaches to working with the landowners and the GWS committee for each supply to improve the water quality, based on the findings of these research projects.

Acknowledgements

These two MSc course projects were supervised by Catherine Coxon (TCD) and Taly Hunter Williams (GSI). Chemical analyses were carried out in the Trinity Centre for the Environment with the assistance of Mark Kavanagh. Analyses for human effluent markers were carried out by Donata Dubber and David O'Connell (TCD), microbial testing was carried out by Mark Chawke (Laois County Council) and microbial source tracking was undertaken by Maria Barrett (NUIG). We are very grateful to the landowners and group scheme committee members for their assistance with the research.

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New Research in Hydrogeology

This section of the Irish Groundwater Newsletter contains summary reports on hydrogeological research being carried out in Ireland. Due to the multi-institutional nature of many of the projects there is an inevitable overlap between some of the reports. Many thanks to the individuals who coordinated the reports from each institution. If you know of research which should be included please contact the editors at groundwaternewsletter@gsi.ie.

NUI Galway OÉ Gaillimh

There are three thematic areas related to water that are the focus of work at NUIG: metals in groundwater; groundwater in coastal dune systems; and, stakeholder engagement in the integrated catchment management process.

Ellen McGrory (supervised by Liam Morrison) is wrapping up her Griffiths-funded PhD which has been looking at the distribution of metals (and arsenic in particular) in the Clew Bay and North Louth areas. Ellen has published her first paper on the national occurrence of arsenic around Ireland and is working on another. Alex Russell (iCRAG PhD student supervised in UCD by Frank McDermott) has submitted a paper to Goldschmidt based on a GSI-short call funded project working on cores recovered in the Louth project area (Tiernan Henry and Liam Morrison are co-PI's on Alex's project).

Tiernan Henry and John Murray are co-PIs (along with Frank McDermott) on another iCRAG project that started in September 2016. Eoin Wynne is looking at the chemistry of mine-water makes*, initially at Lisheen and Galmoy, and in the future at Tara. He has reviewed more than 20,000 separate groundwater analyses recovered from underground water makes over the life of mine at Lisheen, selecting a representative group from across the mine footprint. All of these are clean water (recovered from fissures, faults, weathered ground and seeps) representing formation water. Eoin is exploring the gross chemistry and will be assessing more subtle relationships between metals to better understand the pathways and sources of these formation waters (he presented his initial work at this year's IGRM in TCD).

Tiernan Henry is part of an EPA-funded (2014-CCRP-MS.22) research project (headed up by Eugene Farrell in NUI Galway Geography) looking at the response and recovery of coastal catchment ecosystems to the impacts of large storms. The study area is Doogort on the north side of Achill island. Tiernan has installed a number of loggers in piezometer tubes across the dune complex to assess groundwater flow direction, and response to terrestrial drainage and seawater inflows.

Grainne Barron is halfway through her research MSc (supervised by Tiernan Henry and Gesche Kindermann (Applied Ecology Unit, NUI Galway)). The project is funded by the Burren and Cliffs of Moher UNESCO Geopark through EU Life. This community based research project has focused on catchment mapping with TY secondary school students from Lisdoonvarna. Grainne has taught the TY students to use QGIS and they have been compiling catchment maps of the

*A mine-water make of a given body of mine workings may be defined as the total volume of water entering the working over a specific period of time, and which must therefore be removed by any active or passive dewatering system.

Aille River (their catchment). The students have presented their work to the recent European Geopark Network conference and have made it through the ECO-UNESCO Young Environmentalist Award semi-finals (awaiting results as this goes to publication!), and Grainne presented her work at this year's IAH Annual Conference in Tullamore and the 27th Irish Environmental Researchers Colloquium (ENVIRON) in Athlone.

A number of the EOS 2017 graduates are completing groundwater MSc programmes in Strathclyde and Newcastle with a larger cohort from this year's 4th year class hoping to get into the same or similar groundwater programmes, and EOS graduates are working successfully on the TELLUS data collection programme.

Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

The Schools of Natural Sciences and Engineering in Trinity College are a major partner in the SFI funded Irish Centre for Research in Applied Geosciences - iCRAG. In the groundwater research "spoke" there are now six ongoing PhD research projects and one postdoctoral researcher led by TCD, supervised by Catherine Coxon, Laurence Gill, Bruce Misstear, and Carlos Rocha (see details below), on the subjects of :

- flow pathways through karst aquifers,
- groundwater terrestrial dependent ecosystems,
- contamination of karst springs by on-site wastewater,
- submarine groundwater discharge, and
- 3-D modelling.

All TCD-based research projects within the SFI funded Irish Centre for Research in Applied Geosciences (iCRAG) have now started. The seven projects in the groundwater spoke in TCD are as follows:

1. Characterisation of diffuse recharge into karst aquifers using chemical and numerical modelling techniques

The project aims to differentiate between diffuse and conduit flow pathways into a karst network using both chemical (isotopic and trace element water quality) and spring hydrograph source separation techniques. The aim is then to develop numerical models of different karst networks with a focus on characterising the fissure flow more accurately as well as linking this to contaminant transport. In the past year the fieldwork focus has been on the Bell Harbour catchment in the Burren in which some significant findings with respect to multi-level submarine discharge from the catchment have been hypothesised.

Contact: PhD student Philip Schuler (schulerp@tcd.ie) and supervisor Laurence Gill (laurence.gill@tcd.ie)

2. Impacts of changing climate on groundwater recharge in low storativity fractured-rock aquifers

The aim is to investigate the effects of forecast changes in climate parameters on groundwater recharge. The project objectives are to investigate:

- How bedrock properties affect the response of Irish aquifers to present and future recharge.
- How climate change impacts on our regional groundwater resources.
- How climate change impacts on dependent wetlands (GWDTEs).

- How climate change impacts on Source Protection Areas (SPAs).

Work to date has focussed on catchment selection and then sensitivity analysis of impacts of changing climatic and hydrogeological parameters on groundwater recharge using a GIS platform.

Contact: PhD student Èlia Cantoni (cantonil@tcd.ie) and supervisor Bruce Misstear (bmisster@tcd.ie)

3. Emerging organic contaminants arising in rural environments: investigations in karst and fractured bedrock aquifers

This project (which started in September 2015) is investigating the occurrence of agro-chemicals in Irish karst and fractured bedrock aquifers, focussing on three groups of compounds commonly used in Irish agriculture: anthelmintics, anticoccidials and pyrethroids. Pilot sampling for anthelmintic drugs was undertaken in autumn 2016, with detections in 8% of groundwaters and 20% of surface waters. Further sampling for anthelmintics was undertaken in March – April 2017: data analysis and interpretation is currently in progress.

Contact: PhD student Damien Mooney (mooneyd2@tcd.ie) and supervisor Catherine Coxon (cecoxon@tcd.ie). Co-supervisors: Karl Richards & Per-Erik Mellander (Teagasc Johnstown Castle), Martin Danaher (Teagasc Ashtown) and Laurence Gill (TCD).

4. The impact of on-site wastewater effluent on karst springs

The aim of the research is to carry out a more systematic investigation of karst springs in Ireland with the objective to characterise the diffuse recharge from DWTS effluent in order to develop a better understanding of risk of the groundwater pollutant contamination and linked risks to human health from such sanitation systems. Karst springs will be sampled over a range of hydrological events to determine contribution of on-site effluent contaminants by chemical and microbiological fingerprinting methodologies. To date, the research has focussed on catchment selection for the fieldwork sites.

Contact: PhD student Luka Vucinic (vucinicl@tcd.ie), supervisors Laurence Gill (laurence.gill@tcd.ie) and Catherine Coxon (cecoxon@tcd.ie)

5. Ecosystem services provided by groundwater dependent wetlands in karst areas

This research aims to identify and quantify the ecosystem services associated with turloughs, particularly in relation to the need for habitat conservation in the face of external pressures associated with agriculture, road drainage schemes, water supply and wastewater disposal. The primary aim of the research will be to evaluate the ecosystem services of turloughs and develop a framework that outlines the methodology and actions to be undertaken when attempting to assess damage from external pressures. Research will focus primarily on quantifying the ecosystem functions responsible for producing terrestrial hydrologic and climatic services, as well as intrinsic biodiversity services, and use this context to lay out a blueprint for a more detailed ecosystem service assessment.

Contact: PhD student Fabio Delle Grazie (dellegrf@tcd.ie), supervisors Laurence Gill (laurence.gill@tcd.ie) and Owen Naughton (naughto@tcd.ie)

6. Effects of Groundwater-Surface water Interactions (GSI) on the biogeochemistry of coastal

areas hosting aquaculture activities

This research aims to refine the developed approaches to incorporate the biogeochemical role of aquaculture in mitigating N pollution from land and quantify its potential value as a component of natural capital. A primary goal of this project is to develop and refine nutrient budget and flux models for SGD-impacted systems hosting aquaculture that will help support the quest for more efficient and sustainable nitrogen use in human activities at regional level, while simultaneously developing the non-existent quantitative knowledge to evaluate pollution mitigating measures from the economical point of view and support decision-making structures to this regard.

Contact: PhD student Maxime Savatier (savatiem@tcd.ie) and supervisor Carlos Rocha (rochac@tcd.ie)

7. Visualisation of flow and contaminant transport through karst aquifers

The primary aim of this research project is to develop a state of the art modelling methodology in order to make the groundwater flow and contaminant transport through karst aquifers more understandable by means of visual 3D models. This will be applied to a number of Irish karstic catchments in order to shed light on their hydrologic operation.

Contact: postdoctoral researcher Lea Duran (duranl@tcd.ie) and supervisor: Laurence Gill (laurence.gill@tcd.ie)

Other on-going TCD research (i.e. non-iCRAG)

The Environmental Engineering research group in the Dept. of Civil, Structural and Environmental Engineering continued to carry out the EPA funded project (ref. 2012-W-MS-12) to quantify the impact of on-site wastewater effluent on rivers and wells. The fieldwork on this project has now finished and the final report is being produced. This project focused on studying private wells across four different areas, two characterised as Low vulnerability (in counties Wexford and Cavan) and two characterised as Extreme vulnerability (in counties Wexford and Kilkenny). 216 wells were sampled for contamination as well as surveyed for pollutant source susceptibility. 24 wells of these wells have been sampled once per month since September 2016 to build up a temporal picture. The research has also identified appropriate chemical and/or microbiological fingerprinting methods (in collaboration with the Dept. of Microbiology in NUIG) for on-site effluent contaminants in both surface water and groundwater environments.

Contact: Chris Fennell (fennelca@tcd.ie) and Donata Dubber (dubberd@tcd.ie).

An on-going postdoctoral fellowship within Environmental Engineering has funded by the Irish Research Council and the GSI in collaboration with the Swiss Institute for Speleology and Karst Studies (SISKA) is now drawing to an end. The project has developed numerical models of two Irish karst catchments using the KARSYS methodology (as developed by SISKA): Bell Harbour catchment in the Burren and the Shanballymore/ Castletownroach spring catchments (north Cork).

Contact Ted McCormack (mccormte@tcd.ie).

Due to the unprecedented flood events of 2009 and 2015, flood risk management is seen as a major challenge facing communities across the country. Hence, the Department of Communications, Climate Action and Environment has provided funding to the Geological Survey of Ireland on a new 3 years research project in collaboration with Environmental Engineering in TCD to

Research

establish a groundwater flood monitoring and modelling programme for Ireland. This post doctoral project is focussed on monitoring the flooding regime of turloughs in the west of Ireland as well as the development of numerical models which can be used to provide the fundamental technical knowledge and information necessary to enable the development of appropriate groundwater flood mitigation measures, and allow for informed flood assessments to be made in future.

Contact post doctoral researcher Patrick Morrissey (morrispj@tcd.ie) and supervisors Ted McCormack (mccormte@gsi.ie), Owen Naughton (naughto@tcd.ie) and Laurence Gill (laurence.gill@tcd.ie).

A new EPA funded project entitled EcoMetrics - environmental supporting conditions for Groundwater Dependent Terrestrial Ecosystems started in April 2017 led by the Environmental Engineering research group and School of Natural Sciences in Trinity College. The aim of the research is to define appropriate metrics for the different GWDTEs - fens, raised bogs and turloughs. The development of environmental supporting condition metrics for the water bodies that support the GWDTE is a prerequisite for undertaking assessments under the WFD characterisation process.

Contact Laurence Gill (laurence.gill@tcd.ie) and Catherine Coxon (cecoxon@tcd.ie)

Research by the Environmental Engineering group also continues into the transport and attenuation of on-site effluent contaminants with a new project in collaboration with the Dept. of Mathematics in Limerick to develop numerical models of pollutant transport from on-site systems to groundwater. Two instrumented field sites in County Limerick in different soil types are being continuously monitored to determine vadose zone contaminant transport and attenuation with an additional field site in north County Dublin recently constructed and instrumented.

Contact Jan Knappe: (jan.knappe@tcd.ie) and Laurence Gill (laurence.gill@tcd.ie).

A research collaboration between Environmental Engineering and the Dept. of Geology has continued using rare earth elements as tracers of flow pathways in the lowland karst catchment in south Galway.

Contact: Laurence Gill (laurence.gill@tcd.ie) and Balz Kamber (kamberbs@tcd.ie).

Laurence Gill and David O'Connell (post-doc) have completed for a project entitled, "Characteristics of stable isotope fractionations during reactive transport of phosphate in groundwater discharging to a groundwater fed lake (Lough Gur, Co Limerick)" funded by a GSI Short Call research grant and are currently compiling results for publication.

Contact: Laurence Gill (laurence.gill@tcd.ie)

Bruce Misstear is now the Secretary General of IAH. He is working to increase outreach activities between IAH and other organisations involved in water science, policy and management. A second edition of the textbook Water Wells and Boreholes by Bruce Misstear and his co-authors has just been published by Wiley (see review by David Ball in the newsletter).

In the School of Natural Sciences, the joint TCD – Teagasc project on nitrogen attenuation along delivery pathways in agricultural catchments is nearing completion. This research projects aims to investigate nitrogen attenuation processes along groundwater pathways in two Irish agricultural catchments: an arable catchment in Co. Wexford and an intensive grassland catchment in Co. Cork. Factors influencing groundwater denitrification are being investigated.

Contact: PhD student Eoin McAleer (Eoin.McAleer@teagasc.ie) and Catherine Coxon (cecoxon@tcd.ie). Co-supervisors: Per-Erik Mellander and Karl Richards (Teagasc).

Two TCD MSc course projects on nitrate in water supplies, undertaken as joint studies with Geological Survey Ireland and the National Federation of Group Water Schemes, are reported on in this newsletter.

Two PhD projects focusing on naturally occurring redox-sensitive metal and metalloid contamination in groundwater have recently commenced in the UCD School of Earth Sciences, funded by SFI through the Irish Centre for Research in Applied Geosciences (iCRAG). An iCRAG funded post-doctoral research project on the potential of geothermal systems in Ireland commenced recently. A fourth iCRAG funded project on the behaviour of engineered metallic nanoparticles in groundwater systems will commence in summer 2017 at UCD following recruitment of a post-doctoral researcher.

In addition a project on public perception of groundwater use and resources in Ireland has been funded recently by the Irish Research Council.

1. An investigation of arsenic sources, speciation and mobilization processes in selected Irish aquifers

This four year PhD project will investigate the occurrence, speciation and geochemical processes responsible for the mobilisation of geogenic arsenic in selected Irish groundwaters. Geological environments similar to those in which high levels of dissolved arsenic occur elsewhere (e.g. sulphide bearing volcano-sedimentary sequences, unconsolidated glacial, fluvioglacial and alluvial deposits) are common in Ireland, yet reliable ppb-level As data for Irish groundwaters are sparse. Reconnaissance studies of groundwaters from Ordovician volcanics, glacial tills, fluvioglacial sediments, the Longford-Down massif and the Dalradian Supergroup have revealed elevated arsenic concentrations that significantly exceed WHO limits locally. Data generated in this PhD project will offer new scientific insights into the 'arsenic problem' that are applicable globally.

Contact: PhD student Alex Russell (alex.russell@ucdconnect.ie) and supervisors: Frank McDermott (frank.mcdermott@ucd.ie), Tiernan Henry (tiernan.henry@nuigalway.ie) and Liam Morrison (liam.morrison@nuigalway.ie)

2. An investigation of uranium occurrence, sources and mobilization processes in selected Irish groundwaters

This four year PhD project will investigate the occurrence, sources and processes responsible for geogenic uranium contamination in selected Irish groundwaters. Groundwaters from fractured Caledonian and Tertiary granites and from Carboniferous limestone-shale successions can contain levels of dissolved uranium that exceed World Health Organisation (WHO) limits. Reliable uranium data for Irish groundwater at the ppb level remain sparse however. This project seeks to better understand and quantify the fundamental hydrogeological and hydrochemical processes that control uranium mobilisation and transport in these aquifer types. In a recently published reconnaissance survey of 200 public groundwater samples from across the Republic of Ireland, dissolved uranium concentrations exceeded the WHO limit in 10% of the sampled wells. However, almost no reliable data exist for large number of private wells (>100,000) that provide the main source of drinking water in several regions. The underlying geochemical processes responsible for uranium mobilisation and transport are currently not well characterised, and this will be a major focus of the PhD.

Contact: PhD student Fani Papageorgiou (fani.papageorgiou@ucdconnect.ie) and supervisors: Frank McDermott (frank.mcdermott@ucd.ie), Tiernan Henry (tiernan.henry@nuigalway.ie) and Liam Morrison (liam.morrison@nuigalway.ie)

3. A quantitative investigation of potential geothermal systems in Ireland

Dr. Sarah Blake will investigate the viability of geothermal systems in several locations in Ireland using available structural, hydrogeological and geophysical data. An important foundation of this work will be the use of heat demand data, with the specific purpose of locating potential end-users for geothermal energy. The aim of this project will be to build upon previous geothermal research in Ireland in a pragmatic way by investigating the geothermal plays of specific Irish sites, with the objective of identifying promising sites for future geothermal systems and exploration boreholes. Contact sarah.blake@icrag-centre.org.

4. Linked laboratory and field investigations of engineered nanomaterial (ENM) behavior in selected soils and groundwaters.

The main objective of this 2 year project is to develop a basis to assess the risks to groundwaters as receptors of artificial nanoparticles, given the prevalence of engineered nanomaterials (ENMs). The focus is on the fate of ENMs in the recharge zones of groundwater systems following unintentional releases at point sources. Specifically, the project will assess the influence of the mineralogical, compositional and grain size attributes of selected soil/sub-soil/sand-gravel aquifers on nanoparticle mobility, using silver nanoparticles (AgNPs) as the model. The effects of hydrogeological characteristics (e.g. soil permeability, organic content) on the transport and/or agglomeration behaviour of AgNPs based on linked laboratory and field studies will be investigated. Field sites where releases of AgNPs already occur (e.g. percolation areas of septic tank systems) will be used initially. We anticipate that AgNPs may provide a tracer for such releases, leading to a better understanding of groundwater pathways under physio-chemical conditions that promote mobility. Materials from these sites (e.g. sub-soils) will be sampled to further constrain the influence of physicochemical variables (e.g. redox state, pH, water ionic strength) on nanoparticle behaviour using manipulated laboratory-scale column experiments with these materials.

Contact: Mentors Frank McDermott (frank.mcdermott@ucd.ie) and Liam Morrison (liam.morrison@nuigalway.ie). Post-doctoral researcher to be appointed.

Other on-going UCD research (i.e. non-iCRAG)

Public perception of groundwater use and resources in Ireland

A post-doctoral researcher will commence shortly in UCD on a 24 month Irish Research Council (IRC) funded project. This project was funded under IRC's Policy and Society Call in late 2016. The aim is to investigate various aspects of public perception of groundwater and related issues for different water user groups (i.e., public supplies, private group water schemes, private well owners). The aim is to understand how they differ in awareness, beliefs, concerns and understanding of groundwater related issues. Part of this survey will focus on private well owners, as their health risks are relatively high. In the survey we focus on well owners' perceptions of groundwater and risks, and awareness of surface and natural contamination of wells. Next, we will develop communication strategies to increase well owners' awareness of the health risks and the provision of tailored advice to reduce these risks. We focus on visualization tools, which has been very successful in making "invisible" problems visual. The effectiveness of these communication tools will be systematically tested in the lab, before presenting them to well owners in focus groups. The results of this project will inform policy advice for government departments, agencies and geoscientists on knowledge gaps, and a guideline for addressing them. Further, the communication tools can provide important input for guidelines and policies around well construction and maintenance.

Contact: Mentors Dr Geertje Schuitema, UCD Smurfit School of Business, (geertje.schuitema@ucd.ie) and Frank McDermott, UCD School of Earth Sciences and (frank.mcdermott@ucd.ie). Post-doctoral researcher to be appointed.

Teagasc
Agriculture and Food Development Authority

Groundwater studies related to nutrient loss and associated processes are on-going at the Environmental Research Centre in Johnstown Castle, Wexford.

A new Walsh Fellow project started in May 2016 on the theme of P mobilisation and leaching to groundwater. This project will address previously identified knowledge gaps related to P mobilisation and attenuation processes in the subsurface continuum at the catchment scale. Catchments with well-drained soils and of different P buffering capacity, within the Agricultural Catchments Programme, have been chosen to examine the speciation of P in groundwater and mechanisms of P release and retention from soil. This will provide the basis for identifying Critical Source Areas of P for discharge to groundwater and exploring ways to minimise such losses.

Contact: Walsh fellow Andrea Villa (Andrea.Villa@teagasc.ie).

In another project a holistic assessment of N and P pressures and legacies in karst landscapes has been carried out (Fenton et al., 2017). This work has highlighted and quantified both hydrological and biogeochemical time lags in an agricultural karst spring contribution zone. Concluding that biogeochemical time lag can have long lasting effects on water quality.

A new EU H2020 Marie Curie Innovative Training Network called INSPIRATION - Managing soil and groundwater impacts from agriculture for sustainable intensification has started in Teagasc Johnstown Castle. There are 15 early stage researchers employed across a very wide range of topics including:

- development of smart monitoring networks,
- groundwater sensors that incorporate flow measurements,
- decision support systems , and
- soil and water amendments to attenuate contamination from multiple sources e.g. locally sourced media to remediate mixed contaminants in drainage water.

A field site is being setup to bring groups on field visits and the consortium will help to train all the early stage researchers through secondments and by hosting workshops (open to all) at various times on related topics.

Contact: Owen Fenton (owen.fenton@teagasc.ie). Further information will be posted on www.inspirationitn.eu or follow us on Twitter @inspiration_itn.

In June a new three-year European Union Horizon 2020 funded project, WATERPROTECT will start. The objective is to contribute to an effective uptake and realisation of management practices and mitigation measures to protect drinking water resources. The project has a multi-actor approach with seven case studies over Europe, coordinated by VITO in Belgium. The Irish case study is led by Teagasc with University of Ulster, Wexford County Council and Glanbia Ingredients Ireland as partners.

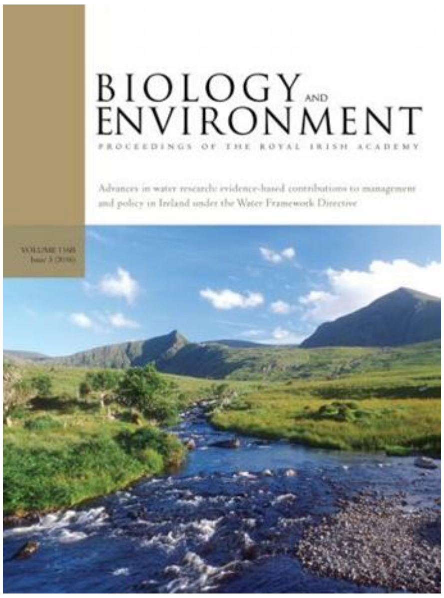
Contact: Per-Erik Mellander (Per-Erik.Mellander@teagasc.ie.) for more details

Hydrogeological News

This section of the newsletter contains news of interest to hydrogeologists in Ireland. It includes short reports on the recent activities of the IAH Irish Chapter as well as the IAH International. It also includes other groundwater related material such as new publications that may be of interest and where groundwater has featured in the media. If you are involved in, or aware of, any items which may be of relevance for this section of the newsletter please contact the editors at groundwaternewsletter@gsi.ie

Open access Biology and Environment Special Issue on the Water Framework Directive in Ireland published

Advances in water research: evidence-based contributions to management and policy in Ireland under the Water Framework Directive



The EU Water Framework Directive (WFD; 2000/60/EC) has provided a structure for integrated water resource management across the European Union over the last fifteen years. Here in Ireland, our implementation of this directive has been underpinned by a substantial body of scientific research on water body classification, characterisation and management. Some of the initial Irish WFD-related research was presented seven years ago in a previous special issue of Biology and Environment (volume 109B issue 3). In the intervening years, a sizeable body of further research underpinning implementation of the WFD has been undertaken, much of it funded by the Environmental Protection Agency (EPA). The impetus for this special issue came from a group of EPA Research Fellows involved in these research projects: the key characteristic of the WFD is integrated water resource management, with recognition of the linkages between rivers, lakes, groundwaters, transitional and coastal waters, so it was felt appropriate that these different aspects should be brought together in a single special issue.

The issue opens with a discussion of the Irish and EU water research programmes which provide the context for this research, and an overview of the new approach to integrated catchment management in Ireland. This is followed by five papers focussing on water body typologies and classification, including a review paper on distinctive river types which are insufficiently represented in the existing national typology, a presentation of research on assigning key typology parameters to unmonitored Irish lakes, an evaluation of the performance of ecological assessment metrics in responding to lake eutrophication pressure, a discussion of the development of fish classification tools for lakes, rivers and transitional waters, and an analysis of fish community status assessments. The third part of the special issue presents a diverse range of research underpinning the new phase of WFD water body characterisation and management. This includes a paper addressing the main pathways delivering water and nutrients to rivers, followed by the presentation of a new model to predict sources of phosphorus and nitrogen loads to water. A further paper outlines a screening tool for assessing the potential for groundwater discharge to lakes, while another utilises a range of data to understand the eutrophication history of a lake and to simulate responses to future changes in land use and climate. Moving downstream to estuarine (transitional) and coastal waters, a pair of papers investigate the relationship between changing nutrient loads in river catchments from diffuse and point sources and the response in estuarine and coastal water quality. Finally, an opinion article suggests that further effort is required to satisfactorily incorporate nature conservation objectives and measures into the WFD.

To summarise, the special issue presents diverse research that draws on learning from the first cycle of WFD river basin management planning, develops an evidence base and new tools for decision-making that are informing the second planning cycle, and provides research insights to meet future management challenges.

Papers of particular interest to groundwater newsletter readers include:

Integrated catchment management in Ireland

The EPA's flexible and responsive Water Research Programme has supported extensive high-quality policy relevant research, supporting water management in Ireland.

Integrated catchment management will result in multiple environmental benefits including water quantity/quality, biodiversity, flood mitigation and reduced greenhouse gas emissions.

Water body typologies and classification

Do rare river types in Ireland host biological communities distinct from non-rare types? Review of the complexity of characterising some distinctive river types in Ireland.

Decision-tree learning used to categorise lakes into WFD typologies was particularly successful for the low alkalinity category.

How do different measures of lake ecology perform in responding to differences in lake water quality? An important step towards developing lake nutrient standards for WFD.

Fish classification tools have been developed in Ireland for lakes, rivers and transitional waters, and inter-calibrated across Europe. An investigation of fish communities in Irish estuaries and their value in assessing ecological quality status.

Characterisation and management

Field studies emphasise that achieving successful WFD outcomes depends on having a local, three-dimensional understanding of contaminant transfer pathways.

The Source Load Apportionment Model (SLAM) predicts the sectors contributing phosphorus and nitrogen loads to water, facilitating scenario analyses.

GIS and remote sensing tool developed identifies groundwater discharges to lakes.

Climate change may hinder the improvement of Lough Leane's water quality.

A holistic view along the freshwater – marine continuum must be taken to ensure that nutrient imbalances are not created in downstream coastal areas.

Significant reduction in phosphorus (72%), ammonia (77%) and nitrogen (39%) in Irish rivers in recent decades points to effectiveness changes in wastewater, industrial and agriculture management practices.

Scientists and policy makers need to communicate the drivers for nature conservation using approaches such as ecosystems services and natural capital.

Catherine Coxon, Trinity College Dublin and Caroline Wynne, EPA. Editors.

Hydrogeology Journal Special Issue on Hydrogeology and Human Health

Hydrogeology and Human Health

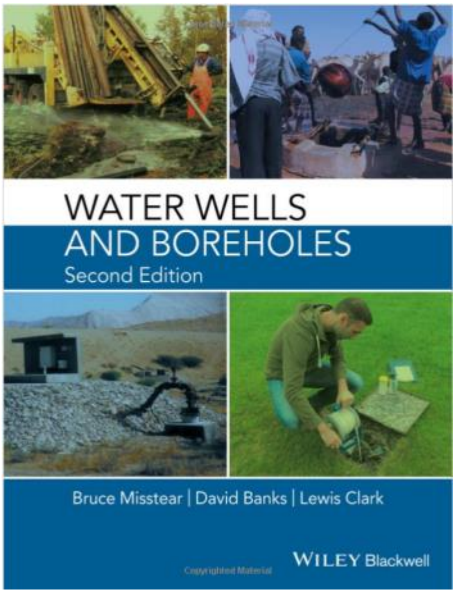
In the mid-1800s, Dr John Snow (1813-1858), an obstetrician and anaesthesiologist, theorised that cholera, a highly infectious gastrointestinal infection associated with extremely high rates of mortality, was caused by faecal contamination of water supplies (Donaldson & Donaldson, 2005). During the summer of 1854, a significant cholera outbreak occurred in the Soho district of London, resulting in the deaths of 616 people. As part of this first modern epidemiological investigation, Dr Snow noted that "within 250 yards of the spot where Cambridge Street joins Broad Street there were upwards of 500 fatal attacks of cholera in 10 days . . . suspected some contamination of the water of the much-frequented street-pump (a public well) in Broad Street." Snow subsequently developed what is now referred to as "The Ghost Map", a geographical grid indicating where and when cholera cases and associated mortalities occurred in relation to the public well (Hempel, 2013). Not only did the map confirm that almost all cases related to drinking water from the pump, but also that specific residential clusters were not associated with infection; for example, workers in an adjacent brewery did not contract the illness due to their daily allowance of beer. Later research discovered that the hand-dug well had been constructed just 0.9m from a defunct septic tank/cesspit (Johnson, 2006; Hempel, 2013). Thus, it might be said that the science of epidemiology, considered the cornerstone of public health and defined as "the study and analysis of the patterns, causes, and effects of health and disease conditions within specific populations" (Porta, 2014), has its very roots in hydrogeology and the subsurface.

This year's Hydrogeology Journal Special Issue on Hydrogeology and Human Health has been borne of myriad issues and pressures pertaining to global groundwater resources, some longstanding, and some more recently acknowledged. Among them, climate change, exponential population growth, increasing urbanisation, increasing food production and waste management requirements, and inconsistent regulation perhaps stand the tallest. Our groundwater resources have never been more valuable or necessary, nor have they been under such strain. Accordingly, the guest editors (Dr Paul Hynds, DIT; Dr Mark Borchardt, USDA, and Dr Motomu Ibaraki, OSU) have assembled a collection of papers which seeks to provide the reader, not only with a new perspective on the topic of medical geology, or as coined by Rehman (2009) "Geomedical Engineering", but also to solidify the role and importance of hydrogeology and hydrogeologists in global public health. This Special Issue is aimed at anyone with an interest in waterborne infection, groundwater contamination, or "hydro-epidemiology", from undergraduate students and new postgraduate researchers, right up to those with decades of experience. As such, the issue comprises 22 peer-reviewed papers from myriad countries, climactic regions, and hydrogeological settings, including contributions from Prof Beth Parker (Canada), Prof

News

Charles Gerba (USA), Dr Dan Lapworth (UK), and Prof Bjorn Klove (Finland). This year, the Special Issue has a distinctly Irish flavour, highlighting not only our high levels of groundwater reliance and vulnerability, but also our interests, expertise, and international standing in groundwater research. In all, four Irish institutions (DIT, UL, TCD, and QUB) are associated with three included articles. Thus, I would encourage all Irish IAH members and Groundwater Newsletter readers to keep an eye out for the Special Issue in early Summer. Paul Hynds, DIT, Editor.

Review of "Water Wells and Boreholes" by Bruce Misstear, David Banks Lewis Clarke (2nd edition)



I have a battered, mud spattered copy of the first edition. It accompanies me in the field and back into the office. I am still reading it and learning from it, even though I have been drilling boreholes and digging wells, for some time. It is the only book that I take everywhere.

Now, there is a new edition. I have been reading it for over a week. It is excellent, and even better than the original. The new content brings the book up to date and includes new material and new sections on, for example, new drilling methods, groundwater for heating and cooling and how to analyse non-ideal (i.e. for us in Ireland, often normal) pumping test data. There are new illustrations that enhance the text. It has been written with great clarity, and an easy, approachable style. The text is not stuffy and awkward. It is often inclusive; starting sentences with 'We', as if the authors and the reader are on a journey of discovery together. The text is also interspersed with very successful special text boxes containing examples, extra detail, background or ancillary information that add great interest. Though I know the first edition, I enjoyed discovering new ideas and information in the second edition. Did you know about the mysterious 'Noordbergum effect'? I had never heard of it; a situation where the water levels in an upper aquifer rose, when water was pumped out of a lower aquifer.

This book is important. There are now many books on hydrogeology and groundwater, but there are very few that deal with the most essential fundamental part of hydrogeology. Whether you work in the field, lab or office, you need to know how to get into the subsurface, and how to make observations and take measurements that enable an understanding of the characteristics of the groundwater flow and biochemical system in the rocks and soils.

There is no such thing as a standard borehole or well.

Each borehole or well should be designed and constructed on the basis of the conditions in the subsurface at the specific site and the specific purpose. Each borehole should be supervised and directed at the site by someone who knows what they are looking for and how to make the best of the conditions that they encounter in the subsurface.

This new edition is 'the book' that gives you the information on how to do this.

This book is more than a manual; it is an education. It is comprehensive. It enables the reader to understand the infinite variety of holes that can be constructed and used in different ways, in different countries, for different needs and conditions. Reading this book will also provide invaluable help for students, researchers, water quality sampling technicians, regulators, hydrogeologists and engineers who aren't directly involved in drilling and well digging. Boreholes are not just 'dots on maps'; each of equal value. This book provides an understanding that will enable these professionals and scientists to assess the integrity of an existing borehole as a data source, and the value and representative nature of the data obtained by others from a particular borehole.

Bruce, David and Lewis' book on Water Wells and Boreholes is the best book covering the most essential foundation of our science and profession. Everyone should have one, and read it (after 45 years doing this work, I am still learning; so that includes me).

David Ball , Hydrogeologist

Geothermal Association of Ireland conference, April 2017

The Geothermal Association of Ireland (GAI) hosted a one day conference in Dublin on the 7th of April 2017. The now annual event took place alongside the Sustainable Energy Authority of Ireland's Energy Show in the RDS. The event hosted a varied panel of speakers discussing a range of interesting geothermal and district heating projects from Ireland and across Europe.

Split into two sessions, the morning speakers discussed broad strategies and geothermal technologies utilised in the pursuit of sustainable energy. Strategies in the heating sector were explored by representatives from ESB, Dara Connolly and Brian Montayne, who highlighted the need to overcome barriers to low carbon solutions in the heating sector. Aoife Braiden of the GSI discussed the role of the Geological Survey as a funding agency for geothermal projects in Ireland at present and into the future. The role of geothermal technology in sustainable energy was then highlighted with three case study examples discussed by Bartomeu Casals of Tellus

Figure: Geothermal Association of Ireland committee members

Figure:The GAI conference took place alongside the Sustainable Energy Authority of Ireland's energy show at the RDS

Ignus, Jay Stuart of EcoCo and James McAteer of GeoServ.

The afternoon session explored the use of geothermal energy in large-scale heating schemes across Europe. David Simons of Geoop shared his experience of the growing deep geothermal heating sector in Denmark. Bas Godschalk of IF Technology showcased a gold standard of geothermal energy utilisation, storage and management with examples from the Netherlands. Closer to home, Liz Alston of Worcestershire County Council in the UK talked through their motivation in pursuing geothermal energy as an input heat source to their district heating plans, and Donna Gartland of Codema brought the talks to a close by discussing the potential for a 4th generation district heating scheme with geothermal input in Dublin.

This year's conference highlighted the potential impact geothermal technologies can have in the decarbonisation of the heat sector here in Ireland and across Europe. With the implementation of innovative strategies, and by utilising well-proven technologies currently in operation on number of successful projects across the globe, the GAI considers geothermal energy to have the potential to significantly contribute to Ireland's future energy needs.

For more information on the talks outlined above, geothermal energy or the GAI please visit geothermalassociation.ie or email info@geothermalassociation.ie.

Sarah Blake, GAI events officer

James McAteer, GAI secretary

Irish Group

IAH (Irish Group) 2015 Training course: Statistics for Hydrogeologists, January 2017

In recent years, the IAH group has organised short professional training courses for practicing hydrogeologists that are intended to aid them in their interpretation and communication of groundwater data. As part of this series a one-day course on 'Statistics for Hydrogeologists' was run in January 2016, and facilitated by the Geological Survey of Ireland. The aim of the course was to provide attendees with an overview of essential statistical inference techniques with demonstrated examples applicable to hydrological and groundwater problems.

The course was delivered by means of lectures from experts who actively use statistics in their professional work. The IAH were grateful to Dr Paul Hynds, from the Dublin Institute of Technology Health Institute, Dr Bidisha Gosh from the Trinity College Dublin Civil Engineering Department, Professor Michael Bruen from the University College Dublin Centre of Water Resources Research and Mr Tim Joyce from the Office of Public Works, who all delivered excellent lectures on their respective areas of expertise.

Topics covered included a session on the core concepts in statistics, such as data, distributions, and statistical hypotheses, extreme value distributions and time-series analysis, followed by a session on statistical applications, including examples on baseflow analysis, water quality risk modelling and climate change. The course was well received by the 30 IAH members in attendance.

Shane Regan, Education and Publicity Secretary

Irish Group

IAH (Irish Group) update

Barry Sexton - Secretary

Annual David Burdon Lecture

The IAH hosted the annual David Burdon lecture in the GSI on the 8th of March 2017. The lecture was delivered by Dr. Adrian Butler of the Imperial College London. The title of the lecture was "Medical Hydrogeology: lessons for groundwater and health from southeast Asia". The lecture focused on collaborative work completed by hydrogeologists working with epidemiologists in the Ganges-Brahmaputra Delta in Bangladesh. Dr Butler highlighted the links between medical conditions including hypertension and the increased salinity of shallow groundwater due to inundation of drinking water ponds caused by tidal surges and flooding in the delta. The lecture also highlighted the health impacts of elevated levels of naturally occurring arsenic in shallow groundwater well across the region. The lecture was well received and generated a lot of interest and debate amongst those in attendance.

IAH Extraordinary General Meeting (EGM)

The IAH are currently in the process of applying for charitable status from the Irish Charity Regulator. To comply with the requirements of the regulator we had to make a number of amendments to our constitution. These amendments related specifically to financial regulation measures and their enshrinement in our constitution. Under the existing constitution an EGM was required to make any amendment to it. The EGM was held on the 8th of March in the GSI following the Annual David Burdon Lecture.

The constitution had remained unchanged from its inception back in 1995. The constitution was composed by an IAH subcommittee comprised of David Ball, Catherine Coxon and Eugene Daly. David Ball was good enough to speak to the members on the night about the about the origin of the constitution and the difficult task they had set themselves in trying to distil it into one A4 page. The simplicity and succinctness of the original constitution was a testament to their efforts.

Following the brief history lesson from David a vote was held. The members in attendance voted unanimously to amend the constitution to allow the IAH application for charitable status to proceed.

The final application was submitted to the Regulator at the end of March and hopefully we will have achieved charitable status before the end of 2017.

IAH outreach opportunities – Promotion of Hydrogeology

The constitution of the Irish Group of the IAH has a number of aims or aspirations, which include:

- To represent members of the IAH (Irish Group) in the activities of IAH and in other international activities, as appropriate;
- To promote activities which further the science, technology and profession of hydrogeology;
- To further the continuing education of members in hydrogeology and related activities;
- To promote best practice in all aspects of hydrogeology;
- To promote public awareness of the role and value of hydrogeologist and hydrogeology in society; and

Have your say on IAH outreach opportunities!

Figures: Hydrogeological outreach. From the top: Irish Group 2016 fieldtrip Mullenmore spring (photo source @IAH_Ireland); IAH Irish Group conference 2017 ECHN panel discussion (photo source: @GsiGroundwater); GSI groundwater 's Shane Carey explains groundwater model to minister Sean Kyne (photo source: @GsiGroundwater).

- To encourage contact and co-operation with other national and international groups concerned with hydrogeology.

We have been very good at implementing a number of these aims including promoting best practice in hydrogeology, representing members, continuing education of members and encouraging co-operation with other national and international groups.

Have your say on IAH outreach opportunities!

Figures: Hydrogeological outreach. iCRAG and GSI outreach event at Powerstown National School (photo source @alexrussell290).

One of the aspects that we may have been falling behind in is the ***promotion of public awareness of the role and value of hydrogeologist and hydrogeology in society***. We are hoping in 2017 and 2018 to try and get out into the public sphere and make the wider public more aware of what a hydrogeologist is, what we do and the links between the work we do and everyday life.

The IAH committee have been coming up some ideas on how to do this but we would love to open it out to the membership to see what kind of ideas you have. If you have any ideas about who to get us out there write them down and send them to me at secretary@iah-ireland.org

What we do is important and adds values to society so we should let everyone know.

Irish Group

IAH (Irish Group) 2017 conference

"Developments in Irish Hydrogeology in a Changing Water Services and Planning Environment"

Philip Schuler—conference secretary

The 37th annual IAH conference was dedicated to "Developments in Irish Hydrogeology in a Changing Water Services and Planning Environment". The aim of the conference was to highlight topics that are shaping and otherwise influencing the hydrogeological profession and community at current, and to engage with the technical and scientific challenges that are emerging from a changing water services environment. The main challenges of water resources management and the methods hydrogeologists can use to contribute towards problem-solving were grouped into five sessions, in addition to two keynote sessions: a) Towards Safe and Effective Groundwater Supply, b) Groundwater Hazards and Pathways, c) Early Career Hydrogeologists Network, d) Geo-Risks Related to Groundwater and e) Dissolved Organic Carbon and Trihalomethanes.

A wide range of 24 national and international speakers from academia, industry, local and national public authorities shared their expertise among the very broad group in attendance over the two days. This year's keynotes were addressed by Donal Daly, Mike Packman and Dr. Attila Kovács.

Attila is a Senior Researcher at the Geological and Geophysical Institute of Hungary and at the Hungarian Academy of Sciences with 20 years of international experience in hydrogeology and groundwater modelling. Attila has developed novel hydrograph analytical techniques and clarified some fundamental aspects of the hydraulic functioning of karst and fractured hydrogeological systems.

Mike is the Chief Hydrogeologist at Southern Water, one of the UK's largest water utilities, where he has gained more than 42 years of experience. During this period, Mike has been responsible for providing on-the-job training, groundwater augmentation schemes, borehole design and rehabilitation and groundwater protection zone delineation and policy.

Donal is the manager of the Catchment Science & Management Unit of the Environmental Protection Agency (EPA). The role of this Unit is to lead and facilitate the EPA's WFD implementation responsibilities in the areas of catchment characterisation, reviewing the impact of human activities, designing management strategies and inputting to the River Basin Management Plan.

Donal and Mike set the stage for the first day, firstly by reflecting on the individuum in a socio-economic context and resulting responsibilities for sustainable and integrated catchment-based water management, and secondly, by presenting the role that hydrogeology plays in a modern water utility that covers 80% of the demand by groundwater resources in the Southern Water area.

The first session, "Towards Safe and Effective Groundwater Supply", examined the potential role of groundwater in Irish national water planning within Irish Water; clarification of groundwater source protection terminology and usage; the relevance on groundwater for public water supply in County Laois; and the energy-efficient design of water wells through optimization of well hydraulics. This talk was presented by the international guest Georg Houben from the Federal Institute for Geosciences and Natural Resources (BGR), Germany.

Following on from this, the "Groundwater Hazards and Pathways" session focused on nutrient and contaminant transport processes

and pathways - on the catchment scale, in single aquifers as well as at point sources; the latter being exemplified by the case study of the Avoca mine site. The perspectives of Co. Meath local authority on discharges to groundwater and implementing guidance on its authorization completed the session.

Within the Early Career Hydrogeologists Network (ECHN) session national research on groundwater recharge in the framework of the Irish Centre for Research in Applied Geosciences (iCRAG) was presented along with results of a GSI dye-tracing study in Co. Roscommon. Also, the very relevant and important subject was raised of how the hydrogeological profession can bridge the gap between science and society in general and in particular between science and secondary schools students. Attendees were delighted to hear a presentation by one of the founders and main contributors of the ECHN: the international guest Viviana Re from the University of Pavia, Italy.

The last session of the first day was completed by 3 minute long poster presentations of the ECHN, as well as the presentation of the winner of the competition for the best hydrogeological Conceptual Site Model (CSM) - Janka Nitsche (RPS Aquaterra). The competition, run for the first time, was initiated by Gerry Baker in conjunction with the Geological Survey Ireland and the IAH Irish Group.

Day two began begin with the keynote speaker Attila Kovács providing a historical and geo-chemical look at the impact of regional dewatering of a karst region in Hungary between 1960 and 1990 followed by today's re-emergence of karst springs. As water levels continue to rise, they are expected to reach an equilibrium in the near future, posing major challenges to existing infrastructure.

The "Geo-Risks Related to Groundwater" session discussed questions such as: what innovative methods, e.g. Interferometric synthetic aperture radar (InSAR), are available to detect geo-risks; how do we assess them, and what will it mean to society? The session covered topics such as groundwater flooding, karstification, land-subsidence and, for example, high concentrations of arsenic which are factors that impose challenges to humans and how they shape and use the environment. The international guest Alessandro Novellino from the British Geological Survey (BGS) provided technical insights into the potential of remote sensing related to geo-risks.

The "Dissolved Organic Carbon and Trihalomethanes" session elaborated on factors affecting the formation of trihalomethanes, the role of a properly completed borehole in achieving stable natural organic matter contents, and exemplified the strategic role of groundwater as opposed to surface water in order to reduce treatment efforts by Irish Water. An overview on the impacts of DOC on human health, research gaps and recommendations for future research completed the final oral session of the conference.

This year's workshop demonstrated the use of telemetric data transmission for participants, highlighted by the Office of Public Works (OPW) and the EPA.

Interest in the conference was good this year with >150 attendees over the two days and 17 exhibitors, to whom all the committee of the IAH is deeply thankful, as they all contributed to making the conference once more, a very lively and truly respectful place of exchange.

The committee of the Irish group of the IAH wishes to thank all the speakers, sponsors, members and friends of the IAH for their continuing support of the organization which will hopefully continue into the future. The committee is already looking forward to the IAH field trip that will take place in October 2017 – details to follow.

IAH: News on the international front

Bruce Misstear—Secretary General, IAH

Below you will find some information about this year's IAH congress in Croatia, IAH's latest Strategic Overview paper, the results of the 2016 Council Elections, and the appointment of a new Executive Manager.

Groundwater
Heritage&Sustainability

44th IAH Congress, Dubrovnik Croatia, 25th to 29th September 2017

Following a very successful congress in Montpellier last September, during which we celebrated the 60th anniversary of IAH, attention now turns to this year's congress which will be held in Dubrovnik in late September. As many readers will know Dubrovnik is a very beautiful city (and a UNESCO world heritage site). The congress venue is the Dubrovnik Palace hotel, which enjoys stunning views over Lapad bay (I sound like an estate agent here – but it is a lovely location). It is only 4 or 5 km from the old city, and there is a regular bus service. Tamara Marković and her colleagues are busy making the final preparations for the congress, and we hope that there will be many delegates from Ireland. As is the norm with IAH congresses, there will be a wide range of technical sessions on offer. However, Dubrovnik is in a major karst area and so karst hydrogeology is likely to feature prominently in both the talks and in the mid-week congress excursions. Details of the congress, including how to register, can be found at: http://iah2017.org/.

From top: Dubrovnik old town; View over Lapad bay from congress hotel; and congress venue on Lapad peninsula.

Obla spring (one of the mid-week excursion sites)

Strategic Overview Papers

Our publication of Strategic Overview papers has continued with "The UN-SDGs for 2030: Essential Indicators for Groundwater." The Sustainable Development Goals will influence international water development actions during the next decade, yet they make very little reference to groundwater. This paper seeks to explain to stakeholders the importance of groundwater in meeting the SDGs, and provides guidance on the complexities involved in groundwater monitoring. This and other strategic overview papers are available for download at https://iah.org/knowledge/learning-resources.

International Association of Hydrogeologists

THE UN-SDGs for 2030
ESSENTIAL INDICATORS FOR GROUNDWATER

KEY MESSAGES

- groundwater is a key resource for the achievement of the UN Sustainable Development Agenda for 2030 — but is still weakly conceptualised in the SDG Indicators
- there is a strong case for defining new 'groundwater resource status indicators' for SDG Targets 6.3, 6.4 and 6.6, because groundwater resources are integral to these but not dealt with adequately at present
- there is urgent need to strengthen current data collection protocols to focus more clearly on the level, types and modes of groundwater use for municipal water-supply and direct drinking water-supply
- professional appraisals of 'source design and integrity' will be a critical for assessing the achievement of SDG Target 6.1, given constraints on field monitoring
- professional assessment of groundwater status, trends and risks will be required to interpret the condition of the resource base, whose sustainability is essential for achievement of SDG-6 Targets

How do groundwater resources underpin the UN Sustainable Development Agenda for 2030?

Since earliest times humankind has met much of its needs for good quality water from subterranean sources. During the 20th century there was an enormous boom in waterwell construction for urban water-supply, agricultural irrigation and industrial processing – facilitated by advances in well drilling, pump technology and geological knowledge – and groundwater became a key resource supporting human well-being and economic development.

Comprehensive statistics on groundwater abstraction are not available, but global withdrawals are estimated to have passed 900 km³/a in 2010, providing some 36% of potable water-supply, 42% of water for irrigated agriculture and 24% of direct industrial water-supply[1], with proportions varying widely from country to country and across larger countries. Moreover, groundwater is also often the only option for meeting rural water-supply needs.

The social value of groundwater should not be gauged solely by volumetric use, since it brings major economic benefits per unit volume, because of local availability, scaling to demand, high drought reliability and generally good quality (requiring minimal treatment). The dependence of many cities and innumerable medium-sized towns on

[1]Döll et al. 2012 : Journal Geodynamics 59-60

This Series is designed both to inform professionals in other sectors of key interactions with groundwater resources and hydrogeological science, and to guide IAH members in their outreach to related sectors.

Front cover of the UN-SDG for 2030 essential indicators for groundwater. Available from https://iah.org/knowledge/learning-resources

Election of New IAH Council

A new Council was elected in September 2016 and will serve until 2020. Full details can be found at https://iah.org/about/council. Antonio Chambel from Portugal has taken over as President from Ken Howard, and I have succeeded Shammy Puri as Secretary General. The new Vice President for Finance and Membership is Teodora Szocs from Hungary, whilst Dave Kreamer from USA has been elected Vice President Science and Programme.

Appointment of New Executive Manager

After nine years of excellent service to the Association, John Chilton has decided to retire as Executive Manager. His replacement is Ian Davey: Ian is a hydrogeologist with over 30 years' experience of working for the Environment Agency in England. In recent years, this has included project management and advisory work outside of UK (including Poland, Bulgaria and Turkey). We wish him well in his new (part-time) role as Executive Manager of IAH.

And finally…….

You can find out more about IAH activities on the main IAH website at https://iah.org/. This includes details of how to join the Association. The full annual membership fee is €83 if you wish to receive a paper copy of Hydrogeology Journal as part of your membership, or €73 if you receive the journal online. Students can join for as little as €19 (with the online journal option).

Previous issues available at www.gsi.ie

The contributors are responsible for the content of the material in this Newsletter. The views expressed are not necessarily those of the Geological Survey of Ireland.

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If you are involved in an event which you would like to be advertised in the groundwater newsletter please email details to groundwaternewsletter@gsi.ie

Upcoming Events

2017

26 May 2017	**GSI lunchtime webinar series** - GSI lecture theatre 12-1:45pm Midwest geosciences webinar - Allen Shapiro, USGS "Interpreting Aquifer Testing in Fractured Rocks"
5-7 Jun 2017	**IAH Fractured rock conference** GwFR17 - Chaves, Portugal https://portugal.iah.org/gwfr2017
13 Jun 2017	**Geothermal Association of Ireland (GAI)** - GSI lecture theatre 5:30pm David McNamara, NUIG "Geothermal energy in New Zealand" @geothermalassoc for further information
19-23 Jun 2017	**25th International Karstological School** "Classical karst" - Postojna, Slovenia http://iks.zrc-sazu.si/en/
21-22 Jun 2017	**EPA national water event** "Ireland's water future" - Galway Bay hotel http://www.epa.ie/newsandevents/events/
28 Jun 2017	**GeolSoc lecture** - GeolSoc, London - Dr Anthony Cooper, "Sinkholes – collapsing houses, Alice in Wonderland and witches" https://www.geolsoc.org.uk/Sinkholes17
TBC Sep 2017	**Geothermal Association of Ireland (GAI)** programme of regular lectures @geothermalassoc for further information
1-2 Sep 2017	**Early Career Hydrogeologists conference**, 2017 - University of Strathclyde Contact echc2017-conf@strath.ac.uk for more information
19-21 Sep 2017	**National Ploughing Championships** - Screggan, Offaly http://www.npa.ie/
25-27 Sep 2017	**IAH congress** - Groundwater heritage and sustainability -Dubrovnik, Croatia http://iah2017.org/
TBC Oct 2017	**IAH Irish Group** programme of monthly **Technical Discussion Meetings** www.iah-ireland.org or @iah_ireland for further information Email tdm@iah-ireland.org to be added to TDM mailing list
TBC Oct 2017	**IAH Irish group** fieldtrip Contact Robbie Meehan fieldtrip@iah-ireland.org for more information
25 Oct 2017	**IAH British chapter Ineson lecture** - GeolSoc, London Callist Tindimugaya, Ministry of Water, Uganda "Africa, groundwater and the sustainable development goals" www.iah-british.org for more information
TBC Nov 2017	**National hydrology conference**

2018

3-7 Jul 2018	**geoENV** - geostatistical methods in environmental applications - QUB Belfast See https://geoenvia.org/ for more details

The editors welcome feedback on the contents of the newsletter, as well as suggestions for contributions to the next issue.

Please contact: Groundwaternewsletter@gsi.ie

Contributions for the next issue should arrive before **1 Oct 2017.**