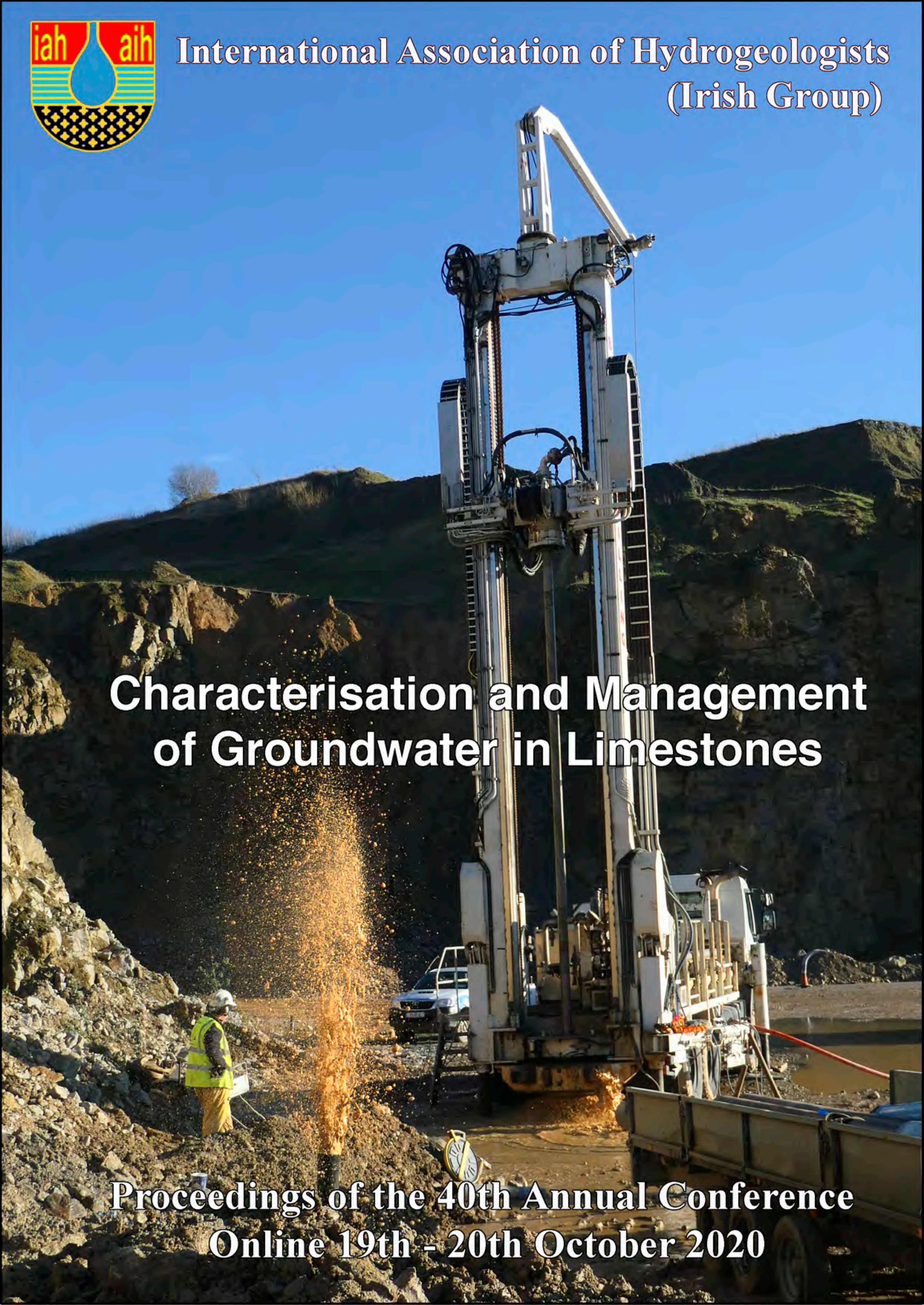

International Association of Hydrogeologists
(Irish Group)

Characterisation and Management of Groundwater in Limestones

Proceedings of the 40th Annual Conference
Online 19th - 20th October 2020

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(IRISH GROUP)

Presents

Characterisation and Management of Groundwater in Limestones

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INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS (IRISH GROUP)

Introduction

Founded in January 1976, the IAH-Irish Group has grown from 10 members to over 150 in 2018 and draws individuals from professional backgrounds ranging from academic to state agencies to private consultancies. The IAH committee consists of: President, Secretary, Treasurer, Burdon Secretary, Northern Region Secretary, Fieldtrip Secretary, Education & Publicity Secretary, Conference Secretary, plus a conference sub-committee.

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

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

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

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

2020 IAH (Irish Group) Conference "**Characterisation and Management of Groundwater in Limestones"**

Firstly, on behalf of the organising committee, I would like to welcome you all to the 40th annual IAH Irish Group Conference. Thank you for your continued support and involvement in the activities of the IAH Irish Chapter.

Due to the Covid-19 pandemic restrictions, we were unable to hold the conference as originally planned in Tullamore in April 2020. As it became clear that holding an in-person event was not going to be possible, we decided to move to the online world, and so, for the first time, the annual conference is being held virtually over two half-days in October 2020. As it's an online event, which, in general are more tiring to attend and where attention spans tend to be shorter, we decided to reduce the number of talks to fit a programme into two half-days and postpone the workshop and student presentations. For the same reasons, keynote talks have been dropped, and all presentations are the same length. We are maintaining audience interaction by scheduling live Q&A sessions with the speakers after each set of talks. Questions can be submitted by attendees through the video conferencing software (Zoom). Following the conference, we will be sending out a survey to all registrants and we would be keen to hear your thoughts or recommendations on improving the online experience, as, depending on the situation with the pandemic, we may be hosting the conference online in 2021.

When the conference sub-committee sat down to consider ideas for the 2020 conference, we had a number of overarching objectives which we wanted to meet: the conference should be relevant and interesting to members in their professional work; that attendees would have the opportunity to learn something from the conference; and that the conference would be representative of the groundwater community.

With these objectives in mind, we decided on the theme of "Characterisation and Management of Groundwater in Limestones". Limestones are the dominant rock type in Ireland, comprising about 50% of the island. The focus of the conference this year is not only on the pure limestones (which are usually associated with karstification), but also the impure limestones (such as the "Calp"). Given its prominence in the Irish landscape, limestone interacts with all aspects of hydrogeology. The conference sessions aim to provide insights into these important interactions such as those involving water resources management, contamination, ecology and surface water, as well as practical characterisation and investigation techniques in limestone.

The first session is an overview of Irish limestone aquifers and their natural capital. The first presentation will be given by Taly Hunter-Williams. Taly is a senior hydrogeologist at the Geological Survey Ireland (GSI) and she will draw from her significant experience to give insights on the occurrence, nature and characteristics of Irish limestones. Coran Kelly of Tobin Consulting Engineers will then introduce the Irish Aquifer Properties Manual in the context of limestone aquifers, followed by Catherine Farrell of Trinity College Dublin (TCD) who will speak on limestone's contribution to Ireland's natural capital.

The theme of the second session is regional groundwater management. Paul Wilson of the Geological Survey of Northern Ireland (GSNI) will present on the Cretaceous and Carboniferous Limestone Aquifers of Northern Ireland, followed by Robbie Meehan presenting the GSI's recent work on evaluating regional groundwater resources in the Boyne catchment, with a focus on limestones. Janka Nitsche from the Environmental Protection Agency (EPA) will give a regulator's perspective on the assessment of abstractions. Deirdre Larkin (Atkins) will close out this session, and Day 1, with a talk on developing a hydrogeological conceptual model in karst limestone for an urban expansion area in East Cork.

Half-day number two kicks off with a session on management and protection of water resources, firstly with two talks from the perspective of the water supply sector. Miriam Grant from Irish Water will present on Irish Water's new National Water Resources Plan and, Barry Dean (National Federation of Group Water Schemes, NFGWS) will speak about the NFGWS's recently published Framework for Drinking Water Source Protection. These talks will be followed by a presentation on the suitability of using the Water Framework Directive (WFD) status assessment results in water management by Philip Maher (EPA).

Session four explores the characterisation and investigation of Irish limestones. The first talk, by David Ball, will discuss common drilling problems from his vast practical knowledge and experience. Peter O'Connor (APEX Geophysics Ltd.) will present an interesting array of geophysical case studies across the Irish Carboniferous. This will be followed by a talk from Maurice Ryan (Byrne Looby) who looks at the Calp through geotechnical work in basement construction, and the final talk is from Sean Needham of Geosyntec on characterisation and remediation of a chlorinated hydrocarbon in fractured limestone.

We hope you find the conference an inclusive, educational and inspiring experience, and, again, the organising committee wishes to express their sincerest gratitude to all of those attending this year's and previous year's conferences, particularly the speakers, exhibitors and sponsors.

Philip Maher
IAH (Irish Group)
Conference Secretary

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The IAH (Irish Group) would also like to acknowledge the support of the following members and organisations whose staff have worked on the committee of the IAH-Irish Group throughout the year and helped to organise the conference:

Donal Daly

TOBIN CONSULTING ENGINEERS

STREAM BIOENERGY

Sonja Masterson

OCSC O'CONNOR | SUTTON | CRONIN Multidisciplinary Consulting Engineers

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Department of Communications, Climate Action & Environment

GDG GAVIN & DOHERTY GEOSOLUTIONS

‘Characterisation and Management of Groundwater in Limestones’

International Association of Hydrogeologists – Irish Group
40th Annual Groundwater Conference – Online Event
Monday 19th October – Tuesday 20th October 2020

Programme Day 1, Monday 19th October

13.20	*Conference Login Open*
SESSION I:	**Irish Limestone Aquifers and their Natural Capital**
13:30	Welcome & Introduction - Philip Maher (EPA), Conference Secretary, IAH (Irish Group)
13:40	**Taly Hunter-Williams** (GSI): *Irish Limestone Aquifers*
14:00	**Coran Kelly** (Tobin Consulting Engineers): *An Introduction to the Irish Aquifer Properties Manual*
14:20	**Catherine Farrell** (TCD): *The Contribution of Limestones in Ireland to our Natural Capital*
14:40	Q&A
15:00	Break

SESSION II: Regional Groundwater Management

15:15	Introduction – Orla Murphy (Arup)
15:20	**Paul Wilson** (GSNI): *Conceptual models for Northern Ireland's Cretaceous and Carboniferous Limestone Aquifers*
15:40	**Robbie Meehan** (Consultant, GSI): *GSI’s Regional Assessments of Groundwater Resources: A Case Study from the Boyne Catchment, with a Focus on Limestones*
16:00	**Janka Nitsche** (EPA): *Are Abstractions Significant Pressures on our Water Resources?*
16:20	**Deirdre Larkin** (Atkins): *Development of a Hydrogeological Conceptual Model for the Water Rock Urban Expansion Area in East Cork*
16:40	Q & A
17:00	**End of Day 1**

Characterisation and Management of Groundwater in Limestones'

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Programme Day 2, Tuesday 20th October

09:20 *Conference Login Open*

SESSION III: Management and Protection of Water Resources

09:30 Introduction – Paul Wilson (GSNI)

09:35 **Miriam Grant** (Irish Water): *National Water Resources Plan – The Future of Our Water Supplies*

09:55 **Barry Deane** (NFGWS): *A Framework for Drinking Water Source Protection*

10:15 **Philip Maher** (EPA): *WFD Groundwater Status: The Whole Truth and Nothing but the Truth?*

10:35 Q&A

10:50 Break

SESSION IV: Characterisation and Investigation of Irish Limestones

11:05 Introduction – Janka Nitsche (EPA)

11:10 **David Ball** (Consultant): *Practical Issues when Drilling Boreholes in Irish Limestones*

11:30 **Peter O'Connor** (APEX Geophysics Ltd.): *Hidden Limestone Landscapes – Geophysical Surveys across the Irish Carboniferous*

11:50 **Maurice Ryan** (Byrne Looby): *Basement Construction in Dublin and Interaction with the Underlying Calp Limestone*

12:10 **Sean Needham** (Geosyntec): *Characterisation of a TCE Source Area in Fractured Limestone to Improve the CSM and Development of an Appropriate Remedial Strategy*

12:30 Q & A

12:50 Closing Address – Niamh Rogan (EPA), Secretary, IAH (Irish Group)

13:00 End of conference

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SESSION I

IRISH LIMESTONE AQUIFERS

Natalya Hunter Williams, Caoimhe Hickey

Geological Survey Ireland, Beggars Bush, Haddington Road, Dublin D04 K7X4

ABSTRACT

Limestone or carbonate-rich bedrock aquifers underlie a significant proportion of the island of Ireland. They provide an important source of drinking water for public and group scheme supplies, as well as private, industrial and agricultural users. Groundwater emerging from limestones provides important environmental supports to rivers, lakes and terrestrial ecosystems.

The carbonate rock units are predominantly Carboniferous-age, although there are small occurrences of Precambrian marbles and Lower Palaeozoic limestones, and the Cretaceous chalk. Due to their long geological history, Carboniferous and older limestones have negligible primary porosity, with porosity and permeability being due to the presence of fractures and/or solutionally-enlarged fissures. Additionally, in parts of the Midlands, dolomitisation has taken place, resulting in the formation of secondary intergranular porosity in the limestones that otherwise have only secondary fissure porosity.

The purity of a limestone has a strong influence on the degree of karstification. Within Ireland, approximately half of the limestone bedrock is impure or shaley, whilst the remainder is pure. This results in some limestone or carbonate-rich aquifers being dominated by fracture flow, whilst others are dominated by groundwater flow through solutionally-enlarged karst conduits. Tectonic events have influenced both the distribution of different types of limestone, and also the amount of fracturing and fissuring. This, along with lithology, influences permeability. Karstification has taken place at different times via uplift and exposure or global low sea-level stands. Lithology, sedimentary structure, dolomitisation, karstification and tectonic history combine to determine the groundwater flow regime, porosity, permeability, transmissivity and yield characteristics.

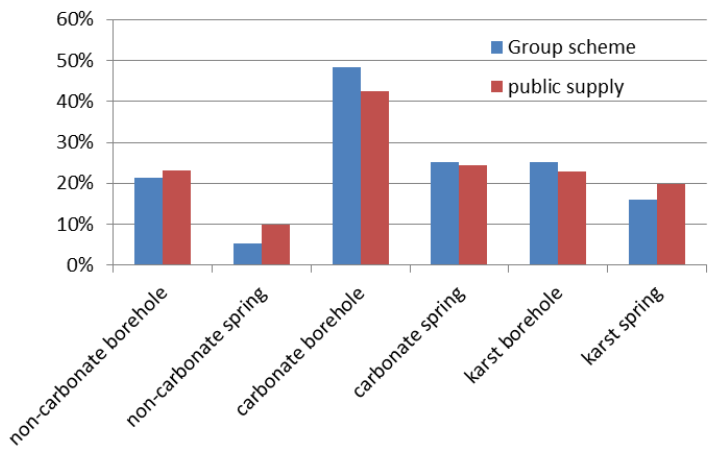
1. INTRODUCTION

Limestones are very widespread in Ireland and carbonate rocks underlie approximately 40% of the island of Ireland and 45% of the Republic of Ireland – about 31,000 km^2. By far the most widespread carbonate rock is Carboniferous-age limestone.

The majority of Ireland's regionally important aquifers are in limestones, and they are an important source of groundwater for drinking and other purposes (**Figure 1**). Large springs occur and significant borehole yields can be obtained from them. On the other hand, some of the impure limestone aquifers are poorly productive, capable of providing yields to meet small town or even only domestic supplies. Some limestone aquifers, particularly the karstified ones, also have important environmental functions, such as providing baseflow to rivers, and groundwater flow support to ecosystems such as turloughs or petrifying springs.

This paper aims to provide an overview of the limestone aquifers in Ireland. It focuses on the limestones in the Republic, but touches on the limestones in Northern Ireland. The information in this paper is derived from the book, "The Karst of Ireland" (Drew, 2018), and from the GSI's "Aquifer

Classification for the Republic of Ireland" (in draft), and also draws on material from the GSI publication "Understanding Earth Processes, Rocks and the Geological History of Ireland" (Sleeman *et al.*, 2004).



Karst is subset of carbonate aquifers.

Figure 1: proportion of group and public supply schemes that are supplied from carbonate aquifers via borehole or spring.

The total volume abstracted by GWSs is approximately 39,500 m^3/d, with total daily public supply abstraction almost an order of magnitude greater at about 366,500 m^3/d. Combined, this is about 21% of total volume abstracted from lakes, reservoirs and rivers by group and public supply schemes (1.9 Mm^3/d). Data from EPA

2. OCCURRENCE AND TYPES OF IRISH LIMESTONES

2.1 DISTRIBUTION OF LIMESTONES IN IRELAND

Carboniferous limestone outcrops in all the counties of the Republic of Ireland with the exception of County Wicklow. In Northern Ireland, the Carboniferous Limestones are mainly found in Counties Fermanagh, Tyrone and Armagh. A notable limestone unit in Northern Ireland is the Cretaceous Ulster White Limestone (chalk), which is only found in a few tiny inliers in the rest of the island. Carbonate rocks are also found in: Ordovician and Silurian strata in the east, northeast and west of Ireland; and in Dalradian rocks in Connemara, in northwest County Mayo, and Counties Donegal, Derry, Tyrone and Antrim (**Figure 2**).

Carboniferous limestones typically occupy lower-lying ground across much of midlands and south. However limestones form plateaux karsts in County Clare (the Burren) and in Sligo, Leitrim, Cavan and Fermanagh (the latter of which hosts the Marble Arch caves), where they have recently been exposed from under a protective cap of sandstones and shales.

2.2 ORIGIN AND CHARACTER OF LIMESTONES IN IRELAND

Carboniferous limestones are the most widespread carbonates in Ireland. They started life as sediments deposited after a northwards marine transgression of the arid 'Old Red Sandstone' landscape. The early Carboniferous sea covered most of Ireland south of a line from Galway City through Sligo to Belfast. This was a time of global rising sea-level. The central plain at this time was part of a broad shallow-water shelf sea where mainly muddy limestones formed. Later on this broad area of limestone deposition was broken up by tectonic movements into shallow shelf areas and deep-water basinal areas (**Figure 3**). This temporal and spatial variation has resulted in different types of limestone found in different parts of modern-day Ireland.

2.3 ROCK UNIT GROUP COMPOSITION AND OCCURRENCE

As a result of the varying depositional environments in which carbonate sediments were laid down, there are a variety of types of limestone, which are distinguished by their sedimentary structure (bedded or unbedded), their composition or lithology (pure limestones, or shaley or sandy limestones, or calcareous shales), their grain size and grain type (fine- or coarse-grained, lime pellets or shell fragments), the type and nature of fossils, colour, plus other factors. There are hundreds of different limestone and carbonate formations and members identified across Ireland. The Carboniferous rocks have therefore been simplified to eight Rock Unit Groups (RUGs) that are hydrogeologically significant (WGGW, 2005), which are shown on **Figure 2**. There are additional Rock Unit Groups for the Cretaceous chalk and the Precambrian marbles. Ordovician and Silurian limestones are incorporated in the respective Silurian or Ordovician Metasediments RUGs (there are 30 RUGs in the island of Ireland).

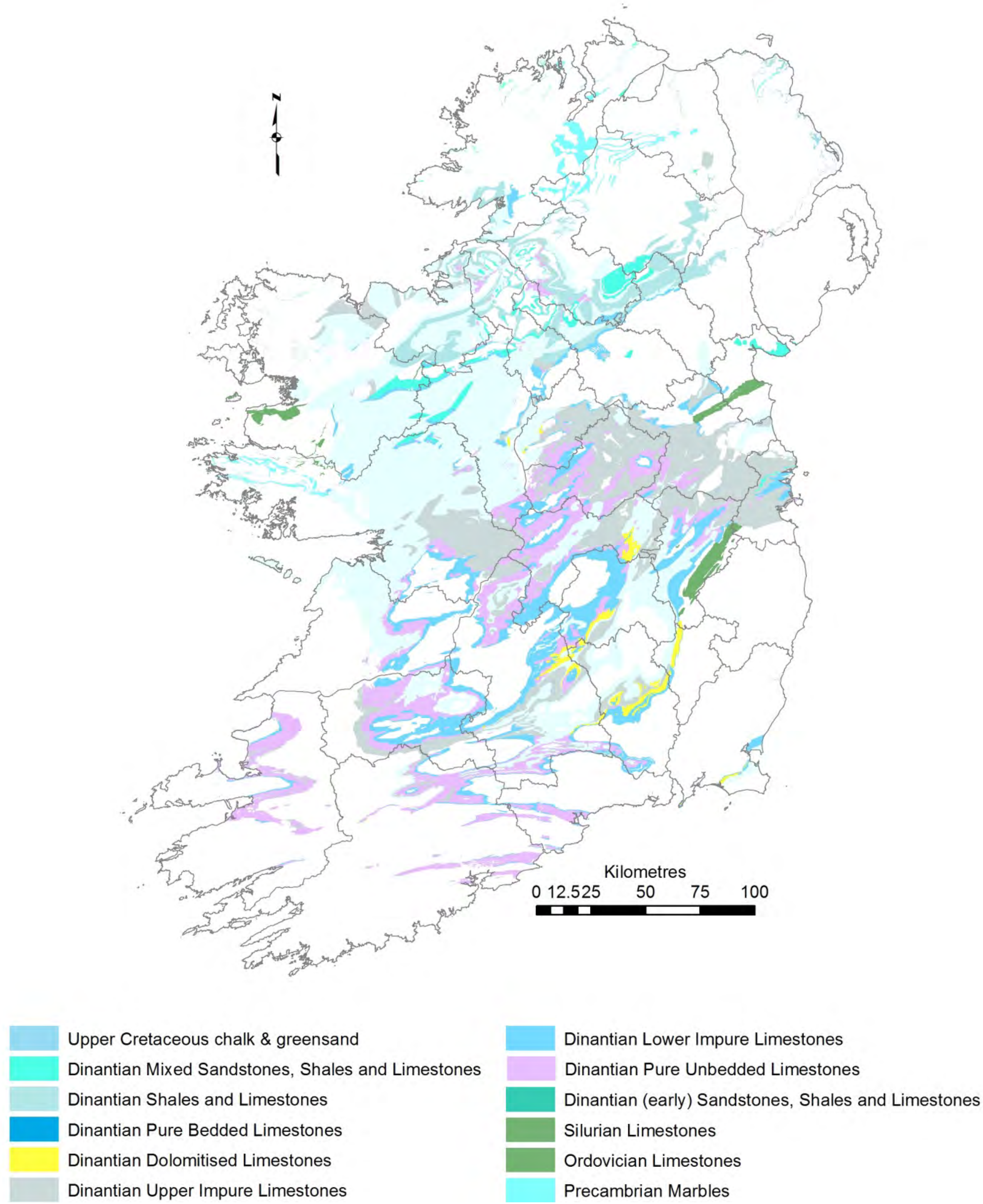


Figure 2: the distribution of carbonate rocks in Ireland (distribution based on all-island Rock Unit Groups map)

The earliest Carboniferous carbonate rocks were a mixture of sandstone, shale and limestone deposited in a restricted shallow marine environment. In most places, they are called the "Lower Limestone Shales". They form the Dinantian (early) Sandstones, Shales and Limestones RUG.

In most part of Ireland, this relatively thin RUG is succeeded by still shaley, but not sandy, limestones known as the "Ballysteen Limestones", which were formed in deepening seas that were still close to shore and the influx of sediments from land. This Rock Unit Group is called the Dinantian Lower Impure Limestones.

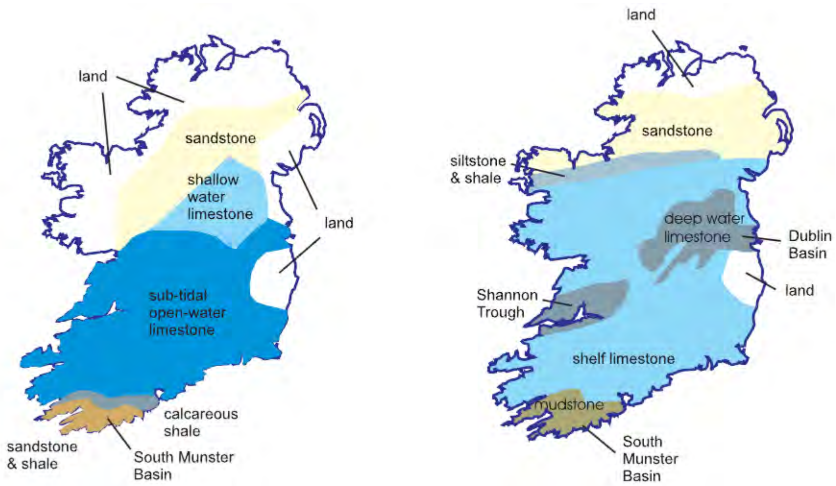
As the sea deepened further and the shoreline receded northwards, large steep-sided mounds of fine-grained limestone accumulated. The area around the Shannon Estuary has the thickest development of these "Waulsortian" limestones anywhere in the world. The mounds in Ireland have mostly coalesced to form a continuous sheet of limestone, which can be traced from Cork northwards through the Shannon Estuary to the north midlands (**Figure 2**). Apart from the planes between mounds, the Waulsortian limestones are pure and unbedded ('massive'). They comprise the Dinantian Pure Unbedded Limestones.

Figure 3:

(left) palaeo-geography in early Carboniferous Limestone times (c. 350 mya);

(right) later Carboniferous Limestone times (c. 330 mya).

From: Sleeman *et al.* (2004)



Relatively pure pale to medium-grey coarse-grained limestones dominated the shelf areas across a wide part of Ireland (**Figure 3, right**). The thickly-bedded "Burren Limestones" in north County Clare originated in this depositional environment. The many formations of this type form the Dinantian Pure Bedded RUG.

The basins between the shelf areas, on the other hand, contained very dark-grey fine-grained muddy limestones with interbedded calcareous mudstones. The slabby, dark and fractured "Calp" seen in the road cuttings along the M4 and around Dublin is the result of this interaction between earth movements and sediment deposition. Bedrock units of this type belong to the Dinantian Upper Impure Limestones.

In the north midlands, there were thick accumulations of calcareous shales in a shallow sea, sometimes with evaporites (Dinantian Shales and Limestones, and Mixed Sandstones, Shales and Limestones RUGs). In other parts of what is now the north midlands, there were accumulations of pure limestones, both bedded and mudbank mounds.

The older Precambrian and Lower Palaeozoic age limestones and carbonates are diverse, and are limited in modern-day occurrence. The Cretaceous-age Ulster White Limestone are chalks formed in a shallow warm sea hundreds of millions of years after the main Carboniferous period of limestone formation, and after a significant period of erosion, deposition of terrestrial sediments, and then another marine transgression.

3. FACTORS INFLUENCING AQUIFER PROPERTIES AND DISTRIBUTION

Cementation in all of the limestones has been extensive, with virtually no primary porosity remaining in the bedrock (the exception being the chalk in Antrim). Of main significance to the development of porosity and permeability in limestones are: the frequency of fracturing and the degree to which the fracturing is open to water movement; any widening of fissures and bedding planes from solutional processes (karstification) and any alteration processes that have occurred during burial (dolomitisation). The hydrogeological characteristics of the Carboniferous limestones are therefore related to a number of factors. The interaction of these factors influences the type and degree of porosity and permeability of the limestones.

Structural history: Deformation of the limestones has taken place since early after their deposition: faulting, which was an early result of Variscan tectonics, gave rise to the shelf and basin depositional settings described above. As the Variscan deformation from the south intensified, folds developed in the south of Ireland (the "Munster Synclines"), and large-scale E-W and N-S faulting of the rocks occurred.

The main factors influencing the development of fissure permeability are the intensity of the structural stress, the rock type, the depth of burial at the time of deformation, the orientation of stress and the bedding thickness. Current understanding of these factors and their influence on the regional distribution of fracture patterns is outlined in Dunphy (2003), Fitzsimons et al. (2005) and Moore and Walsh (2013). Moore and Walsh (2013) summarised the main post-Devonian fault and fracture systems controlling groundwater flow in Irish bedrock aquifers. The most important structures in terms of flow volumes are considered to be:

- N-NNW trending Variscan veins and NNW- and NE- trending Tertiary strike-slip faults. These structures are most susceptible to karstification because they are vertically persistent structures which are not clay-rich and are often dilational – they therefore often provide open pathways between the aquifer and near-ground surface.
- Normal faults, Variscan reverse faults, thrusts and ENE dextral strike-slip faults are barriers to flow where sealed and unaffected by solution. However, they can be significant conduits where karstified, particularly at intersections with other flow conduits, such as N-NNW veins and Tertiary strike-slip faults.
- Joints, which increase in frequency within shallow bedrock (< approximately 10 m depth), and can be more weathered and karstified, to provide highly transmissive zones.

Lithology: Limestone purity is the key factor which influences the solubility of the limestone which in turn influences the development of solutionally-enlarged fissures and conduits and the degree of karstification. Pure limestones are susceptible to karstification, whereas impure limestones are much less so.

The proportion of clays and their dissemination through the rock also influences the rock's response to deformation, with pure limestones tending to be more brittle than impure limestones. Brittle rocks fracture compared to more ductile shales undergoing the same amount of deformation. In addition, fractures in fine-grained rocks are often infilled by weathered material, reducing their ability to transmit groundwater.

The presence of chert layers or clay wayboards in pure limestones create barriers to (usually) vertical flow, and can impede flow or act as inception horizons (locations favouring localised inception of dissolution – i.e. location where karstification starts). Sulphide-rich shales can give rise to acidic conditions through oxidation processes, which can cause solution of the adjacent limestone.

Sedimentary structure: The presence of bedding planes provides a potential groundwater flow pathway – particularly if the bedding parting has been opened by structural deformation, and possibly become solutionally-enlarged. When deformed, thinner beds have more frequent joints than thicker beds of the same lithology, thus creating more fracture flow pathways.

Dolomitisation: The process of dolomitisation increases the porosity and permeability of the rock as the crystal lattice of dolomite occupies about 13% less space than that of calcite (Freeze and Cherry, 1979). Dolomitised rocks are usually highly weathered, 'sandy', with significant void space and poor core recovery. Dolomitisation is often very localised, occurring at large fault zones and more commonly in purer limestones.

Karstification: The process by which soluble rocks undergo solutional processes by water that is acidic due to its dissolved CO_2 content (in the case of limestones) percolating or flowing through the fissures in the bedrock, for example veins, faults, joints, bedding planes, or stylolites. This process progressively and preferentially enlarges some of the cracks and openings in the bedrock, and an underground drainage system starts to develop. The consequent development of secondary porosity and permeability in the limestone depends on the maturity of the karst system and the degree to which it has concentrated and localised groundwater flow, as well as the above factors such as limestone purity and the nature and spatial distribution of the fissures.

There are examples of ancient karst within Ordovician limestones at Portrane in Co. Dublin. Very early karstification taking place in Carboniferous shelf limestones in response to sea level drops is evidenced by karstified limestone surfaces that were later covered by soil. The fossil soil horizons are now represented by distinctive clay horizons called clay wayboards. Sometimes small rootlets can be seen penetrating down into the underlying limestone.

Karstification may have been widespread during the Neogene and Palaeogene, and particularly in the Holocene, but the extent to which it is still active varies, with some conduits being blocked or inactive. Karstification has taken place episodically in the Quaternary period in non-glacial periods, and forms a large part of the modern-day active karst.

4. GROUNDWATER FLOW SYSTEM DEVELOPMENT AND CHARACTER, AQUIFER CLASSIFICATION AND DEVELOPMENT POTENTIAL

Other factors being equal, pure limestones will have higher fissure permeabilities than impure limestones. Impure limestones will generally have negligible or only very localised karstification, and therefore behave as a fractured bedrock aquifer. Pure limestones are susceptible to karstification, but the degree of primary fractures and bedding planes, and degree to which karstification has taken place are important. Overall, the relevant issue according to Drew (2018) is 'to what extent does the aquifer system behave karstically rather than as a fractured rock aquifer?' Further is how mature and flow-focussed is karstification, if it exists.

Lithology, the type and degree of structural deformation and karstification, plus other factors such as the presence of large springs, consistent or variable large borehole yields, and productivity (Wright, 2000) and transmissivity are used to determine the aquifer category of a particular volume of rock (GSI, 2006). The Irish bedrock aquifer map for carbonates is shown in **Figure 4**.

The characteristics and development potential of selected regions are described below. This is a generalised description, and for reasons of space and doesn't capture all of the variations. Readers are referred to Drew (2018), Kelly *et al*. (this proceedings and 2015), the GSI bedrock aquifer map and the forthcoming Aquifer Classification of Ireland report.

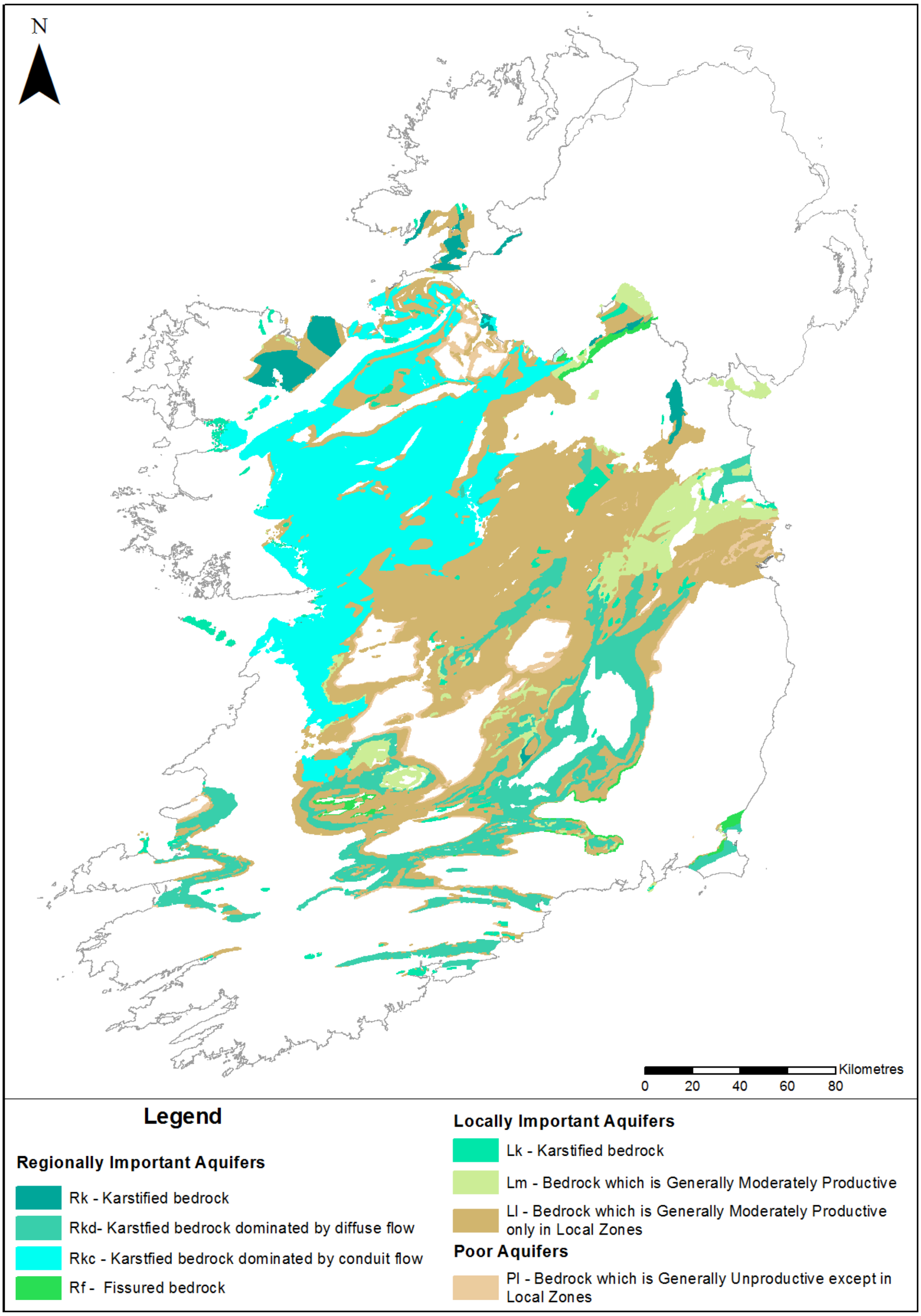


Figure 4: Aquifer categories within the carbonate bedrock in Ireland

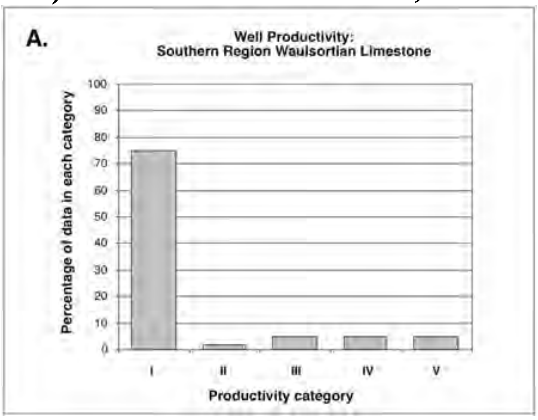
The Pure Bedded Limestones of the West of Ireland: The large area of karstified limestone in the West is complex, with a mixture of karst ages and characteristics (Drew, 2018). The Regionally important karst aquifer is dominated by conduit flow (*Rkc*). Around 99% of groundwater flows are concentrated in conduits occupying <0.1% of the volume of the aquifer (Drew, 2018). Conduits occur at different depths, having formed in response to local or regional drainage base levels, including sea level low stands. Observed conduits to between 60 and 88 m below modern sea level are summarised in Drew (2018). A conduit encountered at c. 100 m bsl at Gortgarrow has been reported (Doak, pers. Comm.). This ties in with relative sea level minima modelled by Edwards and Craven (2017) of -80 to -95 m bsl off Co. Kerry. Most flow is thought to occur in the top 30 m bgl, however, with additional groundwater flow and storage within the epikarst (Daly, 1995 and Drew, 2018). Although large springs occur in this region, the concentration of groundwater flow in conduits can make development of this aquifer difficult, as yields are low away from the conduits.

The Pure Unbedded Limestones of the Midlands and South of Ireland: These limestones have undergone different degrees of deformation, with extensive E-W and N-S faulting and fracturing in the south, and more modest N-S veining in the midlands. The difference in fracture density and degree of subsequent karstification varies spatially. In the Munster Synclines, a high density of fracturing related to Variscan deformation provided many pathways for groundwater to flow. Therefore, although karstification of the fracture and fault planes has occurred, flow has not concentrated to discrete conduits, and groundwater flow is diffuse although conduits and caves are known in these aquifers, which are therefore classified as Regionally important karst aquifers dominated by diffuse flow (*Rkd*). In the Midlands, deformation was far less intense. Because these limestones are massive (Unbedded), there is no jointing or bedding plane parting, and fracturing and faulting is much less frequent. These limestones are not observed to have developed significant karstification over much of the midlands, although epikarst is observed in these rocks in some locations. Yields are moderate to good (typically less than 200 m^3/d), and productivities are skewed to lower classes (IV and V). These factors result in a Locally important fissured bedrock aquifer productive in local zones (*Ll*). This is in comparison to productivities in the southern area, which are skewed to I's and II's (**Figure 5(a) and (b)**).

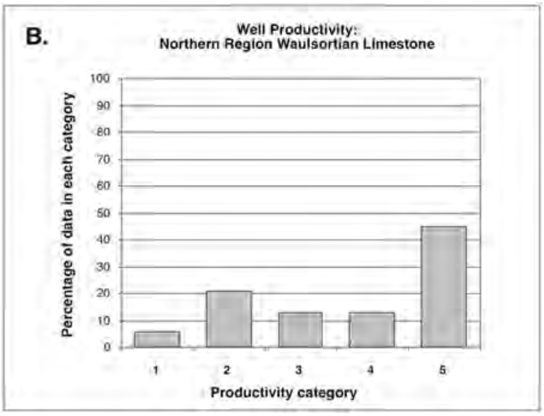
The Impure Limestones: The majority of the impure limestones comprise the Calp and Ballysteen limestones. They are widespread across the midland lowlands, from Dublin to east Galway, and Monaghan south to Limerick and Kilkenny. These rocks are not susceptible to karstification except where there are local variations in lithology. Therefore, groundwater movement typically restricted to the shallow, weathered and jointed sub-surface zone, and along fractures and fault zones. Groundwater flow overall is shallow, probably mainly occurring within the top 30 m or so of the aquifer although deeper water strikes associated with isolated fractures or intersection of fault zones, and yields are typically less than 150-200 m^3/d. Productivities are skewed to lower values (**Figure 5(c)**) and the aquifer category is *Ll*. There is a relatively extensive area in north Dublin and east Meath where deformation of the impure limestones is much more intense - intense folding and fracturing can also be seen in these rocks at the coast near Rush. Moore and Walsh (2013) and Blake *et al.* (2018) identify Tertiary strike slip faults as key structures carrying groundwater flow. Groundwater flows through a connected, higher density of predominantly non-karst fissures and yields can be significant, with a significant proportion greater than 400 m^3/d, and productivities dominated by I's and II's (**Figure 5(d)**). The aquifer classification is therefore Locally important fractured bedrock aquifer that is generally moderately productive (*Lm*).

Figure 5: Selected productivity graphs for different limestone aquifers. From GSI (in prep) and reproduced in Drew (2018). Productivity is a measure related to aquifer transmissivity (Wright, 2000). I is high productivity and V is low productivity.

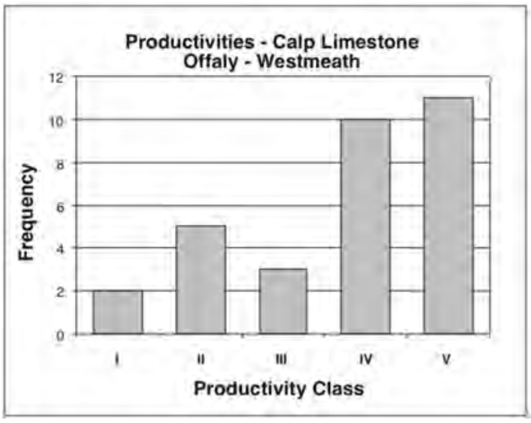
b) Pure Unbedded Limestones, South



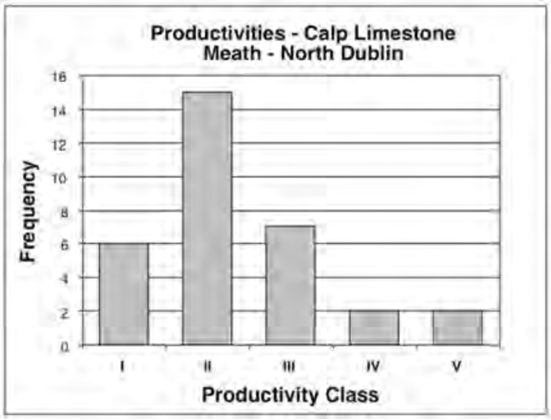
c) Pure Unbedded Limestones, Midlands/North



d) Upper Impure Limestones, central Midland



e) Upper Impure Limestones, N Dublin/Meath



5. CONCLUSIONS

Limestones underlie almost half of Ireland, and are important source of groundwater for drinking and other purposes. The type of limestone (purity and sedimentary structures), its history of deformation and degree and type of the resulting faulting and fissuring, and the degree of karstification undergone influence how groundwater flows through these aquifers, and in what volumes. These and other factors inform the groundwater resource value or aquifer classification. The majority of Ireland's regionally important aquifers are in limestones. Large springs occur and significant borehole yields can be obtained from them. On the other hand, some of the impure limestone aquifers are poorly productive, capable of providing yields to meet small town or even only domestic supplies. It should be noted that the groundwater resource value represented by the aquifer classification is one aspect of development potential. Groundwater recharge and other factors are also crucial and are not discussed here. The GSI's GW3D project is addressing groundwater resources on a catchment scale currently.

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AN INTRODUCTION TO THE IRISH AQUIFER PROPERTIES MANUAL

Coran Kelly (Tobin Consulting Engineers)
Taly Hunter Williams (Geological Survey Ireland)
Bruce Misstear (Trinity College Dublin)

ABSTRACT

This paper presents an introduction to the Irish Aquifer Properties reference manual and guide (2015). It provides an overview of the data sources and the analysis of available data on bedrock and subsoils used to estimate hydrogeological parameters. The manual and guide present summary data for transmissivity, hydraulic conductivity and storage properties according to the aquifer categories and Rock Unit Groups. The manual also includes advice on parameter estimation techniques appropriate to Ireland.

INTRODUCTION

In the context of groundwater protection, the Irish Aquifer Properties reference manual and guide represents a collaborative project, initiated by the Environmental Protection Agency (EPA) in co-operation with Geological Survey Ireland (GSI), and undertaken by Tobin Consulting Engineers. The main objectives were to:

- Establish a framework under which a database of aquifer parameters can be determined, maintained and updated.
- Compile and publish aquifer parameters, and relate them to the aquifer categories and the Rock Unit Groups (RUGs).

It was considered that the database needed to account for aquifer heterogeneity, pathways and scale; and be as large as possible, representative and reliable. It is termed '*Irish Aquifer Properties, a reference manual and guide*' (2015). It is made available from GSI at this address:

https://www.gsi.ie/en-ie/programmes-and-projects/groundwater/activities/understanding-ireland-groundwater/Pages/Aquifer-parameters.aspx.

The purpose of this paper is to introduce the reader to the manual and encourage its use. The manual can be used to inform:

- quantitative hydrogeological risk assessments and groundwater modelling;
- aquifer classification;
- quantitative groundwater discharge assessments;
- groundwater resource developments.

Overview of the manual

The manual is divided into two parts. Part 1 describes the methodologies used and documents the data sources relied upon to establish the parameters database. It outlines:

- the hydrogeological framework for the parameters database;
- the appropriate parameters for Irish aquifers;
- methods for parameter estimation;
- limitations of existing data;

- appropriate parameter estimation for Irish aquifers.

Part 2 covers the organisation and structure of the parameter database. The manual documents the data analysis and the statistical approach to assess the data in order to determine summary tables of basic hydrogeological parameters as a function of aquifer category and Rock Unit Group. Part 2 also indicates where further work and improvements are required. The following sections take the reader through some selected areas of the manual and highlight some of the important messages.

Deriving robust aquifer PARAMETER values

Appropriate aquifer parameters for Irish aquifers

The preferred parameter to assess hydraulic properties in hard rock aquifers or fractured rock aquifers is transmissivity due to its practical importance, availability of data and more reliable values as compared to hydraulic conductivity where data from well pumping tests usually reflect single or a handful of highly permeable factures surrounded by massive blocks of very low hydraulic conductivity rock. In many countries, including Ireland, where fractured aquifers dominate, borehole yield and drawdown are often used to assess, predict and generalise aquifer hydraulic properties, since specific capacity is proportional to transmissivity (Wright, 1997, 2000; Misstear, 2001; Banks, *et al.*, 2005; Misstear *et al.*, 2017). In practical terms, the basic concept is about moving away from a single fracture to a sufficient volume of rock whose properties are broadly representative of that rock unit as a whole. However, for contaminant fate and transport issues, where first arrival is a key concern, then focussing on the fracture permeabilities may be most appropriate, particularly where the distance between contaminant and receptor/compliance point is small/similar compared to the fissure length scales.

Limitations associated with existing data and with Irish groundwater flow system conditions

Limitations on deriving aquifer parameters from existing data can occur due to the data themselves and what the data relate to in terms of the geological framework (pathway), and the purpose for which they were collected. The main limitations can be related to the test type, purpose and length, the test pumping set-up, borehole construction, and the hydrogeological assumptions. This paper focuses briefly on the hydrogeological assumptions and the reader is directed to the manual for further information.

Irish aquifers do not generally conform to the basic assumptions underlying aquifer tests; they are generally heterogeneous, anisotropic, not really infinite, and the boreholes generally do not fully penetrate the aquifer. Assessment is further complicated because the vast majority of bedrock aquifers are fractured, and it is often difficult to assess if confining conditions are present or not. Sometimes a borehole may intersect a large fracture which simply delivers all the water to a borehole to such a degree that the drawdown rapidly accelerates to the fracture zone, remains there until the fracture is depleted, after which the drawdown rapidly accelerates again down towards the pump intake. Furthermore, recharge may be occurring during the pumping test since the majority of Irish groundwater systems are unconfined. Bias from a particular fracture may skew the data suggesting a highly transmissive aquifer whereas, in fact, outside the fracture it is very weakly transmissive. This may not be evident during a standard short-term pumping test, but only become apparent during operational pumping. Therefore, the limitations of typical Irish pumping tests are associated with:

- relatively short duration tests, typically three days or less;
- declining or variable pumping rates;
- unknown borehole geology and/or well construction details;
- the absence of observation well data;
- multiple straight-line segments on a semi-log drawdown versus time plot due to the influence of different fractures;

- bias towards one single large fracture;
- other test assumptions that are not met in practice.

These factors can inhibit obtaining a reliable estimate of transmissivity and, perhaps especially, an estimate of storativity (good observation well data are required for storativity calculations). As well as challenges in interpreting pumping test data from fractured aquifers, there can be difficulties in obtaining reliable transmissivity values in sand and gravel aquifers, especially in thin gravel deposits, as the continually-reducing saturated thickness around the pumping well indicates a reducing transmissivity. In many reports involving the type of tests above, the well yield and the specific capacity are all that is reported.

The bulk of the existing data are predominantly water supply data. Inherently these data tend to be associated with wells that have been successful and achieved higher yields. GSI groundwater data also include private well data acquired *via* the well grant scheme. The drilling and yield assessment of a well for a private house is generally quite limited, owing to the low water demand required. Hence, a short test, low test pumping rate, and a relatively deep borehole, are likely to result in non-steady state specific capacity data, which will result in overestimation of derived aquifer parameter values.

Appropriate parameter estimation for Irish aquifers

Analysis methods for fractured aquifers

Ireland is dominated by fractured rock and karstified aquifers, and it is widely accepted that analysing test data in hard rock aquifers is difficult, as many of the assumptions underpinning standard approaches may not be wholly satisfied (Banks *et al*., 2005; Comte *et al*., 2012; Moe *et al.*, 2010; Misstear *et al*., 2017). Misstear *et al*. (2017) synthesise approaches to interpretation of test data in hard rock aquifers, covering both high and low yielding scenarios. Simple information on borehole yield and steady-state drawdown are useful for estimating the transmissivity, since specific capacity is proportional to apparent transmissivity (Banks *et al.,* 2005; Misstear *et al.*, 2017).

Approach to assessing test pumping data

The general focus is on larger-scale tests as these are the most commonly undertaken and most readily available data. These data also better inform the broad characteristics and hydraulic behaviour rather than small scale tests. Adaptations of Theis such as the Cooper–Jacob straight line method remain one of the most widely used methods to assess pumping test data. This method can be useful for interpreting the test pumping data in Ireland despite the complexities associated with recharge, variable pumping rates, apparent changing transmissivity in response to interaction with different fracture zones, boundary effects and relatively short-duration tests. However, the test data require careful consideration given that the fractured rock environment generates a variety of potential responses (Misstear *et al.*, 2017).

Test pumping data give ‘bulk’ aquifer estimates for transmissivity and thereby hydraulic conductivity over a relatively large scale, and are a useful approximation for the groundwater environment for an area covered by a known aquifer and Rock Unit Group. However, for groundwater seepage velocity calculations, hydraulic conductivity can vary greatly over small distances. Thus, there may be zones and/or fractures that may have a significantly higher hydraulic conductivity than that calculated from the bulk transmissivity value. Hydraulic conductivity decreases with depth in most bedrock aquifers in Ireland (Comte *et al*., 2012). For instance, the ‘transition zone’ will tend to comprise higher hydraulic conductivity values than the shallow or deep bedrock zones. The ‘transition zone’ is defined by GSI as ‘*the broken, weathered zone between the subsoils and the competent, unaltered bedrock*’. The extent and variability of the ‘transition zone’ are being investigated by GSI. Further information, including examples, on the ‘transition zone’ is available at the following link:

https://www.gsi.ie/en-ie/programmes-and-projects/groundwater/projects/gw3d/Pages/Transition-Zone.aspx.

The flow pathways also offer different opportunities for contaminant attenuation and dispersion. The 'transition zone', depending on bedrock type can offer greater opportunity for chemical and physical weathering, particularly in shaley units. It is likely that dispersion will be greater in the transition zone due to greater surface area, *i.e.*, greater tortuosity. Where the bedrock tends to be more extensively fractured, with greater connectivity, dispersion may be higher.

Diagnostic plots provide an additional technique to assessing test pumping data, and can offer a useful insight into the data (Renard, *et al.*, 2009). High resolution data from a data logger is required to reduce the scatter in the data. These are covered in further detail in the manual.

Data analysis

Statistical Approach

Best, Upper and Lower Estimate values were determined using a statistical characterisation based on summary descriptive statistics and graphical plots/distributions. The statistical distributions of hydraulic conductivity and transmissivity data, and borehole yields have been widely observed to be approximately log-normal, in common with other natural data (*e.g.*, Banks, 1998; Banks *et al*., 1994, 2005, 2010). A visual inspection of the graphical plot presented in Figure 1 which represents the available data with specific capacity in GSI's groundwater well database demonstrate an approximate log-normal distribution for the transmissivity data, and it yields a straight line through the majority of the data which is diagnostic of an approximate log-normal distribution. Similar to observations in data presented by Banks *et al.* (2010), and importantly, there is a good fit with the majority of the central portion of the data.

The geometric mean and the standard deviation characterise log-normal distributions, and the bulk transmissivity is best represented by the geometric mean or median (approximately equal for log-normal distributions) (Banks *et al.*, 2005, 2010). A 'Best' estimate for transmissivity is derived for the fractured bedrock aquifers, using the geometric mean. Arithmetic and harmonic averages are included for karst aquifers where conduit flow dominates. Figure 2 and Figure 3 show the 'Best' estimate for each of the bedrock aquifer categories graphically. 'Upper' and 'Lower' estimates are provided that correspond with the 90^{th} and 95^{th} percentiles, and the 5^{th} and 10^{th} percentiles respectively (Figure 3). A detailed table and individual histograms for each aquifer category are provided in the manual. The GSI karst database provides travel times (velocities). Information on the GSI karst database is available here:

https://www.gsi.ie/en-ie/programmes-and-projects/groundwater/activities/understanding-irish-karst/Pages/Karst-databases.aspx.

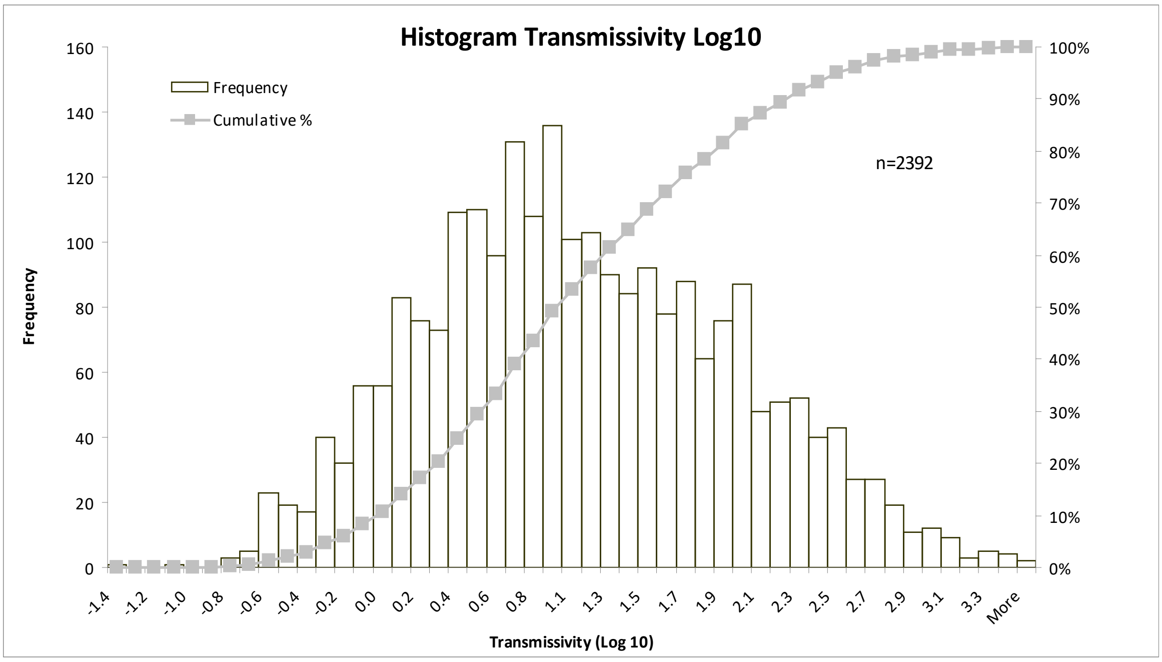

Figure 1: Histogram of transmissivity (Log $_{10}$) using the available bedrock groundwater data records with a specific capacity

transmissivity

Transmissivity as a function of aquifer category

The figures and tabulated data show that the 'Best' estimates for:

- Poorly Productive Aquifers (Pu, Pl and Ll) have T values less than 10 m^2/d.
- Productive Fissured Aquifers (Lm and Rf) have T values in the range 20 m^2/d to 30 m^2/d.
- Karstic Aquifers (Lk, Rk and Rk^d) have T values in the range of 20 m^2/d to 70 m^2/d.
- Sand and Gravel Aquifers (Rg and Lg) have T values of approximately 350 m^2/d (geometric mean).

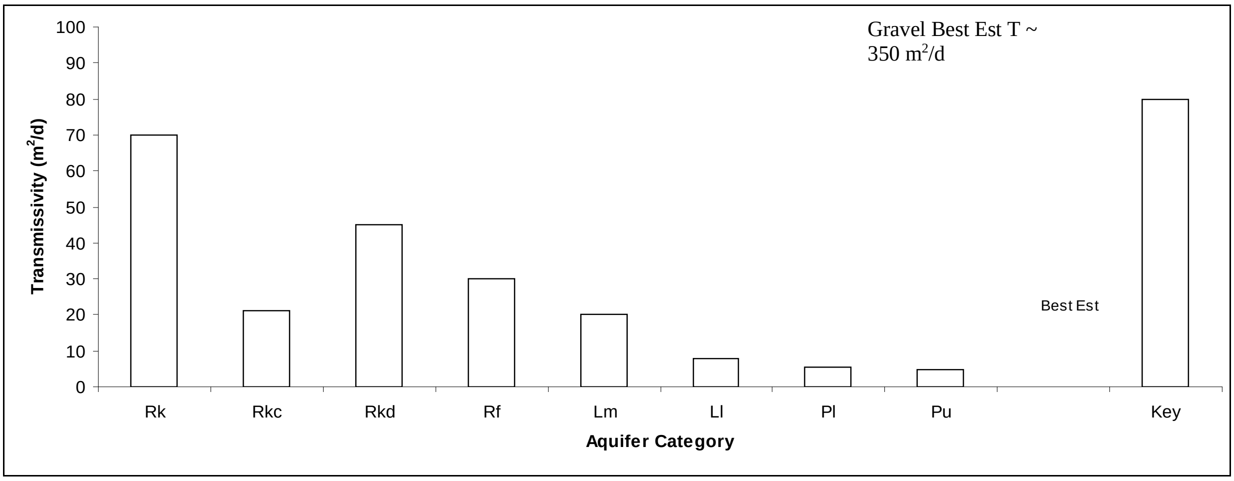

Figure 2: Best estimate transmissivity values (m^2/d) for different bedrock aquifer categories

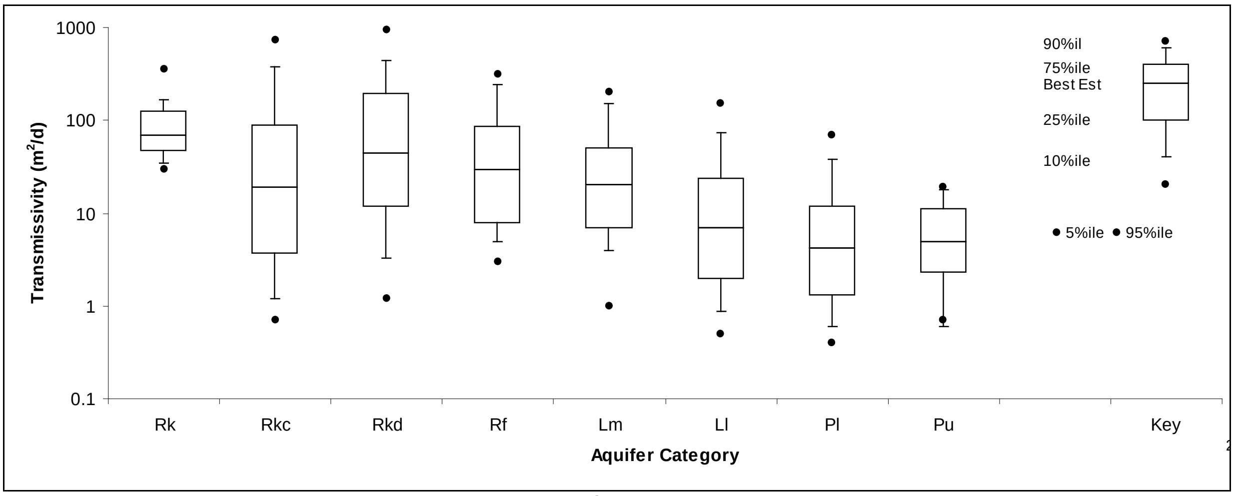

Figure 3: Distribution of transmissivity values (m^2/d) for different bedrock aquifer categories shown on a 'box and whisker' style graph.

Transmissivity as a function of Rock Unit Groups

One of the main limitations in assessing the Rock Unit Group data is the lack of data for some of the units under their different aquifer categories. A selected graphical plot is provided in Figure 4. The reader is directed to the manual to see the full suite. Regional differences in groundwater flow properties owing to greater/lesser geological deformation within the same rock type is well known and captured as part of the national aquifer classification, *e.g.* the Waulsortian in the south is categorised as Rk^d, but in the midlands as Ll. These regional differences can be seen in the summary statistics and best estimates, and are discussed within the manual.

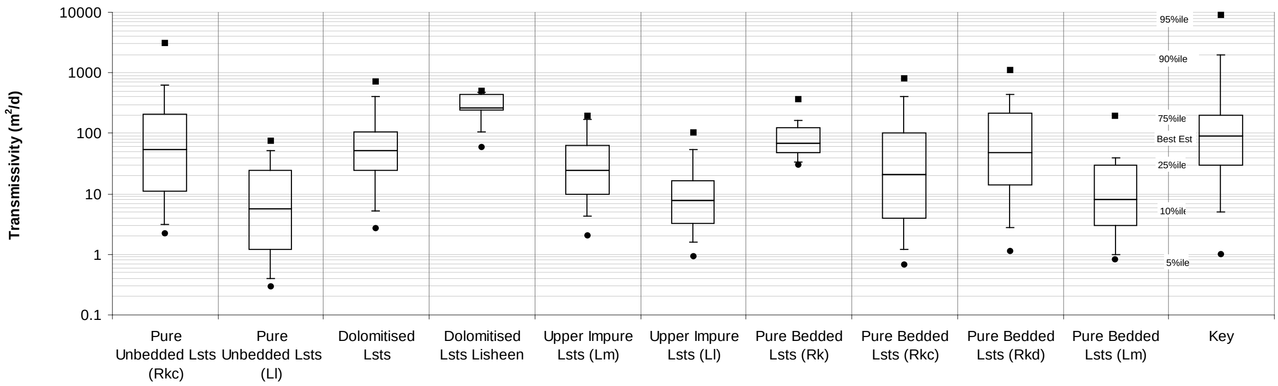

Figure 4: Log scale whisker plot of selected RUGs Transmissivities

Hydraulic conductivity

There are few reliable data readily available for direct estimations of hydraulic conductivity (K). The reader is directed to the manual for further information on hydraulic conductivity. A few observations on hydraulic conductivity of the bedrock and tills are included as follows.

Bedrock

The bulk of the available hydraulic conductivity data are clustered around the Dublin area obtained from major infrastructural developments such as the Metro, Dart underground and Port Tunnel and Interconnector, and therefore do not represent hydraulic conductivity nationally. The few 'good' data represent relatively small test scales, where the typical 'screen length' or 'test length' is 1 m to 2 m. The data show an expected decrease in hydraulic conductivity with depth.

Till

The extensive till deposits that cover large parts of the landscape influence recharge and groundwater vulnerability (Fitzsimons and Misstear, 2006; Hunter Williams *et al.*, 2013). The tills are generally unsorted, heterogeneous, comprising a wide range in particle sizes, and primary porosity is significant. Though subsoil hydraulic conductivity varies greatly over short horizontal and vertical distances, there are broad patterns (Meehan and Lee, 2012). The Geological Survey Ireland define and map regional subsoil hydraulic conductivity using an integrated holistic approach that utilises textural descriptions, particle size data, hydraulic measurements, drainage and vegetation indicators, topsoil maps, bedrock maps, digital elevation models, and ice flow models (Swartz, 1999; Lee, 1999, Fitzsimons *et al.,* 2003; Lee, *et al*, 2015). There are three broad hydraulic conductivity categories defined: ‘high’, ‘moderate’ and ‘low’. Most tills in Ireland are considered to have a ‘moderate’ or ‘low’ hydraulic conductivity, as described in Fitzsimons *et al*., 2003. The boundary between ‘moderate’ and ‘low’ hydraulic conductivity is approximately 10^{-8} m/s to 10^{-9} m/s (Swartz, 1999, Fitzsimons *et al.,* 2003), and the boundary between ‘moderate’ and ‘high’ is approximately 10^{-4} m/s to 10^{-5} m/s (O’Suilleabháin, 2000; Misstear *et al.,* 2009).

Storativity

Aquifer storativity and effective porosity data are very limited for Ireland. The available data indicate that specific yield across all bedrock aquifer categories is typically of the order of 0.01 ($1x10^{-2}$), whilst the confined storage coefficient is of the order of 0.0001 ($1x10^{-4}$). Though there are insufficient data to derive a statistically significant relationship there seems to be a weak dependency on aquifer type. Specific yields in sand and gravel deposits range from around 0.10 to 0.19.

CONCLUSIONS

Hydraulic data have been summarised for bedrock units and sand and gravel aquifers as a function of aquifer category and Rock Unit Group. Specific capacity data from GSI groundwater well data provided a more robust statistical basis for the selection of the ‘Best’ estimates and the ‘Upper’ and ‘Lower’ ranges. Summary tables are provided for both bedrock and sand and gravel aquifers. Relevant information on the subsoils is limited to summarising the key hydraulic conductivity boundaries and ranges for the main textural classes.

In general, there is a decrease in the ‘Best’ estimate value for transmissivity of the Regionally Important Aquifers through to the Poor Aquifers. There are insufficient specific *in-situ* hydraulic conductivity data to fully characterise the aquifer and rock unit classifications. Bulk hydraulic conductivity estimates are derived from transmissivity data from the aquifer parameters database. Bulk hydraulic conductivity decreases with depth in the bedrock aquifers as expected. Individual fracture permeabilities are likely to be significantly higher than bulk hydraulic conductivity estimates, particularly as the borehole test interval increases.

It is important to point out for the karstified aquifers that, when estimating a groundwater velocity in the context of a time of travel, the GSI Karst tracing database should also be consulted.

Due to the nature of the available data, storativity and effective porosity data are very limited. Storativity is low within the bedrock aquifers.

Whilst the aquifer properties manual includes some guidance, it is up to the user to assess the most suitable values for their site based on site specific considerations and also the nature and requirements of the study. Also, when undertaking site investigations, the user must choose the most appropriate methods to determine appropriate parameters of interest. Over a particular portion of aquifer that has broadly similar groundwater flow characteristics, the hydraulic parameters need to be consistent with each other due to their interdependence. Parameter interdependence should be borne in mind when selecting appropriate parameter values from the aquifer parameter database, and the parameters should be self-consistent and consistent with any site-specific information. The general approach to parameter estimation as given by Wright (2002) and techniques and methods given in Misstear *et al.* (2017) are appropriate for Irish conditions and the type of test data collected. An integrated approach using cross checks is suggested with the additional use of diagnostic plots.

Further work

It would be useful to update the manual, summary tables, and main parameters data base by including recent hydraulic data, especially data collected since 2015, *e.g.* useful additional data would include Irish Water test pumping during the drought of 2018, and data submitted as part of licence requirements to EPA. The focus of the project was on the bedrock aquifer. A dedicated strand of work to pull together hydraulic data from site investigation for subsoils, especially the tills would also be useful. The outcomes of recent research also need to be examined and integrated in order to update the manual.

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THE CONTRIBUTION OF LIMESTONES IN IRELAND TO OUR NATURAL CAPITAL

Catherine Farrell* and Donal Daly**
*Trinity College Dublin; **Catchment Scientist

ABSTRACT

The natural world we live in underpins human existence. It can be thought of as our stock of natural capital that yields flows of goods and services. These goods and services include the basic requirements of daily living – food, water, clean air, etc. Ensuring those services continue to flow for this generation and future generations is one of the fundamental aspects of sustainable development and the keystone of social and economic welfare as highlighted by global initiatives such as the UN 2030 Agenda for Sustainable Development . The INCASE (Irish Natural Capital Accounting for Sustainable Environments) research project aims to apply NCA at a pilot (catchment) scale in Ireland. Developing natural capital accounts at catchment scale will inform how the accounts (asset extent, condition, supply and use of services, benefits, etc.) can be built using Irish data sources and provide valuable lessons on how best to scale up to the national level. Given that NCA is an emerging discipline, the approach is still in development. This paper serves to highlight the key concepts of natural capital and how NCA may be applied in the context of Limestones and their contribution to Ireland's natural capital.

INTRODUCTION

In the Irish context, the EPA State of the Environment Report (Wall *et al.*, 2016) highlights the need to integrate natural capital accounting (NCA, also referred to as *Green Accounting*) into our measures of prosperity so that we can track and measure our performance alongside related issues such as wellbeing and environmental health. NCA brings a range of data sources together relating to 'nature' – from baseline information on *extent* of natural systems, to data on how well these systems are functioning (referred to as their *condition*). Data behind natural capital accounts, as demonstrated in other countries such as the UK (consider '*the aggregate natural capital rule*[1]) and the Netherlands[2], serve as a standardised data platform that can be used in a multi-disciplinary way.

NCA can be used to identify trends in the quality of the environment, inform trade-offs, identify co-benefits, establish critical links between natural and other capitals (such as built and social capital) as well as identifying knowledge gaps. Such an approach can help us to understand and, combined with the use of other appropriate tools, address the dominant pressures and their impacts - climate change, growth in human population, continued degradation of nature - on Ireland's environment. This paper serves to:

- Introduce the basic concept of natural capital, exploring the term from the perspectives of different assets / stocks (ecosystem, geosystem and atmospheric systems); and flows of nature's services;
- Explore the use of NCA in the context of Limestones and their contribution to natural capital in Ireland; *and*
- Highlight some of the research questions to be addressed by the INCASE project in relation to integrating geo-assets and geosystem services into NCA in Ireland (data sources, condition assessment, valuation etc.).

[1] http://www.dieterhelm.co.uk/natural-capital/

[2] https://www.cbs.nl/en-gb/society/nature-and-environment/natural-capital

NATURAL CAPITAL – KEY CONCEPTS

NATURAL CAPITAL THINKING – DRIVERS

The new European *Green Deal* published at the end of 2019[3] specifically aims to protect, conserve and enhance Europe's natural capital, and protect health and wellbeing from environment-related risks and impacts. The *Green Deal* states that: all EU policies should contribute to preserving and restoring Europe's natural capital. In addition, the development of standardised natural capital accounting (NCA) practices is explicitly mentioned as part of the range of initiatives to pursue green finance and investment. In order to understand the context within which natural capital sits, we first need to understand what capital is and the range of capitals that are considered in thinking about economics and human welfare.

NATURAL CAPITAL – THE FOUNDATION OF ALL CAPITALS

The International Integrated Reporting Council defines the term 'capitals' as referring to any store of value that an organisation can use in the production of goods and services, distinguishing six capitals for reporting purposes as illustrated in Figure 1 (IIRC, 2013). All types of capital are needed to support human welfare, and human capital combines with natural capital to create manufactured and/or financial capital. However, as Figure 1 illustrates, all other capitals *rely* on natural capital. This reflects discussions around the Sustainable Development Goals[4], the nested approach clearly defining the role of nature as that which underpins all else. While this is obvious to those working with and in the Natural Sciences, it is a significant change in thinking for other disciplines, especially political and economic schools of thought.

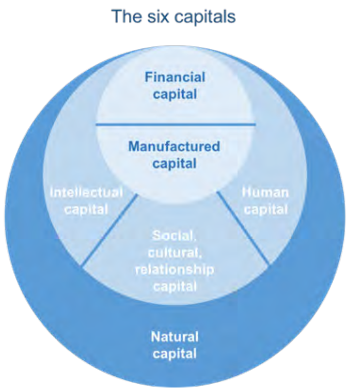

Figure 1. The Six Capitals. Source: https://integratedreporting.org/

DEFINING NATURAL CAPITAL – ASSETS (STOCKS) AND SERVICES (FLOWS)

The term natural capital is now widely used – from academic to business, ecology to economics, international to local levels. The underpinning concepts are nature (everything that occurs naturally – abiotic and biotic components) and capital (stocks or assets). Depending on the perspective of the user and/-or the use, for example the desired outcomes of the NCA process (*see later*), the focus may be on biodiversity (e.g. for the purpose of biodiversity under CBD/EU/National targets) or may encompass materials / resources and broader components of nature (e.g. for the purpose of policy and decision making around water/soil resources).

A number of approaches to the classification of natural capital stocks and flows have emerged since the 1990s. These include the Millennium Ecosystem Assessment (MA, 2005), and The Economics of Ecosystems and Biodiversity (TEEB, established in 2008) initiatives which highlighted the importance of recognising the value of natural capital, ecosystem services and the benefits that we receive from nature. In the EU, these initiatives have been built on by the EU Mapping and

[3] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[4] https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf

Assessment of Ecosystem Services (MAES) project which has been running since 2011[5] and provides the foundation for the EU approach to classification of ecosystems and ecosystem services (Maes *et al.*, 2013) and subsequent EU approaches to NCA in the form of the EU INCA project (EC, 2019).

For the purposes of the INCASE project, Natural Capital is used in the broadest context as the stock of renewable and non-renewable natural resources, (e.g. plants, animals, air water, soils, minerals) that combine to yield a flow of benefits to people (NCC, 2016)). This reflects the work by van Ree *et al.* (van Ree and van Beukering, 2016; van Ree *et al.*, 2017) (Figure 2) and the work by the UN SEEA-EEA[6] in highlighting the need to broaden the discussion and extend the accounting of natural capital provided by ecosystems to include the role and contributions of geosystems and atmospheric systems (as highlighted in the Catchment Services concept in Figure 3 (Rolston *et al.*, 2017)).

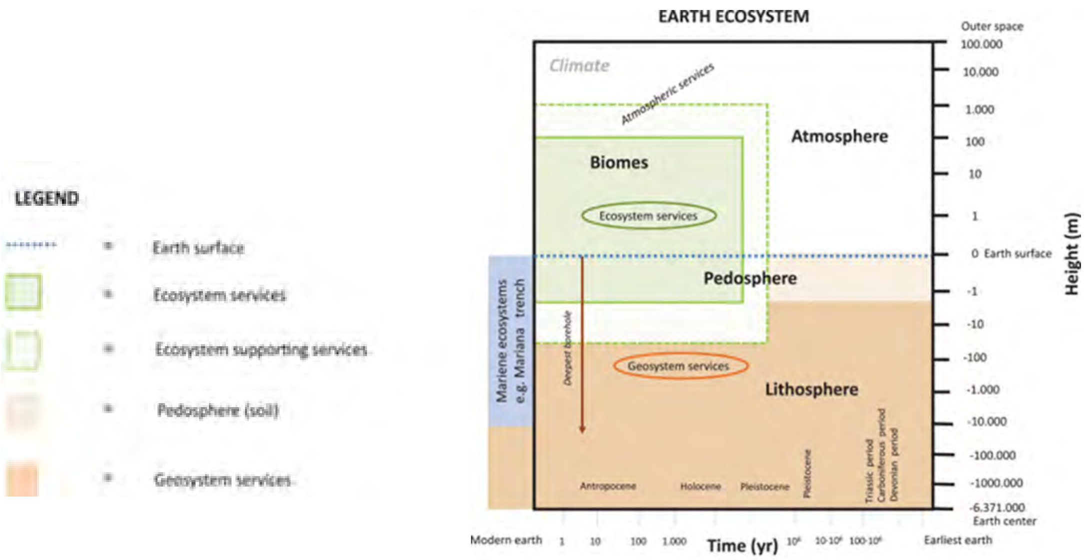

Figure 2: An overview of the temporal and spatial relationships between ecosystems, geosystems and atmospheric systems. The systems are inter-linked and often the boundaries are transitional / not clearly delimited. S*ource*: van Ree *at al*. 2016.

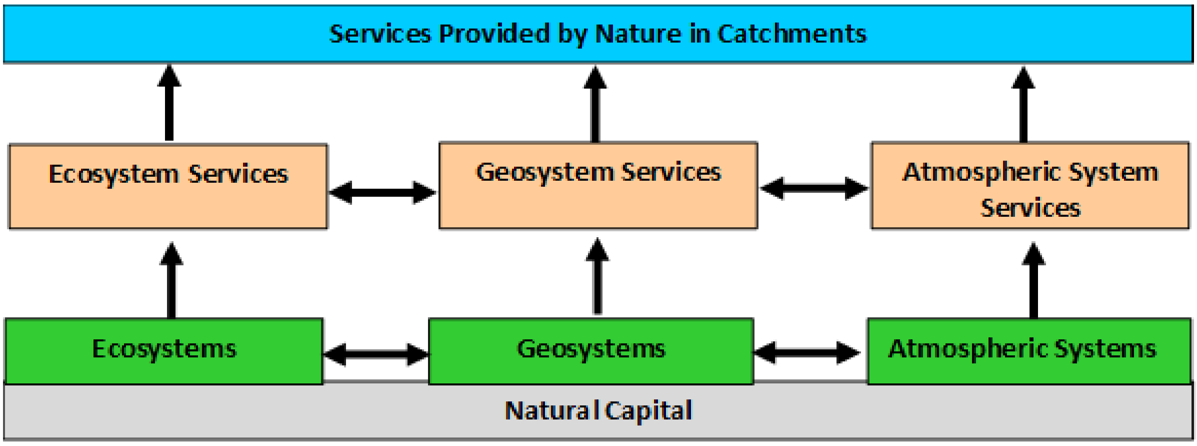

Figure 3. Illustration of the services provided by our Natural Capital and their linkages in a catchment context; adapted from original concept diagram (Daly, 2016).

[5] https://biodiversity.europa.eu/maes

[6] https://seea.un.org/content/seea-experimental-ecosystem-accounting-revision

NATURAL CAPITAL – WELLS OF NATURE'S SERVICES

In a similar way to discussions around natural capital, much of the focus has centred around the role of ecosystems services. Having a clear delineation of the asset, service and benefit is a fundamental requirement for bringing the data into a standardised NCA system and can be challenging in itself given assumptions around services and benefits (*see later*).

There are a number of emerging classifications with the main system in use in Europe being the Common International Classification of Ecosystem Services (CICES) which identifies provisioning, regulating and cultural services at biotic and abiotic levels (Haines-Young and Potschin, 2018). Some services are generally assumed to work within the ecosystem and are not defined as delivering a benefit directly to humans. These are viewed as intermediate, regulating services which are obviously important for the final service delivery. For example, pollination is an intermediate service that leads to the final service of food (provisioning). The main categories of services are outlined as follows:

- *Provisioning services*: services that combine with other capitals to produce food, timber, fish or other 'provisions' such as mineral aggregates;
- *Regulating services* includes those that combine with other capitals to produce flood control, storm protection, water regulation and purification, pollination and climate control. Regulating services are in general less well perceived by humans and include intermediate regulatory services such as pollination, soil formation, primary productivity, and nutrient cycling. These processes and functions are necessary for the delivery of the other services categories[7];
- *Cultural services*: those combined with other capitals to produce recreation, scientific, and other cultural benefits. Landscapes such as the Burren – a product of the interaction of limestone, time, terrestrial ecosystems, atmospheric processes and traditional human management of grazing for agriculture is an example in Ireland . This category is probably the least developed (Chan et al., 2012).

NATURAL CAPITAL ACCOUNTING – TRACKING STOCKS AND FLOWS

SEEA – THE SYSTEM OF ENVIRONMENTAL ECONOMIC ACCOUNTING

From an accounting perspective, defining natural capital as an important and valuable capital or stock brings the discussion around nature into a language more traditionally associated with economics. However, Natural Capital differs from traditional 'capitals', having unique features which relate to the diversity of nature, the complexity of living systems, capacity, condition, non-linearity, feedback loops and resilience. An appropriate asset accounting model is therefore required for the purposes of accounting for natural capital assets and flows; one that can be standardised to allow for comparative and repetitive measurement and reporting at national, regional, catchment, or site/business level.

The main system in development, upon which NCA approaches have formed or have emerged from, is the UN System of Environmental and Economic Accounting, also known as the SEEA[8]. The SEEA is in development since Rio 1992, and works as a set of satellite accounts aligned with the System of National Accounts or SNA, which is collated by the CSO in Ireland and is used to calculate indicators such as Gross Domestic Product (GDP). There are two components of the SEEA: the SEEA-Central Framework (CF) and the SEEA-Experimental Ecosystem Accounting (EEA).

- *The SEEA-CF* covers physical accounts and flows of environmental assets and expenditure with the perspective for measurement purposes on individual environmental assets, such as timber resources, land, mineral and energy resources, and water resources.
- *The SEEA-EEA* is a geospatial approach whereby stocks of natural capital (assets) at a range of scales (e.g. country or catchment scale) are measured. Knowledge of the extent and condition of natural capital assets allows for integration of the supply and use of services (flows) flowing from nature which are then recorded as benefits to humanity, in an accounting framework.

[7] In general, they are classed as intermediate and not included at an accounting level.

[8] https://seea.un.org/

The SEEA-CF is a statistical standard and reporting is mandatory across the EU since 2011[9]. The SEEA-EEA constitutes an integrated statistical framework for organising biophysical data, complementary to that of the SEEA-CF, although it does not yet have the status of an international statistical standard[10]. Both aspects work together, enabling the tracking of changes in stocks and flows over time.

The SEEA approach, and specifically the SEEA-EEA component, represents initial efforts to define a measurement framework for tracking changes in ecosystems and their outputs, and by extension other natural systems; linking those changes to economic and other human activity by means of the combination of the SEEA-CF and SEEA-EEA accounts. The SEEA-EEA is the main focus of the INCASE project – determining the data requirements and linkages with SEEA-CF accounts being the main focus in terms of establishing and defining the process steps at catchment scale, with a view to scaling up to national level.

ACCOUNTING STEPS IN THE SEEA-EEA

There are four key stages (outlined in Figure 4) in the SEEA-EEA to fully outline geospatial extent, condition and relationships of natural capital assets (*stocks*), as well as accounting for *flows* of services and benefits:

- *Asset extent* – type, range and scale of natural capital assets. The output of this stage is a geo-referenced map, the scale depending on the spatial unit (county, catchment or farm) and an asset register or account (in the form of a table / balance sheet).
- *Asset condition* – quality of the asset. For example, a peatland may be drained, which would be lower condition than one with no drains, which impacts on its capacity to sequester carbon but also its biodiversity. Condition of assets influences the ability of an asset to deliver one or more services and as condition will vary over space and over time, condition mapping is a key spatial component. At this stage, maps showing asset condition and pressures, and a *Risk register* - highlighting areas of degradation - can be developed.
- *Services* – identification of the services, whether within the system or as a product of the system. In the case of a peatland this may be carbon sequestration (a service) or emission (a disservice), and/or water attenuation. Similarly, services may rely on a combination of and the interaction of multiple assets. Mapping services will be a product of the pressures and condition mapping in previous steps, as well as using other relevant geo-spatial data.
- *Benefits* – the benefits to humans and who the beneficiaries are. For example, the benefit may be climate regulation and/or flood control, and the beneficiaries either local or downstream (flood mitigation) or global (reduced carbon emissions to atmosphere). For many services there is a spatial correlation between potential beneficiaries and service availability.

Figure 4. The Core NCA Framework. Source: IDEEA Group.

9 https://www.cso.ie/en/statistics/environmentaccounts/

10 It is anticipated that a revised SEEA EEA will be adopted as an international statistical standard in March 2021.

INCASE – WHAT STOCKS AND FLOWS SHOULD WE CONSIDER?

As part of the INCASE project, we need to map out the different aspects of natural capital present and explore what data sources are available to build the different accounts within the NCA (SEEA) system. For the purposes of the project we will consider all systems – ecosystems, geosystems and atmospheric systems, and determine the feasibility of what can be accounted for with available data over the duration of the project and beyond.

ECOSYSTEMS AND ECOSYSTEM SERVICES

Ecosystems are diverse, depending on the physical environment (consider the contrasting conditions of desert and wetland), and diversity is also a feature within ecosystems (consider two wetlands - a pond and a peatland – comprising different sets of species diversity). Diversity thus is a structural feature of ecosystems, and the diversity among ecosystems is an element of biodiversity (MA, 2005).

Ecosystems are generally defined by characteristic features and/or species and can be variable in size. A range of classification systems exist, and the approach taken to delineate, and map ecosystem units generally depends on the classification system used in a given country and/or region. Work is ongoing in the European Union to develop a common approach to mapping ecosystems for natural capital accounting (EC, 2019). In practice, ecosystems are split into terrestrial and marine ecosystems, with most countries using either Corine Land Cover classes to delineate 'ecosystem asset units' or local classification systems (Maes *et al.*, 2013). In Ireland some work has been carried out by the NPWS in relation to developing a Habitat Asset Register (Parker et al., 2016). For INCASE, building on work in the EU and Ireland, habitats as defined in *The Heritage Council Classification* (Fossitt, 2000) will be most likely used as proxies for the ecosystems.

In regard to ecosystem services, to date a general grouping of 10-12 services have been well developed in terms of their accounting by the EU INCA project. These include food (marine and terrestrial), timber, purification of water, pollination, climate regulation, air purification etc. and largely reflect the availability of data to develop the accounts (EU, 2017). In the SEEA-EEA revision this group has been further developed and a broader range of 25 services are in development in terms of accounting approaches. This provides relatively good coverage of the services of immediate relevance in terms of contribution to human benefits. Note that the contribution of groundwater to ecosystems such as fens, wetlands, turloughs etc. is considered an abiotic component of ecosystems.

GEOSYSTEMS AND GEOSYSTEM SERVICES

Geosystem (van Ree and van Beukering, 2016; van Ree *et al.,* 2017) is defined as the underground environment that consists of subsoil, bedrock, minerals, oil, natural gas and groundwater. Note, it does not include soil and the ecosystem associated with soil, or groundwater that provides the abiotic support to ecosystems such as fens.

Geosystem services are considered as the outputs from geosystems that contribute to human wellbeing specifically resulting from the subsurface, including the flow of natural resources from stocks that have built up over geological time (Figure 2). Examples include aggregates, minerals, energy from fossil fuels, pollutant attenuation provided by subsoils, geological heritage sites, landscape geomorphology including associated cultural values, groundwater used for drinking, geothermal energy (potential) and carbon storage.

ATMOSPHERIC SYSTEMS AND SERVICES

The atmospheric system (Figure 2) is the physical and chemical system in the atmosphere consisting of wind, sunshine and precipitation and the outputs (services) from atmospheric systems that contribute to human wellbeing. Examples of the services include wind energy, solar energy, rainfall.

LIMESTONES AS GEOSYSTEMS

LIMESTONES IN THE IRISH LANDSCAPE

Limestones underlie more than 40% of the land surface of Ireland, including the most populated areas, the main agricultural areas and 75% of the total length of motorway (Drew, 2018). They are a major source of minerals, aggregates and building stone, and they provide some of our outstanding landscapes. Limestone aquifers provide most of the groundwater used for drinking water. Therefore, limestones provide a major component of our geosystem assets and our natural capital.

Applying and developing NCA for geosystem assets requires an understanding of not only the *extent* of limestones in Ireland, but also the *condition* of the limestone asset (pressures and condition indicators), the *services* provided, and the *benefits* received. Following through this logic chain we have developed here a high-level overview with the focus on some of the services or contributions of limestones to Ireland's Natural Capital, relying on data and discussions in other papers in *these proceedings* and on the Indecon report (IIEC, 2017) to inform the overview. This overview discussion of four geosystem services is a 'rough cut' of the approach and will be further developed as part of INCASE.

Services delivered by Limestones are discussed briefly here following the outline of asset extent and condition (as relevant to the service), the service itself and the benefit. We outline linkages to other papers in these proceedings and also highlighting further research questions to be answered during the INCASE project work. The services highlighted here[11] are :

- *Provisioning* (groundwater as a drinking source; metallic and non-metallic minerals);
- *Regulatory* (attenuation of pollutants);
- *Cultural* (geological heritage and tourism).

GROUNDWATER AS A DRINKING SOURCE

- *Asset extent*: The extent of limestone aquifers as a drinking source is a key aspect for NCA and is the main indicator for the service (Hunter-Williams, *these Proceedings*).
- *Asset condition*: Service provision will be influenced by pressures such as over-abstraction and contamination by pollutants. For instance, the WFD status results are a possible indicator of asset condition; with 94% of the area of karstic limestone groundwater bodies achieving the good status objective in 2019 (Maher, *these Proceedings*).
- *Services:* A provisioning service – aquifers providing approximately 810,000m^3/d for drinking water. In addition, there are substantial unused resources that have the potential for future use. Unlike in other European countries, there are seldom disservices arising from groundwater abstraction in Ireland due to relatively low level of usage.
- *Benefits*: According to the Indecon Report (2017), more than 160,000 private supplies of drinking water rely on groundwater, over 250 group water schemes (which supply more than 50 people) rely on groundwater and there are over 1,000 public supply wells and springs. The Indecon report puts a price of €0.14 per m^3 used for drinking water, giving a value of €41.3 million annually; while this is for groundwater provided by all aquifers, a high proportion is supplied by limestone aquifers.

METALLIC MINERALS

- *Asset extent*: With the closure of Galmoy and Lisheen mines, Boliden Tara Mines, located in limestones near Navan, is the only remaining lead and zine in Ireland; it is the largest underground zinc mine in Europe (IIEC, 2017).
- *Asset condition*: In the context of minerals, condition is likely to be linked to extent and a quality feature which will be explored during the INCASE project.
- *Services:* A provisioning service - Tara mines provides a vital source of raw materials. Good management of the mine and the tailing ponds ensure that there are no disservices; the facilities

[11] More services may be highlighted over the course of INCASE, but in general the services are highlighted because of their obvious contribution to human well-being.

are licensed by the EPA. As part of the INCASE project, consideration will be given to whether potential future services need to be taken into account.

- *Benefits:* The gross added value (GVA) of the lead and zinc sectors was estimated as €230 million (IIEC, 2017)

NON-METALLIC MINERALS

- *Asset extent*: Aggregate potential has been mapped by the GSI and country wide maps are available[12]. In addition, details on the location of active limestone quarries are available in the GSI Quarry Directory[13].
- *Asset condition*: As above – in the context of minerals, condition is likely to be linked to extent and a quality feature which will be explored during the INCASE project.
- *Services:* A provisioning service – limestones provide crushed rock as aggregates and lime (2 million tonnes annually) to improve lime-deficient soils and building stone. Quarries, if not properly managed, can have disservices such as sediment impacting on watercourses and water abstraction impacting on nearby wells and ecosystems.
- *Benefits:* The GVA of the non-metallic extractive industry was estimated at €233 million. (IIEC, 2017). It was not possible to extract the figures for the limestone component for this paper, but undoubtedly it is a substantial proportion to be investigated where relevant by the INCASE project.

GEO-HERITAGE AND TOURISM

- *Asset extent*: The GSI's Geological Heritage Programme (IGH) in GSI complements other nature conservation efforts by assessing Ireland's geodiversity, and by producing county reports that include County Geological Sites. Two – the Marble Arch Caves (Cavan/Fermanagh) and the Burren and Cliffs of Moher in Clare – of the three UNESCO geoparks in Ireland are in limestone areas.
- *Asset condition:* As the sites do not yet have a statutory designation, they are not protected, and their asset condition is unknown. Pressures include high visitor numbers in the case of landscapes such as the Burren, pollution of karst springs and damaging of caves.
- *Service:* A cultural service through recreation, tourism, intellectual development, spiritual enrichment, reflection, and creative and aesthetic experiences. In some instances, the geosystem service is closely connected to an archaeological or cultural service, e.g. Hill of Tara and the Rock of Cashel.
- *Benefits:* Research in the UK highlights that the UNESCO label added approx. £2.69 million to the UK economy pa for each UNESCO geopark. The Marble Arch Caves is estimated to generate approximately £17.2 million pa to the surrounding economy. It is estimated that the GVA from geo-heritage (fee-paying and free sites) and geoscience activities such as walking and hiking in Ireland was in the order of €176 million (IIEC, 2017).

SUBSOILS – POLLUTANT ATTENUATION

- *Asset extent:* Subsoils – glacial till, fluvio-glacial sands and gravels, alluvium, peat – cover more than 90% of the Irish landscape and their location, thickness, permeability and groundwater vulnerability have been mapped by the GSI.[14]
- *Asset condition:* As above – in the context of attenuation of pollutants, condition is likely to be linked to extent and a quality feature which will be explored during the INCASE project.
- *Service:* A regulating service – subsoils provide a protecting, filtering layer over groundwater to varying degrees, and this service is encompassed in GSI groundwater vulnerability maps, with vulnerability ranging from 'extreme' to 'low'.
- *Benefits:* There are a range of benefits, for instance, groundwater in high, moderate and low vulnerability areas are less prone to pollution than in extreme areas; and therefore, provides more

[12] https://dcenr.maps.arcgis.com/apps/webappviewer/index.html?id=ee8c4c285a49413aa6f1344416dc9956.

[13] https://www.gsi.ie/en-ie/publications/Pages/Quarry-Directory.aspx

[14] https://dcenr.maps.arcgis.com/apps/webappviewer/index.html?id=7e8a202301594687ab14629a10b748ef

value in terms of both safe drinking water supplies and the location of infrastructural developments. However, the means of allocating an economic value to this service is unclear and may not be feasible. This will be examined further by the INCASE project.

DISCUSSION

INCASE HIGH LEVEL OBJECTIVES AND RESEARCH QUESTIONS

This paper sets out some of the key concepts around natural capital and the NCA approach. The work is in its development phase in Ireland and the INCASE project will establish the necessary '*learning by doing*' platform and framework from which NCA can be implemented at catchment scale and inform the basis for national scale NCA, either during or beyond the lifetime of the INCASE project as set out in national and EU targets.

Four catchments[15] have been selected for the project and over the course of the research, a number of challenges will be addressed in terms of high-level concepts about NCA. These include discussions around valuation, the efficacy of the approach in general and basic aspects such as data share and data quality. Once the process to build the accounts is established, some of the potential applications of NCA will be explored, including the potential to inform integrated catchment management (ICM) and water quality. The SEEA approach has many parallels in approach to ICM basic principles and they should work well in a complementary way.

NCA AND GEOSYSTEM STOCKS AND FLOWS

With regard to geosystem assets and services, a number of research questions will be addressed through the INCASE project. Input from the geological and hydrogeological community will be necessary to answer these questions, which include:

- How do we classify geosystem assets (extent and type) using best available Irish data? What assets should we include?
- What is the best way to measure condition for different geosystem assets with Irish data? What pressures and/or condition indicators are presently in use? What is used in other countries / studies?
- What are the main geosystem services of focus in the four INCASE catchments and what about nationally?
- What is the best way to determine and measure *flows* (supply and use of services) using available Irish data?
- What are the benefits of focus in four catchments and how do these compare with the national perspective? Who are the beneficiaries? What benefits do they receive? What valuation system (physical, monetary, relative scale) is useful for each flow? What is used in other countries / studies?

CONCLUSIONS

Pioneering methods, tested and refined at catchment level by INCASE, will contribute to scaling up to national level, delivering effective and efficient use of project outputs to be of immediate use to policy makers. Developing a system of NCA fit for purpose will require addressing a range of challenges from high level epistemological ones (can nature fit into accounting methods?) to practical data sharing and quality issues, which requires a multi-disciplinary approach.

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[15] https://www.incaseproject.com/catchments

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SESSION II

CONCEPTUAL MODELS FOR NORTHERN IRELAND'S CRETACEOUS AND CARBONIFEROUS AQUIFERS

Paul Wilson, *The Geological Survey of Northern Ireland, British Geological Survey, Dundonald House, Upper Newtownards Road, Belfast, BT4 3SB*
Brighid O'Dochartaigh, *British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh, EH14 4AP*
Mark Cooper, *The Geological Survey of Northern Ireland, British Geological Survey, Dundonald House, Upper Newtownards Road, Belfast, BT4 3SB*

ABSTRACT

Northern Ireland's main limestone aquifers are found in the Carboniferous and Cretaceous sequences. Aquifer conceptual models have been developed for these and the other aquifers in Northern Ireland as a consistent platform from which more detailed conceptual models can be developed for any form of hydrogeological investigation and study. These are based on the most up to date research and data available.

The majority of the Carboniferous and Cretaceous limestones are located in upland terrain. Karst systems have developed within them, receiving sinking streams as their main source of recharge. They are predominantly free-flowing and have exploited pre-existing intersecting faults. Transmissivities are moderate to high but storativity is low in these aquifers. This means that episodic high yields are achievable from karst springs and boreholes, but they may not be sustainable as a supply source during drier periods.

Key words: *Aquifer, Cretaceous, Carboniferous, Northern Ireland, Fermanagh, Antrim, Karst, Chalk, Spring, Conceptual model, Fault, Recharge, Flow, Storage, Discharge, Groundwater*

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INTRODUCTION

Northern Ireland has a broad range of bedrock geology ranging from metamorphic Dalradian to sedimentary Oligocene rocks, and everything in between. This means that, unlike the Republic of Ireland, the limestone aquifers are not as dominant. Whereas all the significant limestone aquifers in the Republic of Ireland date from the Carboniferous period, Northern Ireland has significant limestone aquifers from both the Carboniferous and the Cretaceous periods. These limestone aquifers have created iconic landscapes such as the Marble Arch Caves Global Geopark in Counties Fermanagh and Cavan and the 'White Rocks' that are sheltered beneath a protective blanket of black basalt which accompany your drive along the Antrim Coast Road and the Causeway Coast.

In 2018, a project called 'Northern Ireland's Aquifers' was initiated to undertake a regional characterisation of groundwater aquifers in Northern Ireland. A similar exercise was carried out in the early 1990's (Robins, 1996), resulting in what is commonly known as the 'Red Book'. This has been the main reference for all hydrogeology in Northern Ireland in the past 25 years, during which time hydrogeology as a discipline has advanced and the role of groundwater has greatly expanded due in no small part to the EU Water Framework Directive (European Parliament, 2000).

The purpose of this latest project has been to establish a new framework upon which a new period of hydrogeological discovery in Northern Ireland can be based. Central to this is the development of conceptual models that underpin any work that a hydrogeologist or engineer might undertake. They are a powerful tool in their arsenal, often making the complex easier to understand.

The main outputs from the project are a new attributed hydrogeological map of Northern Ireland and an accompanying reference publication containing conceptual models of all the aquifers of Northern Ireland. The models summarise the best available understanding of the recharge, flow, storage and discharge mechanisms that occur in each aquifer, in the Northern Irish context. These will hopefully be launched at the start of 2021. These are the result of a new Groundwater Data Repository of aquifer property and chemistry values containing data from almost 3,000 boreholes and springs gathered from GSNI studies, drillers records and other publically available datasets. An index dataset is available on the GSNI Geoindex with data available upon request. This paper summarises the key characteristics of the Carboniferous Limestone and Cretaceous conceptual aquifer models from this publication.

CARBONIFEROUS

OCCURENCE AND GEOLOGICAL SUMMARY

Carboniferous Limestone rocks in Northern Ireland crop out predominantly in the southwest of the Province, in Counties Fermanagh and Tyrone, with smaller outcrops in Counties Londonderry and Armagh, and in the northeast of County Antrim near Ballycastle.

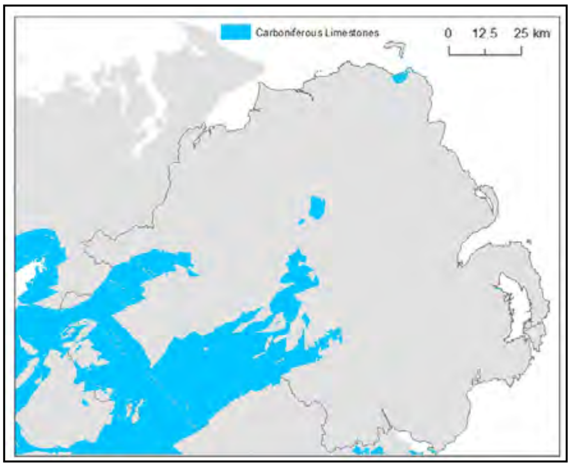

Figure 1: *Carboniferous Limestone Outcrop in the North of Ireland*
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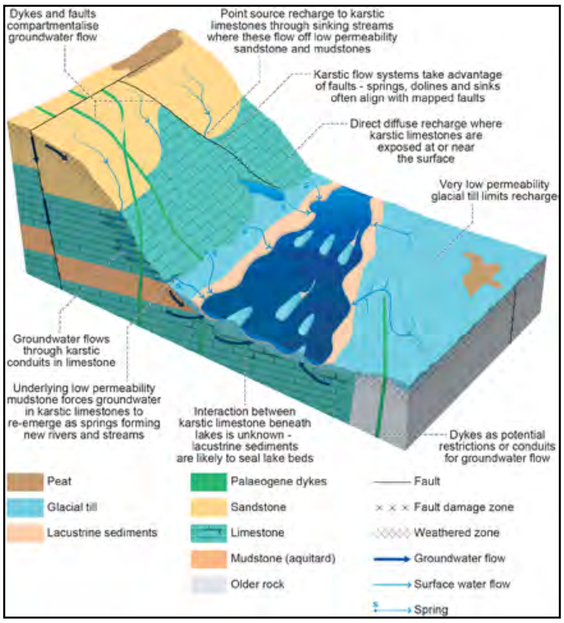


Figure 2: Carboniferous Limestone Conceptual Aquifer Model (*Crown Copyright 2020)*

The Carboniferous Limestone aquifers comprise a sequence of karstic limestones with mudstones, of Lower Carboniferous age. The rocks were formed in a marine deltaic environment with cycles of limestone, mudstone and sandstone deposition. The limestones are characteristically karstified, in some formations particularly so, including the Dartry Limestone Formation, the Knockmore Limestone Member and the Glencar Limestone Formation. These crop out mostly in County Fermanagh on higher ground, such as beneath the Cuilcagh and Belmore Mountains. The older Ballyshannon Limestone Formation is also karstified but is separated in the sequence from the karstic rocks higher in the sequence by the Benbulben Shale Formation, Mullaghmore Sandstone Formation and the Bundoran Shale Formation. Beneath this, the Clogher Valley Formation may also be partly karstified. In general, most of the limestone units are both underlain and overlain by mudstone units.

RECHARGE
The main recharge mechanism to the aquifer system is from surface water infiltrating through karstic sinkholes. The rivers may flow over low permeability mudstones that overlie the limestones, with little infiltration, before flowing onto limestone outcrops and into karstic sink holes. Direct rainfall recharge to the karstic limestone aquifer also occurs where rock is exposed at surface. The high infiltration capacity of the karstic limestone means that in these areas, recharge is similar to total effective rainfall.

FLOW
After sinking underground, groundwater flows through the limestone aquifer in the network of fractures and karstic conduits. Intergranular porosity and permeability are negligible. Carboniferous limestone is classed as a high productivity aquifer. Flow rates are highly variable, dependent not only on the size, interconnectedness and degree of complexity of the karstic system, but also on flow conditions (faster flows during higher flow conditions such as storm events). Typical flow rates measured in tracer tests are around 2–3 km/day (Brown, 2005)

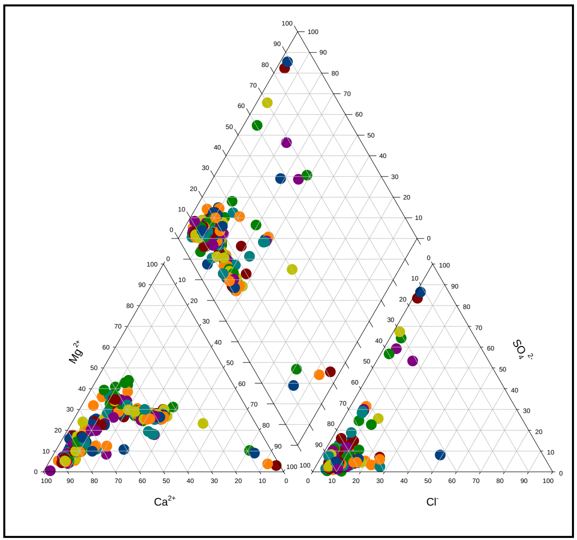
Intrusive igneous dykes are a significant feature to the north of Ireland. The exact role they play in groundwater flow is not well understood but it is expected that they act as barriers to groundwater flow, compartmentalising aquifers, and, in this situation, altering karst development. However, positive tracer tests have been performed between sinks and springs separated by dykes. One such test was conducted from Pigeon Pot to Shannon Cave, between which Cuilcagh dyke intersects the sequence of Carboniferous rocks. It is thought that post intrusion faulting may provide a preferential pathway for groundwater flow through dykes.

STORAGE
This is predominantly a function of the degree of karstification. The more karstified the limestones are, the more groundwater storage is available. However, in the more open karst systems, as can be entered at Marble Arch Caves, the available storage is not fully utilised, with streams flowing along the base of caves and conduits. In the more upland settings, such as in County Fermanagh, the steep hydraulic gradients increases the rates of flow. Therefore, typically groundwater storage is low in these limestones.

DISCHARGE
Groundwater discharge from the karstic limestone is normally as discrete springs, often at the base of individual limestone units immediately above low permeability mudstone units. Spring-fed rivers then flow over the underlying mudstones. Minor discharge also occurs from the aquifer directly into stream beds. The more well-known examples include the resurgence at Marble Arch, Hanging Rock spring and St. Patrick's Holywell near Belcoo.

Some of the lakes in County Fermanagh, such as Lough Erne and Lough Macnean, are underlain by these limestones. It is unknown if there is any significant discharge from the limestones to the lakes. It is likely that glaciolacustrine deposits found around these lakes limit the degree to which the lakes and the limestones interact.

CHEMISTRY



Groundwater in the Carboniferous Limestones is typically highly mineralised (median conductivity 577 µS/cm) and has a moderate pH (median 7.39) compared to other aquifers in Northern Ireland. Groundwaters are mainly calcium-bicarbonate type, with a minority of samples dominated by sulphate instead of bicarbonate (Figure 3). Rapid migration of contaminants as overland flow, into sinking streams and through open conduits make this aquifer extremely vulnerable to pollution. In the normal upland setting, likely sources will be from grazing animals and peat cutting.

Figure 3: *Piper (tri-linear) diagram illustrating the distribution of major ion compositions of Carboniferous Limestone aquifers in Northern Ireland*

AQUIFER PROPERTIES

A summary of the aquifer properties contained within the Northern Ireland Groundwater Data Repository, developed as part of the NIA project, are shown in Table 1. Transmissivity measurements from pumping tests are some of the highest values observed for bedrock aquifers in Northern Ireland, with a median of 174 m^2/d. Only four storativity measurements have been made. These all reflect an aquifer with limited groundwater storage, as described above. Measured yield is not a precise term but it does indicate how productive boreholes drilled in to these rocks can be. The median value recorded was 327 m^3/d. This shows that these rocks have the potential to yield moderate to high yields but this may not be sustainable due to low groundwater storage. These aquifers are not currently used for public water supply, and provide only a small number of private supplies. However, these demonstrate the potential to provide large supplies but may be more vulnerable to fluctuations in water quality.

Table 1:

Parameter	n	Minimum	Median	Maximum
Transmissivity (m^2/d)	9	10	174	2200
Storativity	4	9×10^{-5}	1×10^{-4}	4×10^{-4}
Specific capacity (m^2/d/m)	15	0.64	42	1177
Measured yield (m^3/d)	110	12	327	3382

Carboniferous limestone aquifer property summary data

CRETACEOUS

OCCURANCE AND GEOLOGICAL SUMMARY

Rocks of Cretaceous age in Northern Ireland comprise the Ulster White Limestone Group – also known as the Chalk – and the Hibernian Greensands Group. The Cretaceous sequence has a very limited outcrop, which is modified by Tertiary faulting that also makes the aquifer discontinuous.

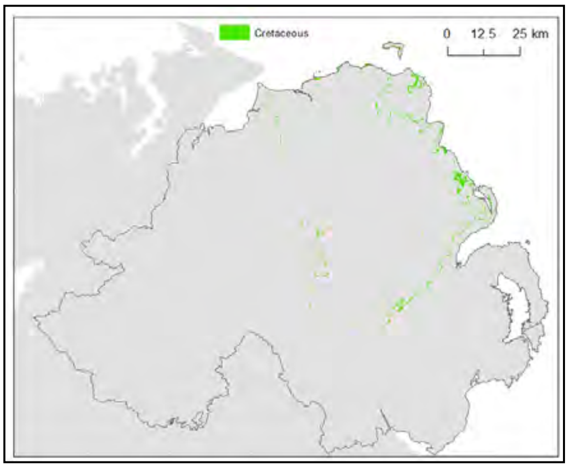


Figure 4: *Cretaceous Limestone Outcrop in the North of Ireland*
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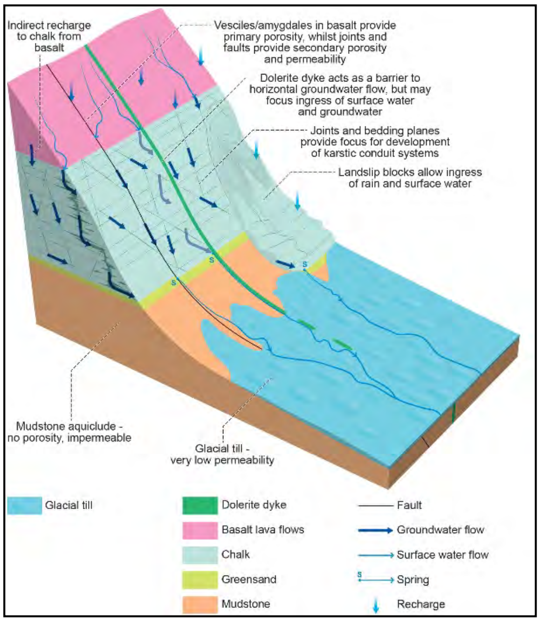


Figure 5: Cretaceous Limestone Conceptual Aquifer Model *(Crown Copyright 2020)*

The Ulster White Limestone Group is the equivalent of the English Chalk. Its total outcrop area is only 80 km^2, around the periphery of the Palaeocene Basalts (Antrim Plateau Lavas), which it underlies in the northeast of the Province. It is typically ~50 m thick, but in some places can be more than 150 m thick (Fowler et al., 1961, Fletcher, 1977). It is typically thickly bedded (0.3 to 1.0 m) with a wide joint spacing (5 to 10 m). It is a hard limestone, significantly harder than most of the English Chalk, due to extensive secondary calcite cementation in pore spaces (Maliva and Dickson, 1997) and can be karstic, forming large openings and conduits due to dissolution of calcium carbonate in the rock (Barnes, 2000).

The Hibernian Greensands Group underlies the Ulster White Limestone Group along the south and eastern edges of the Antrim Plateau between Lisburn and Glenarm, and in a small area east of Limavady. It is thin, with a maximum thickness ~ 30 m. It comprises a variable sequence including glauconitic sands, sandstones, marls and mudstones, and is underlain by Jurassic or Triassic mudstones.

RECHARGE

The chalk is recharged mainly by infiltration of river water through sinkholes in river beds in the active karstic outcrop zone. These rivers can be seen flowing over the basalts aquifer outcrop before reaching the chalk outcrop, where water infiltrates (‘sinks’) through individual large karstic sinkholes or several smaller sinkholes over the course of a short length of river bed.

Where the chalk is covered by basalts, some recharge is also thought to occur by groundwater draining down from the overlying lavas. Studies of a number of chalk springs, such as Toberterin near Stewartstown in County Tyrone, have shown, using water chemistry studies and flow gauging, that the discharging groundwater is predominantly recharge from the basalts (Barnes, 1999).

FLOW

Groundwater flow in the chalk is dominated by fractures, with a significant karstic flow component. Intergranular porosity and permeability are negligible. The chalk is classed as a high productivity aquifer.

The main active karst zone within the chalk occurs in its outcrop area – not where it is buried beneath the basalts – and the highest permeability values are also thought to be in this zone, although there is little measured data (Robins et al., 2011). Karst development has been promoted by groundwater flow, so that it is greatest in areas where recharge potential is highest and there is the most active groundwater flow. Some of the karst is thought to be palaeokarst, developed before the overlying basalts were erupted (Robins et al., 2011). Major sinkholes and springs occur along the Antrim coast, indicating significant active karst conduit systems.

Controls on the depth of active groundwater flow in the chalk vary. At outcrop, its limited thickness is the main control; in the confined zone, where it is covered by basalts, poorer fracture development may restrict flow to the upper part of the chalk. Groundwater flow paths in the chalk beneath the outcrop are likely to be generally short (100s metres), and partly controlled by topography, but preferential flows through fractures and karst features, where they are present, have a significant local influence. There is some potential for limited regional flow down-dip in the confined chalk. Major fault zones may also influence groundwater flow in some areas. In the east, flows appear to be faster (e.g. 500 to 1000 m/day) and flow paths shorter, with a ‘flashier’ groundwater response, with slower responses in the west (Barnes, 1999). Barnes suggested that this indicated rapid flow of young (recently recharged) groundwater in the east; and discharge from the base of the basalts in the west.

As with Carboniferous limestones, intrusive igneous dykes cut through the Cretaceous sequence. They act as barriers to groundwater flow, compartmentalising aquifers (Comte et al., 2017). This can alter what may be the normal conceptualised flow path for groundwater and need to be considered as a significant influence on the development of any conceptual groundwater model.

The chalk and the underlying thin Hibernian Greensands are classed together as a single aquifer group, despite having very different hydrogeological properties, because the available evidence indicates they are hydraulically connected (Foster et al., 1969).

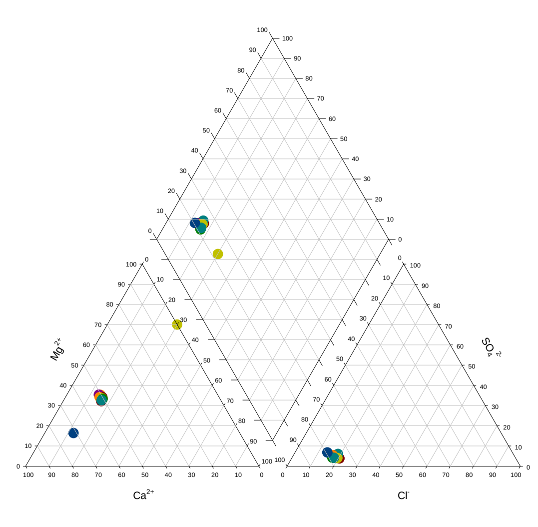
STORAGE

In dry weather, when river flows are low, the chalk aquifer can accept all recharge from sinking river flow, and chalk rivers often have dry beds for a few hundred metres before groundwater discharges to the surface again. However, during high flow conditions, the chalk storage capacity can be exceeded so that the aquifer cannot accept more recharge; groundwater levels rise to the ground surface, including in sinkholes, which become points of groundwater discharge from the aquifer, feeding the previously dry river beds so that they start to flow again.

DISCHARGE

Most groundwater discharge from the chalk is from springs, of which there are many. These typically discharge from the base of the chalk or the base of the underlying Greensands, which is underlain by lower permeability older rocks, such as Jurassic and Triassic mudstones. One of the largest known of these springs is Carey River Spring, which is the main discharge point for water draining from Loughareema (the Vanishing Lake) in north-east Antrim. This has a normal flow rate of at least 30 l/s when the lake is empty, and a largest measured flow of over 200 l/s when the lake is full.

CHEMISTRY



There are relatively little groundwater chemistry data for the Cretaceous aquifer. The available data indicate that groundwater is typically relatively weakly mineralised (median conductivity 349 µS/cm) and has a neutral pH (median 7.51) compared to other aquifers in the Province (Figure 3). The groundwater is typically of calcium bicarbonate type (Figure 7).

Figure 5: *Piper (tri-linear) diagrams illustrating the distribution of major ion compositions of Cretaceous Limestone aquifers in Northern Ireland*

AQUIFER PROPERTIES

A summary of the limited aquifer properties contained within the Northern Ireland Groundwater Data Repository are shown in Table 2. Of the three transmissivity values available, the median was 360 m^2/d. The median measured yield is 327 m^3/d, exactly the same as the Carboniferous limestones.

Due to Chalk outcrop normally only being accessible to drill along the steep-sided cliffs around the Antrim Plateau, drilling a reliable production borehole can be difficult. It is not uncommon for groundwater to be struck at the base of the chalk and for it not to rise within the borehole, indicating it to be free-flowing. This therefore requires a sump to be drilled in to the underlying mudstones from which groundwater can be pumped. In the 1970's a feasibility study was carried out to consider the prospects from an adit drilled in to the chalk cliffs as a water supply source for parts of North Belfast, however this was not progressed due to the limited storage within the chalk aquifer (Bennett, 1978).

Table 2:

Parameter	n	Minimum	Median	Maximum	Single value
Transmissivity (m^2/d)	3	30	360	731	
Storativity	1				0.09
Specific capacity (m^3/d/m)	2	21		875	
Measured yield (m^3/d)	5	17	327	2880	

Cretaceous limestone aquifer property summary data

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GSI'S REGIONAL ASSESSMENT OF GROUNDWATER RESOURCES: A CASE STUDY FROM THE BOYNE CATCHMENT, WITH A FOCUS ON LIMESTONES

Katie Tedd[1], Robbie Meehan[2], Coran Kelly[3], Monica Lee[1], Damien Doherty[3], Natalie Duncan[2], Joe Greene[3], Monika Kabza[2], Ellen Mullarkey[3], Melissa O'Keeffe[2], Alasdair Pilmer[4], Sara Raymond[2], Philip Schuler[2] and Shane Carey[2]

[1] Groundwater Section, Geological Survey of Ireland, Beggars Bush, Haddington Road, Dublin 4
[2] Consultant Geologist, here representing Groundwater Section, Geological Survey of Ireland
[3] Tobin Consulting Engineers, Block 10-4, Blanchardstown Corporate Park, Dublin 15
[4] Gavin & Doherty Geosolutions, Unit A2, Nutgrove Office Park, Rathfarnham, Dublin 14
[5] CDM Smith, 15 Wentworth, Eblana Villas, Dublin 2

ABSTRACT

The main objective of groundwater resource assessment can be summed up by the term "Safe Yield of an aquifer" (Wright, 1987), which is the acceptable limit of annual abstraction from an aquifer. This is the maximum annual yield from the aquifer which can be abstracted without adverse consequences. Geological Survey Ireland (GSI) has recently re-visited the regional assessment of potential groundwater resources. GSI's Groundwater Section are building on previous regional studies undertaken for the groundwater resources in the east of the country, using surface water catchments as the unit for assessment. This follows the principles of integrated catchment management which uses surface water catchments as integrated systems including aspects related to meteorology, bedrock geology, subsoils geology, soils, ecology, hydrology and hydrogeology, in which natural resource applications and ecological and water protection takes place. A case study of this approach in the Boyne Catchment is discussed, as well as the eventual derivation of a National Scale Groundwater Resources Potential map.

INTRODUCTION

It was only in the 1960s that laws affording some level of protection to the rights of persons or companies abstracting groundwater came into being across the developed world (Younger, 2007). These regulations generally involved some form of permit, whereby an onus was placed on a new abstractor to satisfy a public authority that the new pumping operation would not adversely affect the continued availability of water to those abstracting in the vicinity.

An approach such as this may be seen as a 'reactive' tool for managing groundwater, in that water management entities and environmental regulators respond to proposals made by potential abstractors with water needs. Such a *schema* should serve humans well, but also assessing the potential effects on ecosystems is not straightforward. But this is becoming increasingly more important in our modern era of climate and biodiversity crises.

The challenge of having good ecological status in our waterbodies has been taken up in Ireland's endeavour to fulfil the requirements of the Water Framework Directive (European Union, 2000). An important component of this Directive is the assessment of the quantitative or volumetric status of our water bodies, which has been a significant driver in developing the water abstractions register (Government of Ireland, 2018) and the upcoming Water Environment (Abstractions) Bill which will outline how abstractions will be licenced.

It is within this developing regulatory framework that we can now better consider not only the role of groundwater, but also the details and logistics involved in how groundwater resources must be managed to meet both present day as well as future demands, without having a detrimental effect on ecosystems.

Although both groundwater quality and quantity are both critical considerations when assessing groundwater resources, current characterisation work being undertaken by GSI is focussing on the latter. In many respects the main objective of quantitative groundwater resource assessment can be summed up by the term "Safe Yield of an aquifer" (Wright, 1987; Zhou, 2009). The term 'Safe Yield' is the acceptable limit of annual abstraction from an aquifer. Originally it was taken as being equal to the annual recharge to the aquifer, but nowadays it is defined in a more subtle way as "the maximum annual yield from the aquifer which can be abstracted without adverse consequences" (Alley and Leake, 2004). Depletion of the resource is only one of the possible adverse consequences.

The pursuit of *truly* sustainable groundwater resource management might be considered as something of a holy grail, but the key to achieving this is by applying a holistic and iterative approach that updates the method with newly available data and conceptual understanding. This holistic approach must also take scale into account that a potential abstractor is usually interested in abstraction at only one particular locality in the landscape. However, to assess potential impact on the resource or associated ecosystem, the cumulative impact of all abstractions within a waterbody, catchment or region must be considered.

GROUNDWATER RESOURCE MANAGEMENT IN IRELAND – A HISTORY

Perhaps the earliest regional assessment of groundwater resources in Ireland, at a 'top down' level, was commissioned by the Northeast Regional Development Organisation (N.E.R.D.O.) in 1971. They requested that An Foras Forbartha, which was a division of the Irish Government concentrating on physical planning, road and building construction, and protection of heritage, and GSI, to assess the groundwater resources of the northeast region, comprising Cavan, Monaghan and Louth. The study (NERDO, 1981) included data collation, well surveys, and a limited drilling programme. A comprehensive report was produced, recommending future investigations, and a number of viable water supplies (which are largely still in use) were provided as a result.

A few years later, between 1978 and 1979, GSI was commissioned by the European Commission to define the aquifers of the country as far as possible, and then to calculate the available resources of these aquifers (Wright, 1987). This national calculation of groundwater resources was principally driven by the estimation of recharge. The need to meet stream flow was not taken into account, but a saline intrusion constraint was applied where necessary. Existing abstractions were subtracted from the recharge estimate to arrive at a figure for 'surplus resources'. The resulting figures may have been very approximate, but they represent the first attempt to carry out such an exercise in this country (Wright *et al.*, 1982).

It should be borne in mind that during this time the principal water development infrastructure of the country comprised the 'Regional Water Supply Scheme' (Galvin, 1992). Regional schemes were developed in every county through the late 1960s, 1970s and 1980s. The sources developed (river, lake or groundwater) and the type of treatment employed (if any) varied markedly, as did the scale of the schemes. Regardless of size, much of the hydrogeology of these schemes was at a local level, meaning, hydrogeologically, a more 'bottom-up' approach to groundwater resource planning and management. GSI was always mindful of 'top-down' resource assessment during this period (*e.g.* Daly, 1982; Wright, 1987), but at a local level the sole aim of each scheme was identical; to produce potable water meeting the standards required by the Drinking Water Regulations of the day. The design, construction, testing and supervision of water wells were often inadequate, even at a local scale, for any thorough element of hydrogeological characterisation.

An important groundwater resource potential study was completed for the Dublin Region in 2007-08 by Eugene Daly and Associates (EDA, 2008). This high level desk study assessed the potential for the large scale development and abstraction of groundwater to contribute to the water supply requirements of the Dublin Region, by examining the groundwater resources of the principal aquifer units within 80 kilometres of the city. It was concluded that, in order to develop a combined resource of up to 125 megalitres per day, a minimum of twenty wellfields would be required. Overall, 'developable' groundwater resources were considered as relatively limited, geographically disparate, spatially discrete and generally situated at an appreciable distance from Dublin itself (EDA, 2008), meaning that the assessment considered that groundwater could not exclusively meet the significant water resource demands required by Dublin.

A source yield review for the Eastern and Midlands Region Water Supply Project, for Irish Water, was completed in 2015 by Jacobs-Tobin. This report re-calculated the water balance of the EDA (2008) study, using more recent GSI data/datasets on groundwater vulnerability and recharge, and suggested a similar resource magnitude to those originally estimated by EDA in 2008. Importantly, also, the report suggested that significant further information would be required on abstraction volumes and the ecological flow requirements of the rivers and wetlands in order to predict the impacts of abstraction on ecosystems in the region.

Further from the above, some specific historical engineering and hydrological projects required water balance studies, which is one of the crucial contributory elements of groundwater resource assessment and management. An analysis of water resources at Lough Scur in County Leitrim was undertaken for the purpose of water supply to the Ballinamore and Ballyconnell Canal (ESBI, 1990). The results were used in the planning of the pumped water supply system to the summit, and in the identification of areas of canal which will be lined to prevent seepage loss. In the Liffey Catchment, a Conceptual Flood Forecasting Model has been derived using a water balance study (Brogan, 1986). A number of separate flood events were used to verify the modelled output for the catchment. Both of these practical studies indicated that water balance studies are useful in verifying original data, as well as in the investigation of groundwater effects on surface flows in an Irish context.

Most recently, the National Aquifer Map and National Groundwater Recharge Map, initially developed in the late 1990s and late 2000s respectively, are potentially the most widely used and best known groundwater resource potential maps for the country. Initially, county aquifer maps were being produced by GSI as part of the GWPS programmes, started in earnest in the 1990s, but the completion of the national map (in 2004) was expedited for use in the WFD characterisation process. The National Recharge map was also developed for proposes of WFD characterisation, by the WFD Groundwater Working Group (see, for example, Hunter Williams *et al*., 2013). GSI took ownership of hosting and updating the map after its initial development.

GSI's CURRENT GROUNDWATER RESOURCE POTENTIAL ASSESSMENT

GSI's Groundwater Section has recently started to re-visit the regional assessment of potential groundwater resources in eastern Ireland. GSI is building upon previous regional assessments in the east of the country and taking them a stage further by incorporating data that has become available since the above studies were completed. GSI is also using surface water catchments as the unit of assessment, which not only follows the principles of integrated catchment management but also enables more comprehensive water balance assessments to be undertaken as additional catchment-based quantitative data – surface water levels and flows in particular – are based on the same study area. Such an assessment also allows a more thorough understanding of Irish groundwater and its contribution to surface water to be achieved, which will become increasingly important when considering the effects of climate change.

The initial project was developed from discussions with Irish Water regarding its water supply needs – including the emergency issues faced during the 2018 drought – and in considering their information gaps. The work is being conducted to identify potential areas for new groundwater supplies. Public water supplies are a specific focus of the project to provide scientifically-robust information to support Irish Water. One of the key elements to this holistic approach has been close co-operation with the EPA, as providers of data and input into analyses.

The ultimate aim of this assessment will be to formulate a consistent and objective methodology to further assess groundwater resources on a regional basis in Ireland. Although there is already a good general understanding of regional resources in eastern Ireland from previous studies, this work will further develop and refine that knowledge and guide the relevant stakeholders to optimise groundwater resource management.

DATA AND METHODS EMPLOYED IN RESOURCE POTENTIAL ASSESSMENT

Within each catchment studied, physical watershed boundaries are used to delimit the assessment unit (see Figure 1).

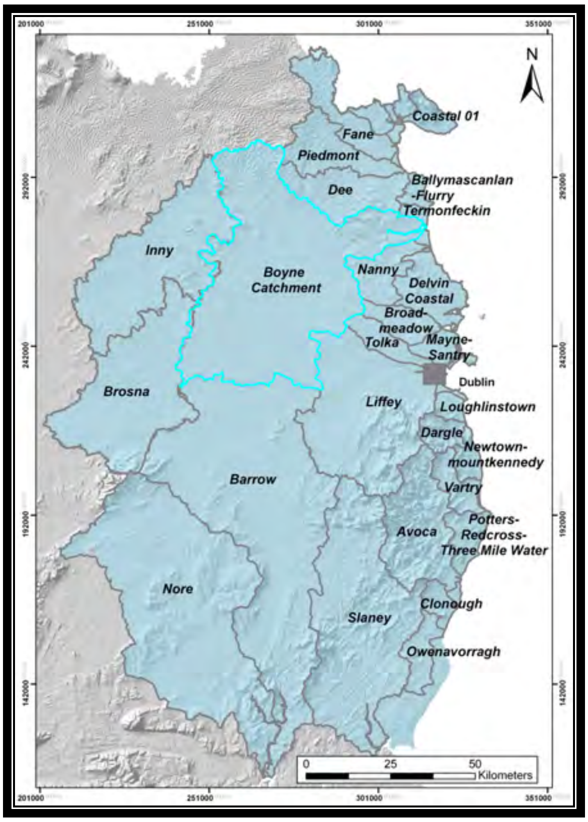

Figure 1: Catchments included in the east of Ireland study area, illustrating the situation of the Boyne.

Within each assessment unit, the catchment is assessed in terms of its natural and anthropogenic setting, to form a conceptual model of the main drivers of hydrological and / or hydrogeological characteristics, flows and properties therein. Site specific data are then examined to ascertain if this matches the regional mapping concept. For example, the Dunshaughlin groundwater monitoring point at the southeastern end of the Boyne Catchment is located in Dinantian Upper Impure ('Calp') limestone bedrock, classified as a locally important, moderately productive, 'Lm' bedrock aquifer. Groundwater levels in the borehole have a relatively wide range (approximately 9 m, see Figure 2).

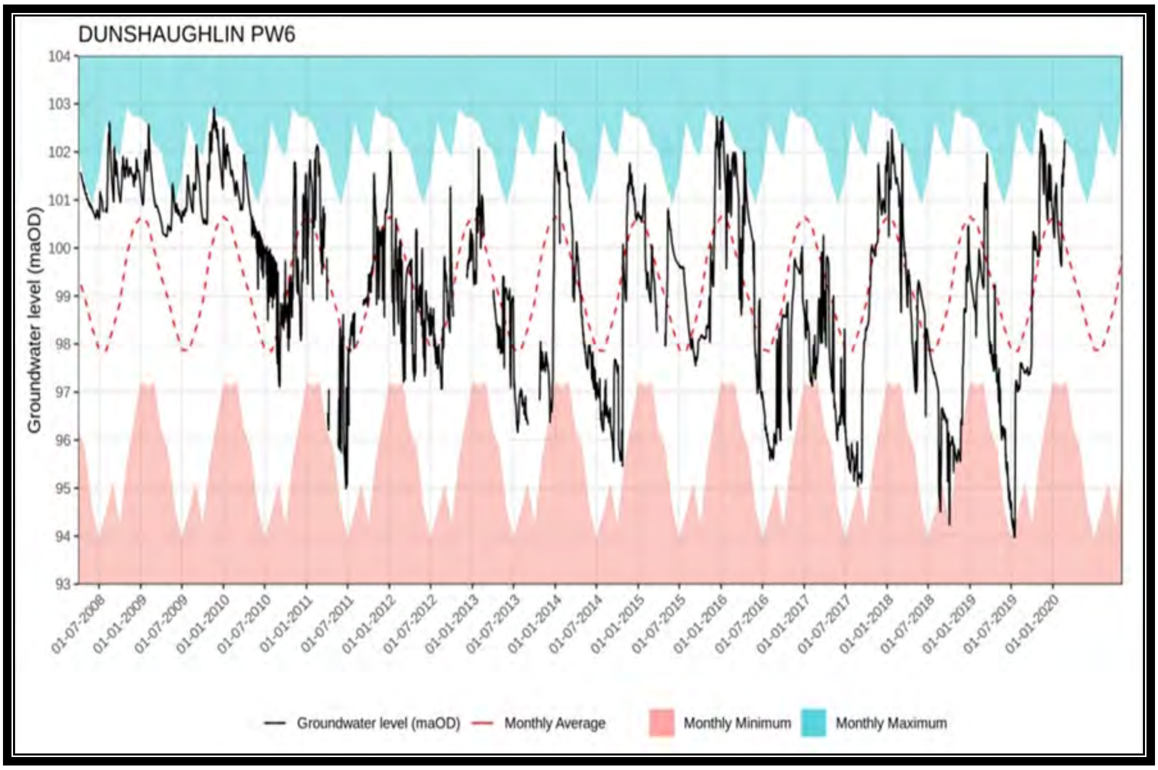

Figure 2. Groundwater levels at the Dunshaughlin Public Water supply borehole, at the southeastern edge of the Boyne Catchment.

Data from the regional and site specific assessments are then collated to develop conceptual models for sub-zones within the larger catchment region, with associated water balance calculations derived. The water balance calculations are holistic and consider groundwater as part of the entire catchment system. The sub-region conceptual models are then used to split the catchment up into similar hydrogeological zones. These zonations and the conceptual understanding of the catchment is then used to rank the different areas in the catchment in terms of groundwater resource potential. The water balance assessment is completed on the entire catchment to understand how water travels through it and how significant groundwater is within the catchment. The water balance consists of a calculation that accounts for all significant inputs and outputs of water to and from both surface water and groundwater systems in the catchment, and any interactions between these two systems.

The final portion of the study assesses potential constraints on future abstractions. An abstraction impact assessment is carried out, based on the Water Framework Directive's groundwater quantitative assessment, and a surface water capacity test is completed, based on EPA QUBE[1] outputs. Other considerations taken into account include the presence and situation of protected areas within each catchment, aspects related to groundwater vulnerability therein, and potential impacts on groundwater quality. An overview appraisal of the potential impacts of climate change is also incorporated.

As well as identifying areas with good groundwater resource potential for further, local scale investigation, these catchment-scale assessments also compile all data relevant to groundwater resources within that catchment into one place, develop hydrogeological conceptual models and water balances which will be of use to many separate and disparate stakeholders in the future, and, given that the studies are data-driven, identify obvious data gaps and areas for potential future research, assessment and monitoring.

[1] QUBE refers to Wallingford Hydrosolutions 'Qube' application, which is a successor to the EPA HydroTool, and which enables accurate assessment of the impacts of surface water and groundwater abstractions and discharges on river flows into the future.

CASE STUDY OF THE BOYNE CATCHMENT

The groundwater resource potential assessments identify significant differences in the limestones across Ireland when compared to other bedrock types, which is expected given that these rocks generally occupy a subset of the more productive aquifer classes.

The River Boyne catchment is in east central Ireland and borders the Erne, Shannon, Barrow and Liffey catchments as well as smaller coastal catchments to the east and northeast (Figure 1). The majority of the catchment is relatively lowlying, with elevation typically below 200m AOD. The river discharges into the Irish Sea *via* the Boyne estuary at Drogheda. The majority of the catchment area is dominated by deep, well drained mineral soils, but both the northern portion and southern half of the catchment have significant areas of poorly drained soils, associated with low permeability subsoils.

In terms of hydrogeology, the southern two-thirds of the catchment area is underlain by limestones, with older shales and siltstones in the northern third. The limestones are classed locally important (Ll), moderately productive (Lm) aquifers in the majority, but two pockets of karstified bedrock do occur; at the eastern extreme, south of Drogheda, where the karst is classified as regionally important aquifer (Rkd), and at the western extreme, near Castlepollard, where a locally important karst aquifer (Lk) is in evidence. Pockets of locally important sand and gravel aquifer (Lg) are also distributed widely throughout the catchment, particularly the southern end.

In terms of groundwater vulnerability, low vulnerability is associated with the low permeability subsoils where they are sufficiently deep, most interestingly capping the regionally important karstified aquifer in the east. The majority of the rest of the catchment area is subdivided generally between high and moderate vulnerability, with a marked band of extreme vulnerability trending west-east between Castlepollard, and through Kells, to Slane.

Integrating with recharge calculations for the various recharge rankings across the catchment, and taking into account protected areas and existing abstractions, the resultant conceptual model of the catchment allows the determination of five 'groundwater resource potential zones'. These are shown in Figure 3.

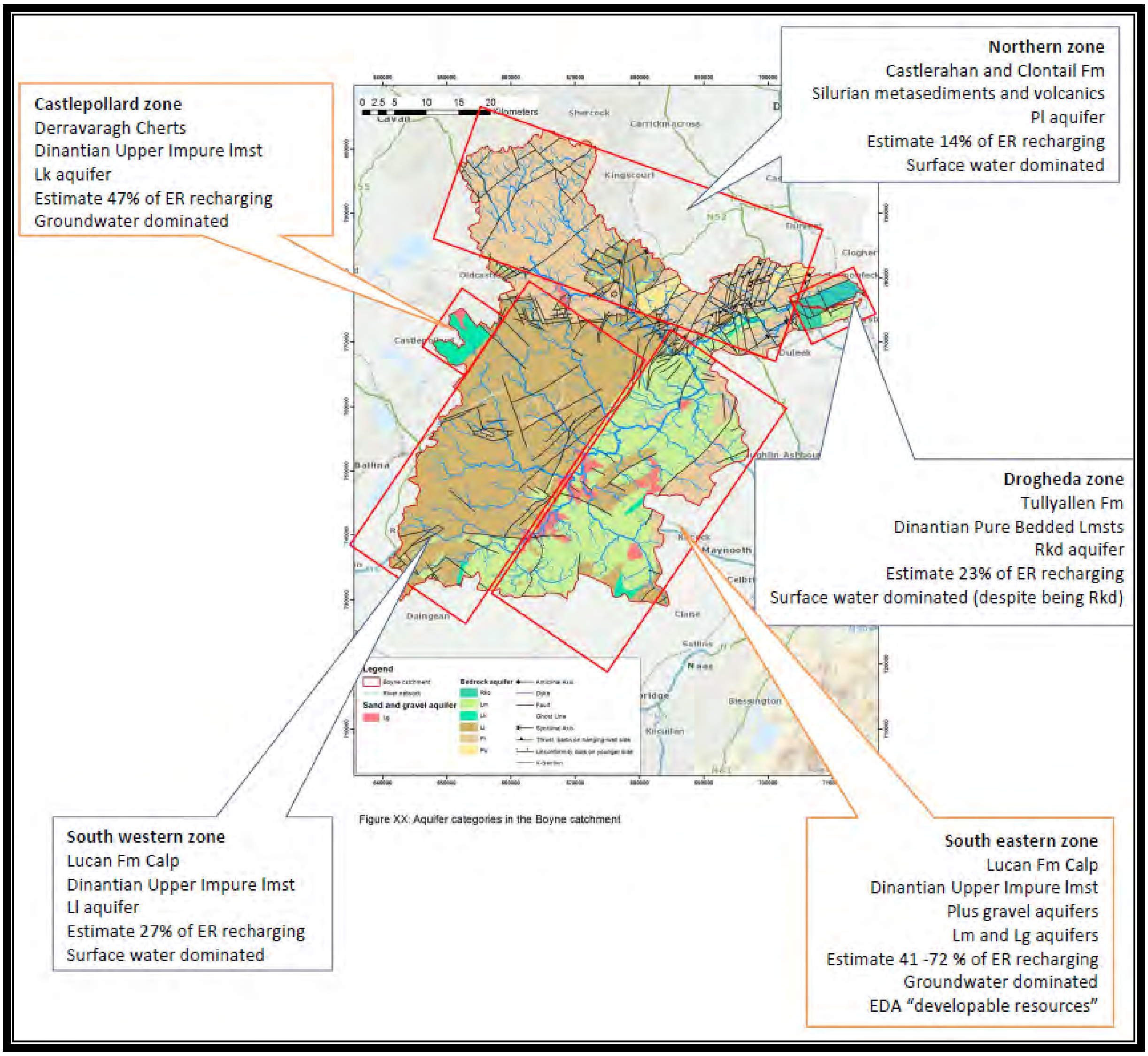

Figure 3. Hydrogeological conceptual model and resultant groundwater resource zonations for the Boyne catchment.

THE NATIONAL GROUNDWATER RESOURCES POTENTIAL MAP

The results of the groundwater resource potential assessment for each catchment only give focussed priorities for within that catchment. The methodology gives such a good empirical conceptual model for the catchments that, when combined, the catchment zonations allow a regional, and eventually national, groundwater resources potential assessment to be derived. Thus, all the results together will mean that a 'top-down' national groundwater resource potential map will be the ultimate deliverable, at national scale, for the study.

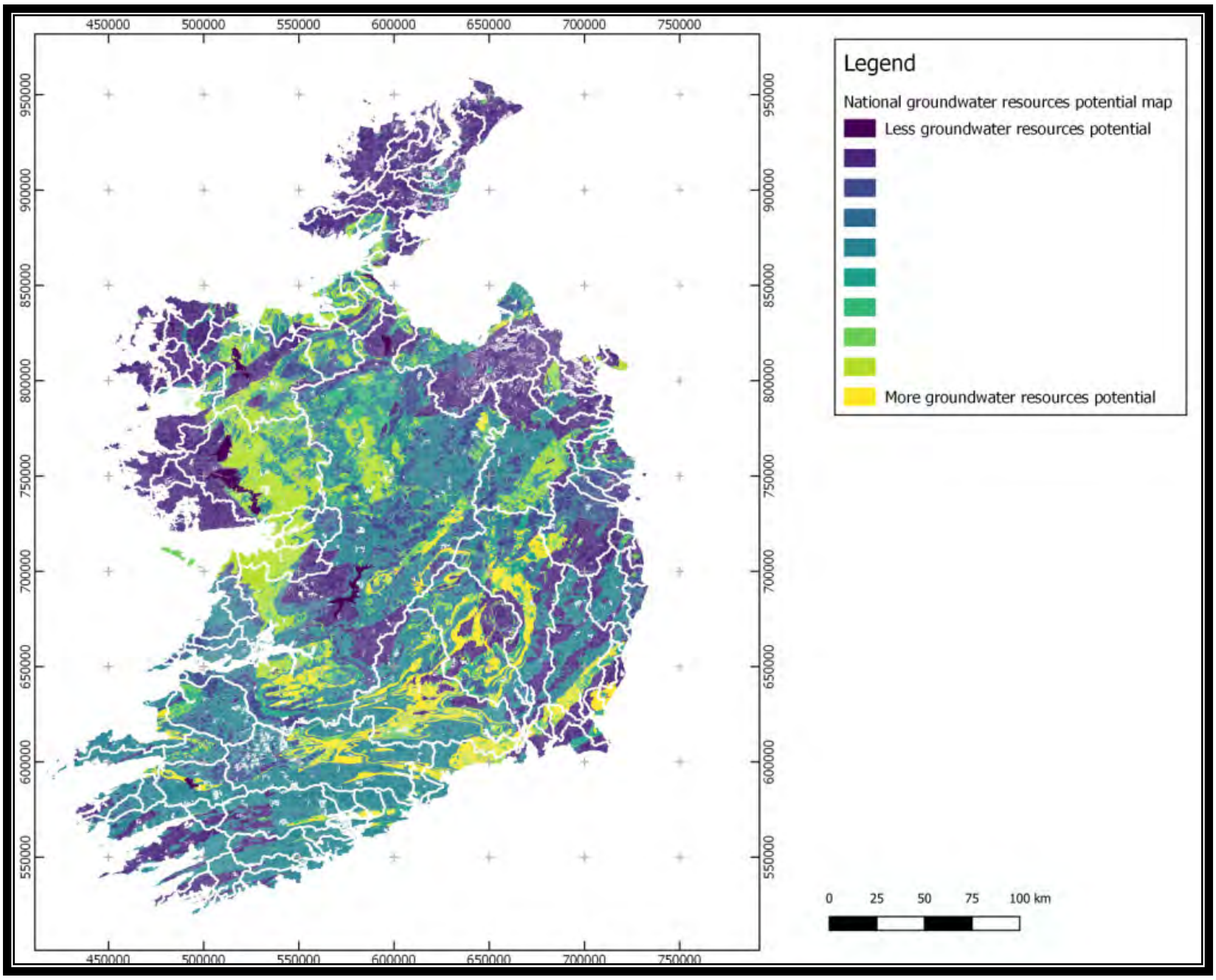

Figure 4. Early version of the National Scale Groundwater Resource Potential map.

A national scale groundwater resource potential map, which shows likely priority areas nationally, has already been developed using the aquifer and recharge GIS layers and criteria for the catchment studies at a national scale (Figure 4). This map will be complimented by a potential constraints map, and will be updated and refined by the results from the individual catchment studies.

CONCLUSIONS

The current groundwater resources assessment work of Groundwater Section in GSI builds upon existing regional work and expertise but now also provides a consistent and objective methodology to assess groundwater resources on a regional and catchment basis. As well as this, the work identifies areas with good potential groundwater resources for further, local scale investigative study. Furthermore, though the 'top-down' study is at a regional scale, the methodology is quite powerful in terms of illustrating where there might be issues, even at a much more detailed, and local, scale.

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ARE ABSTRACTIONS SIGNIFICANT PRESSURES ON OUR WATER RESOURCES?

Janka Nitsche

Environmental Protection Agency, Richview Dublin

ABSTRACT

In early 2020, to support the implementation of the Water Framework Directive (WFD), the EPA completed a national e-flow screening assessment of all natural surface water bodies. The assessment utilised long-term naturalised surface water flows and average abstraction volumes, the latter collated in a register under the EU (Water Policy) (Abstractions Registration) Regulations. By the end of 2019, more than 2,300 water abstractions were registered with the EPA from sectors including; drinking water, industry, quarrying, agriculture, hydropower, aquaculture, navigation.

The assessment identified over 460 of these abstractions to be "significant" and potentially impacting associated surface waterbodies. These include not only direct abstractions from lake and rivers, but also groundwater abstractions. The assessment highlighted that 14% of all lakes and 9% of all river waterbodies in Ireland were potentially impacted by these significant abstractions.

The collected data and results of this national assessment will be utilised for the implementation of a risk-based abstraction licensing regime, for both existing and future abstractions. The precise details are to be confirmed in the finalised legislation, but the overall objective will be to ensure all abstractions are, or will, become sustainable. In this regard, it is crucial that all stakeholders work together so that we have accurate and reliable information and complete each component of the assessment with a high degree of certainty. Only then can we ensure all our waterbodies and their ecological health are managed sustainably into the future and become resilient to climate change.

Key words: *Abstraction register, significant abstractions, E-flows, sustainable abstractions, water resources.*

INTRODUCTION

An understanding of the impact of water abstractions is crucial for the sustainable management of our natural water resources. An integrated assessment of water abstractions considers the cumulative impact of abstractions and discharges on river flows, lake and groundwater levels and their ability to sustain aquatic environments. It can also be used as an indicator of a waterbody's resilience in the face of climate change. Therefore, results of such abstraction assessments drive the decision-making process for catchment management. In 2020, a national abstraction impact assessment of registered water abstractions was carried out by the EPA as part of the Water Framework Directive (WFD) 3rd Cycle River Basin Management Plan characterisation process.

The objective of this paper is to outline the approach used to assess the impacts of surface and groundwater abstractions on river flows and lake levels, and their ability to support and maintain healthy aquatic ecology.

REGULATIONS AND ABSTRACTION REGISTER

Primary legislation dealing with the regulation of abstractions is currently making its way through the Oireachtas and will repeal and replace the Water Supplies Act 1942 and part of the Local Government (Sanitary Services) Act 1964. The proposed legislation would provide for the introduction of a regime for the control of water abstractions using a risk-based approach, as highlighted in the River Basin Management Plan for Ireland (2018 - 2021) to comply with Ireland's obligations under the WFD. Under the proposed legislation, general binding rules would apply to all abstractions irrespective of volume or duration, with specific general binding rules governing construction dewatering and geothermal abstractions.

Since 2018, under EU (Water Policy) (Abstractions Registration) Regulations (S.I. no. 261 of 2018), all water abstractions of 25 cubic metres per day or more, must be registered with the EPA. Registration can be completed via the EDEN portal on the EPA website, free of charge. By the end of 2019, over 1,448 abstractions consisting of 2,337 abstraction points were registered in total on the EPA portal. 1,031 of these abstraction points were 250 cubic metres or more per day and 261 of these were 2,000 cubic metres or more per day. The sectors for water abstractions, in order of total registered sectoral volume, are: drinking water supply, industrial, agriculture, quarrying, drainage, commercial, hydropower and aquaculture and also include the, recreation and navigation sectors.

ASSESSMENT METHODOLGY

RIVER ASSESSMENT METHOD

The impact assessment of abstractions on rivers is based on the e-flow concept (EC CIS no. 31, 2015). A high-level description of the current approach to e-flows in an Irish context was presented at the 2019 IAH (Irish Group) Conference (Quinlan 2019).

Ecological flows (or e-flows) are defined within the context of the WFD as a "hydrological regime consistent with the achievement of the environmental objectives of the WFD in natural surface water bodies as mentioned in Article 4(1)".

Considering Article 4(1) of the WFD, the environmental objectives refer to:

- Non-deterioration of the existing status;
- Achievement of good ecological status in natural surface water body; and
- Compliance with standards and objectives for protected areas, including the ones designated for the protection of habitats and species where the maintenance or improvement of the status of water is an important factor for their protection, including relevant Natura 2000 sites designated under the Birds and Habitats Directives (BHD) (EC, 2015).

The fundamental elements of e-flows have been described in Bunn and Arthington (2002) and refer to the naturally present hydrological regime of a waterbody. These are regimes that support the various organisms which will have adapted to thrive under a specific regime of low flow, high flow and flow dynamics of a given magnitude and frequency during different parts of their life cycles (in a river or lake waterbody). Changing the hydrological flow regime of a waterbody is likely to be detrimental to the biology of an aquatic environment, as it will not provide suitable flows to support the various organisms present during different parts of their life cycles.

The characterisation of e-flows therefore necessitates an understanding of seasonal flows and dynamics over time for the entire reach of the river. There has been limited research on characterising e-flows in Ireland to date, resulting in an insufficient evidence base for setting bespoke Irish e-flow standards. Instead the current assessment uses the e-flow standards for rivers employed in Northern Ireland (NI) and based on the approach set out in UK Technical Advisory Group (UKTAG) on the WFD and environmental standards (2008).

Table 1: *Northern Ireland e-flow river type classification standards (DoE(NI), 2015)*

Column 1	Column 2	Column 3	Column 4	
Type	*Standard Average Annual Rainfall mm (period 1961-1990)*	*Base Flow Index (BFI)*	*Catchment area (km^2)*	
A1	< 810.5	< 0.715	Any	
		≥ 0.715	≥ 251.8	
A2	< 810.5	≥ 0.715	< 251.8	≤ 100 (A2 headwaters) > 100 (A2 downstream)
	≥ 810.5 and < 1413	≥ 0.7495	Any	≤ 100 (A2 headwaters) > 100 (A2 downstream)
B1	≥ 810.5 and < 1155	≥ 0.3615 and < 0.7495	< 267.4	
B2	≥ 810.5 and < 1413	≥ 0.3615 and < 0.7495	< 267.4	
C2	≥ 1155 and < 1413	≥ 0.3615 and < 0.7495	< 267.4	
	≥ 1413	≥ 0.3615	≥ 32.33	
D2	≥ 1413	≥ 0.3615	< 32.33	
	≥ 810.5	< 0.3615	Any	

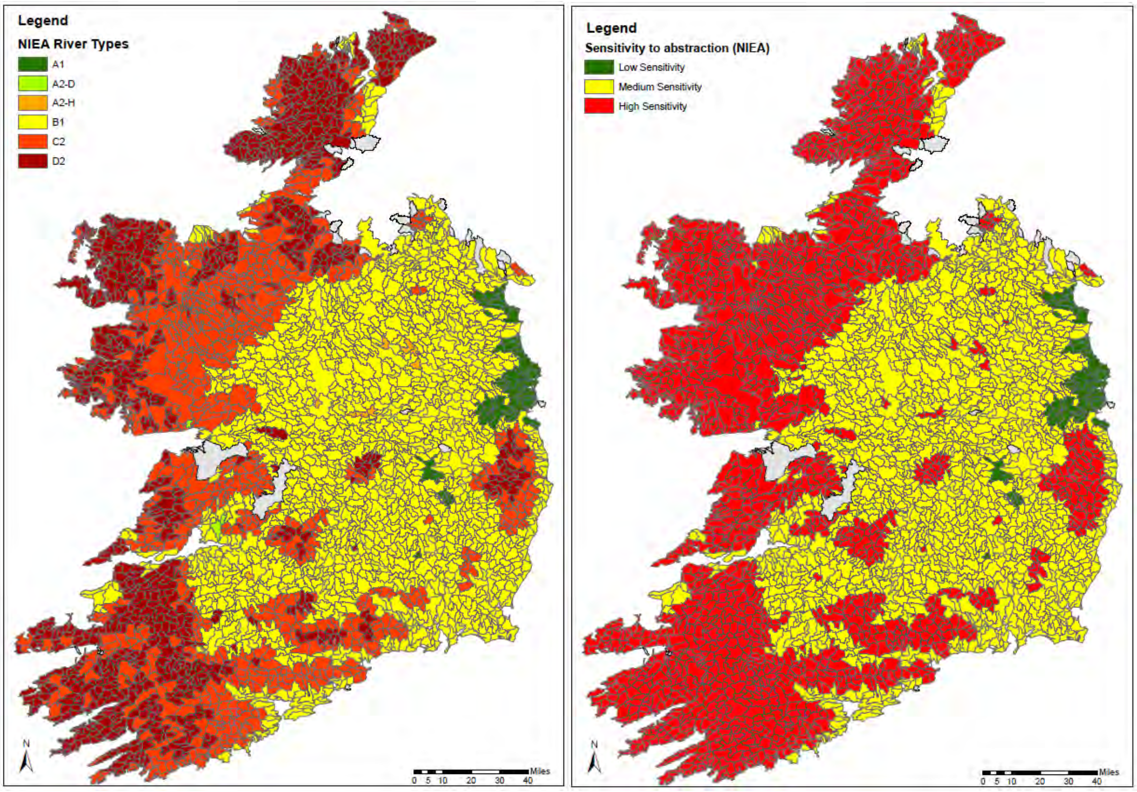

Figure 1: *River typology classification based on the Northern Ireland standards (CDM, 2017)*

The UKTAG approach classifies river catchments into six types based on their rainfall, base flow index and catchment size (see Table 1). River waterbodies are classified nationally into four abstraction sensitivity sub-types based on UKTAG guidelines. High status objective waterbodies are classified as extremely sensitive to abstraction pressures, western and upland areas as highly vulnerable, midland and lowland areas as having medium vulnerability and a small number of relatively high base-flow lowland rivers on the east coast as having a low level of vulnerability to abstraction pressure, see Figure 1 (CDM, 2017).

The UKTAG e-flow standards utilise long-term river flow data and depending on river type permit a maximum abstraction related to a percentage of the natural mean daily flow (Q); where QX is the flow that is expected to be exceeded by 'x' percent of the time, see Table 2. This allows for a higher percentage of abstraction at higher river flows.

The permitted abstraction per day is also dependant on the WFD objective of the waterbody i.e. good or high status, or in some instances a case may be made for a lesser objective. A river with a High Status Objective explicitly requires that the abstraction pressures within the waterbody do not exceed a reduction of more than 5% of the Q95 of the river, see Table 2. Although to achieve 'Good' ecological status, the WFD does not explicitly specify the flow regime as such; only that it must provide conditions 'consistent with the achievement of the values specified for the biological quality elements'. Table 3 shows the good environmental standards for river flows.

Table 2: *Northern Ireland e-flow standards for High Status objective rivers based on flow percentile abstraction proportion by river abstraction sensitivity class (DoE(NI), 2015).*

Permitted abstraction per day as a percentage of the natural mean daily flow(Q)$^{(1)}$		
High		
Column 1	Column 2	Column 3
	Maximum permitted % abstraction at Q exceeding $Q_{95}^{(2)}$	Maximum permitted % abstraction at Q **not** exceeding Q_{95}
A1, A2 (downstream), A2 (headwaters), B1, B2, C2, D2	10	5

(1) 'Q' is the mean daily flow for a specified period of time

(2) 'Qx' is the Q that is expected to be exceeded by 'x' percent for a specified period of time

Table 3: *Northern Ireland e-flow standards for Good Status objective rivers based on flow percentile abstraction proportion by river abstraction sensitivity class (DoE(NI), 2015).*

Permitted abstraction per day as a percentage of the natural mean daily flow(Q)				
Good				
Column 1	Column 2	Column 3	Column 4	Column 5
River type	Maximum % abstraction at Q exceeding Q_{60}	Maximum % abstraction at Q exceeding Q_{70}	Maximum % abstraction at Q exceeding Q_{95}	Maximum % abstraction at Q **not** exceeding Q_{95}
A1	35	30	25	20
A2 (downstream), B1, B2	30	25	20	15
A2 (headwaters), C2, D2	25	20	15	10

The natural daily mean flow for a river is calculated from long-term data and is represented by a Flow Duration Curve (FDC). The FDC is a plot that shows the percentage of time that flow is equalled or exceeded in a river for a period of record. For example; Q95 (5^{th} percentile flow) is the flow equal of exceeded for 95 percent of the flow record for a given river. In ungauged catchments, the EPA use a model known as 'Hydrotool' to estimate the river flows. Hydrotool applies a 'Region of Influence' approach, choosing catchments that are 'similar' to the ungauged site as determined from a weighting of a set of catchment descriptors (i.e. rainfall, topography, soils, subsoils, etc.). This creates a dataset of river flows for the entire country based on measured and estimated data.

Qube (developed by Wallingford Hydrosolutions) is a water resource management application, that combines actual and modelled river flow data, catchment characteristics and known abstraction and discharge data using a simple mass balance approach. Groundwater abstractions are also included in the model due to hydraulic connections to surface water. Mid-range transmissivity and storativity values (from national bedrock and aquifer data sets GSI/EPA, 2015) are used to calculate a stream depletion factor for a given underlying aquifer.

As can be seen in Figure 2, Qube calculates naturalised FDC (BLUE LINE i.e. flows with no anthropogenic influences) and influenced FDC (ORANGE LINE adding in discharges and abstractions) for every river water body and comparison of these estimates allows us to determine which river water bodies exceed the e-flow standards. The overall proportion of an individual waterbody classified as an exceedance is then factored in to produce an overall e-flow impact assessment result.

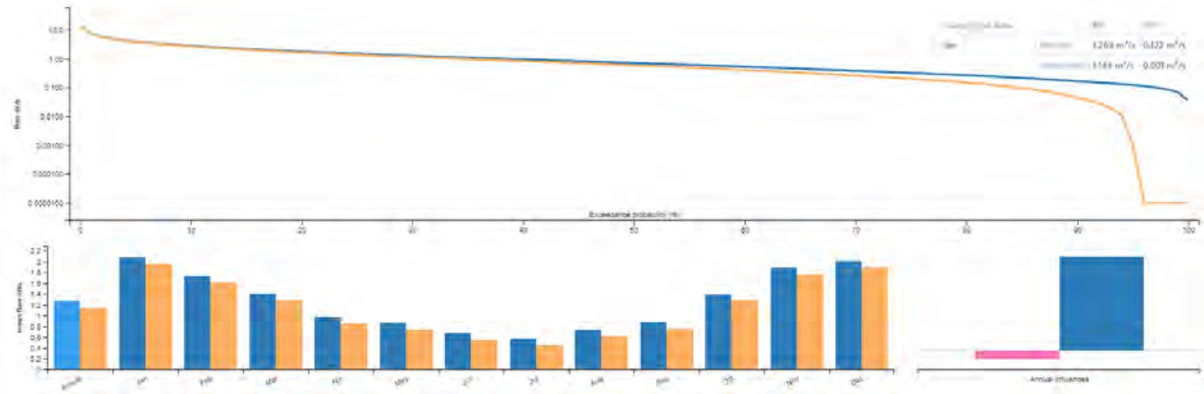

Figure 2: *Qube model output for a sub-catchment*

The Qube application used both modelled and measured river data together with abstraction and discharge data to produce naturalised and influenced flow duration curves. These flow duration curves are used to screen for abstraction impact. The metrics used in the screening process are conservative, especially in the case of lake and groundwater abstractions. This follows the precautionary principle and ensures that all likely significant abstractions are screened in for detailed assessment under the proposed regulatory process.

LAKE ASSESSMENT METHOD

Lake abstractions are assessed separately in a two-stage approach. Firstly, the Qube application is used to determine the Q50 inflow to the lake and compared to the net abstraction pressure. A reduction of greater than 10% of the lake Q50 is considered as being potentially at risk from abstraction pressures. This is also a conservative metric, and in conjunction with the most recent ecological status of the lake, governs which lakes require further assessment. The approach for this further assessment is currently under review but it is envisaged to be similar to that of the UKTAG Guidance i.e. standards specified directly in terms of changes in the area of lake habitat. This stage will require site specific data to be collected by abstractors as part of a licence application and could include lake bathymetry and time series flow and level measurements.

GROUNDWATER ASSESSMENT METHOD

Abstractions from groundwater bodies that impact the status of a groundwater body are already assessed through the existing Irish WFD status assessment methods and not addressed directly in the current abstraction assessment. The WFD status assessment is concluded every six years and based on the tests outlined in Figure 3:

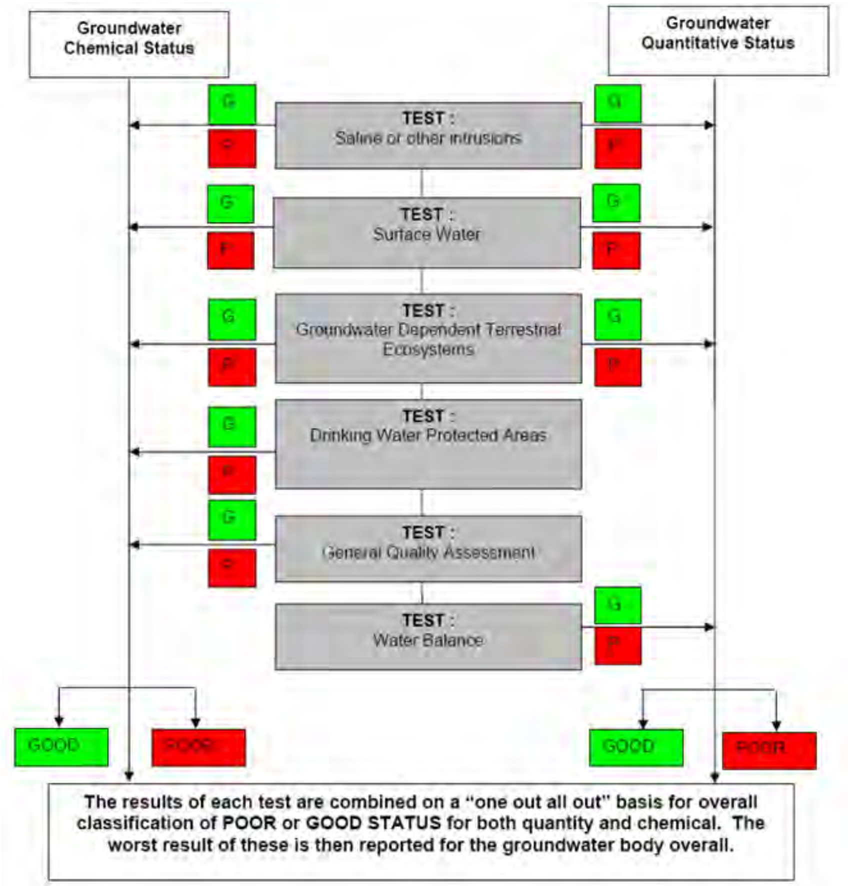

Figure 3: Overview of the Status assessment (Classification) process (UKTAG, 2008)

The groundwater body assessment includes tests for determining quantitative status, including surface water, water balance and groundwater dependent terrestrial ecosystem tests. In cases where a groundwater abstraction potentially impacts on the environmental objectives of an associated surface waterbody, further assessment is necessary before the groundwater body is classified as being at poor status. The most recent evaluation of the ecological health of Ireland's waters including groundwater bodies was carried out by the EPA over the period 2013 to 2018.

RESULTS OF ASSESSMENT

The national abstraction impact assessment examined over 2,337 registered abstractions points and identified 466 abstraction points as potentially significant abstractions (2019 data). These significant abstractions are potentially impacting 14% of all lakes and 9% of all river waterbodies, albeit the actual numbers are expected to be smaller due to the conservative approach used. Based on the groundwater body assessment from data between 2013 to 2018, 2 (or 0.4%) groundwater bodies failed to meet the quantitative status objective. In addition, 76 groundwater abstractions were identified as possibly impacting on the environmental objectives of associated surface waterbodies and must be further assessed to determine if they are having an actual impact on surface water flows or levels.

The vast majority of potentially significant abstractions are for drinking water (82%) followed by industrial use (11%), quarrying (3%) and 2% for the remaining sectors.

A breakdown of potentially significant abstractions by abstraction type shows that almost half (46%) are groundwater abstractions from wells or boreholes, and a further 8% from groundwater springs. River abstractions make up 21% of the total and lakes make up 24%.

IMPLICATIONS

The collected data and results of this national assessment will form the basis of a risk-based abstraction licensing regime, for both existing and future abstractions. Based on the draft legislation, all abstraction points >2,000m^3/d, and abstraction points >250m^3/d which are significant pressures to the environmental objectives of the waterbody will require a licence. The precise conditions around licensing will be confirmed in the finalised legislation.

Existing abstraction points that are over the 250m^3/d threshold, and flagged in the current assessment, will require further assessment potentially including field data to confirm the risk to the waterbody. The overall aim will be to reduce abstraction rates to sustainable levels over reasonable time in line with WFD's objectives, with conditions set out in the abstraction licence. Equally important is the link between ecologically sustainable abstractions and climate change resilient water management. Abstractions which are not ecologically sustainable are unlikely to be resilient and would likely have to be discontinued in many cases as part of climate adaptation. Details of the treatment of unsustainable abstractions that cannot be avoided due to cost or technical infeasibility are expected to be covered in the finalised legislation.

It is envisaged at this stage that all future abstraction points >250m^3/d applications will be assessed by the EPA and licences for unsustainable abstractions will not be granted.

CONCLUSION

The EPA has completed a national scale assessment of water abstractions in Ireland based on registered abstractions. The assessment has identified over 460 potentially significant abstractions that may be impacting 14% of lakes and 9% of river water bodies. Almost half of these potentially significant abstraction points (46%) are groundwater abstractions from wells or boreholes, and a further 8% from groundwater springs. River abstractions make up 21% of the total and lakes make up 24%.

This process forms an important step towards achieving sustainable abstraction management in all catchments. The cumulative nature of this assessment and incoming regulatory regime highlights the importance of stakeholder cooperation to ensure the sustainable and resilient management of our waterbodies which will protect their ecological health and societal benefits now, and into the future.

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DEVELOPMENT OF A HYDROGEOLOGICAL CONCEPTUAL MODEL FOR THE WATER-ROCK URBAN EXPANSION AREA IN EAST CORK

Deirdre Larkin,

WS Atkins Ireland Ltd. (Atkins), Atkins House, 150 Airside Business Park, Swords, Co. Dublin

ABSTRACT

Water-Rock, located in East Cork, is identified as a priority growth area for Midleton, and has been selected by Cork County Council as one of the county's key Urban Expansion Areas (UEA) in terms of future housing development. It is proposed to install key infrastructure to meet the future needs of the Water-Rock UEA. The proposed infrastructure works are located in an area which is underlain by karst limestone (karst features include Water-Rock swallow hole and Baneshane spring), and contains two surface water courses (the Owenacurra River and Water-Rock Stream). A clear understanding of how the groundwater and surface water systems interact was required in order to feed into the site-specific flood model during the engineering design process. A hydrogeological conceptual site model was developed for the UEA Infrastructure works area, through the preparation of desk-based assessment, flow monitoring and tracer testing at key surface water locations, and geophysical surveys. Taking account of all relevant data, a conceptual understanding for the dynamic groundwater system beneath the Water-Rock UEA was determined. This conceptual model was used to inform the development of the site-specific flood model. One of the outcomes of the assessment was that there is no clear evidence that the Water-Rock Cave system is linked directly to Baneshane Spring via a single underground karst conduit, as had previously been thought. Any potential connectivity is likely to be far more complex.

Key words: *Water-Rock Stream, East Cork, Conceptual Site Model, Flow monitoring, Tracer Testing, 2D-Resistivity Survey, Flooding, Baseflow, and Flood Groundwater Discharge Rates.*

INTRODUCTION

In 2016 Cork County Council (CCC) established a team to oversee the implementation and delivery of housing at five Urban Expansion Areas (UEA) across the county. Water-Rock, located in East Cork, is identified as a priority growth area for Midleton, and forms one of the UEA. In order to accelerate housing delivery, it is proposed to install key infrastructure to meet the future needs of the Water-Rock UEA. Atkins is currently assisting CCC on this project, through the provision of engineering design services for the following proposed infrastructure works:

- New Services Corridor Link Road;
- Surface water drainage system for new infrastructure and for UEA;
- Junction upgrade of Cork/ Midleton Road and Northern Relief Road;
- Traffic management measures;
- Road to access railway station and bridge to cross over existing Cork-Midleton Railway line;
- New railway-stop;
- Upgrade/ realignment of existing Water-Rock Road between Water-Rock Road Level Crossing and the Carrigane Road; and,
- Wastewater Pumping Station for Future UEA Development.

The proposed infrastructure works are located in the outskirts of Midleton as presented in Figure 1. The general vicinity is underlain by karst limestone, and contains two surface watercourses: the Owenacurra River and Water-Rock Stream. Flood risk assessment and modelling would form a core requirement of the design process. A clear understanding of how the groundwater and surface water systems interact, in the context of the underlying karst system, was therefore needed.

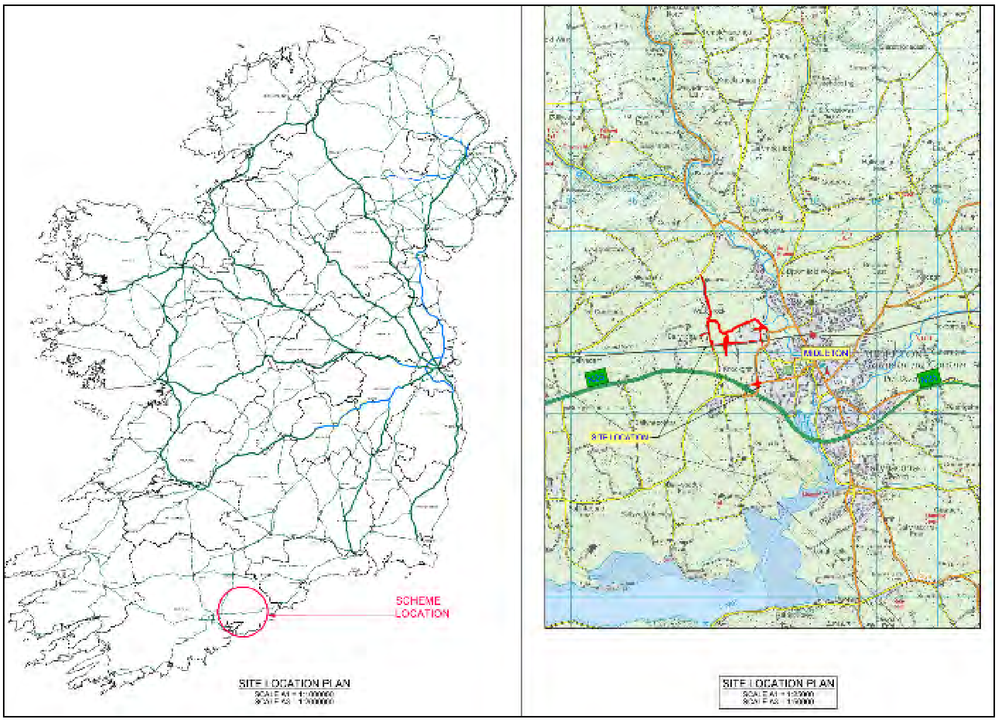


Figure 1: *Location of proposed UEA Infrastructure Works in Water-Rock, East Cork.*

DEVELOPMENT OF CONCEPTUAL SITE MODEL
METHODOLOGY

The following tasks were undertaken in order to develop the hydrogeological Conceptual Site Model (CSM) : -

- Desk-based study and Site Walkover Survey (March 2018);
- Site-specific surface water flow and rainfall level monitoring and tracer testing (18th June to 2nd August 2018);
  - 5no. uni-directional flow probes installed at 4no. locations;
  - Water level monitoring;
  - 3no. rain gauges installed at pre-determined optimal locations;
  - Daily analysis of flow & rainfall data;
  - Weekly inspection of monitoring equipment; and,
  - Dye tracer testing.
- Geophysical survey at key locations within the Study Area (July 2018);
  - 2D-Resistivity, and;
  - Seismic refraction (p-wave).

SITE SETTING

The existing land use within the general vicinity of the UEA (refer to Figure 2 for the general UEA boundary) is primarily agriculture with the Nordic Enterprise Park located in the east, and 2no. Industrial Developments located in the south (Knockgriffin Industrial Park and Europa Business Park). The Cork - Midleton railway line also runs to the south. There are 2no. water courses within the vicinity of the proposed works: Water-Rock Stream; and the Owenacurra River. Water-Rock Stream rises c.3km north west and flows in a general south easterly and southerly direction before discharging to ground at a cave system (Water-Rock swallow hole / cave) located c.100m south west of Water-Rock House. The Owenacurra River, located to the east, flows in a southerly direction towards Midleton. Refer to Figure 2.

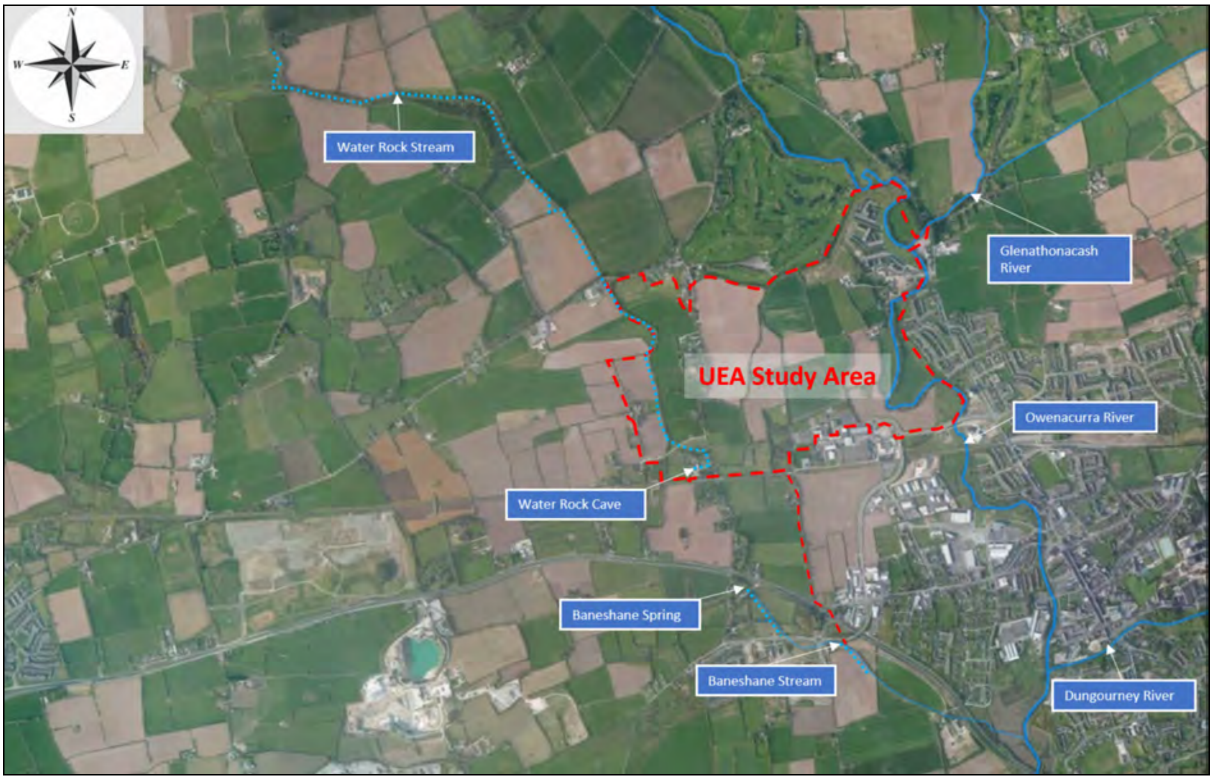


Figure 2: *Key surface water and karst features (Water-Rock Cave / swallow hole and Baneshane Spring).*

Soils beneath the general vicinity of the UEA are classified by the Geological Survey Ireland (GSI) as '*Till derived from Devonian sandstones*', with variable subsoil thickness, ranging from exposed bedrock outcrops up to depths of c.10m. In four areas (Ballyrichard More, Carrigogna, Midleton and Knockgriffin) gravels derived from Devonian sandstones are reported to be present (GSI, 2018); these gravel deposits appear to be hydraulically linked to the Owenacurra River (at Carrigogna and Midleton) and Water-Rock Stream (at Ballyrichard More and Knockgriffin) and likely provide groundwater storage and baseflow to these surface water courses. The geological formation underlying the general northern and southern portions of the UEA comprises the Waulsortian Limestone Formation, which is made up of massive unbedded lime-mudstone. The bedrock underlying the central and eastern portion of the UEA comprises the Cuskinny Member (of the Kinsale Formation) which is made up of flaser-bedded sandstone and mudstone. The south-eastern and central portion of the UEA is underlain by the Ballysteen Formation which is made up of dark muddy limestone and shale.

Limestone bedrock, where present, is classified as 'Rkd', a Regionally important karstified aquifer dominated by diffuse flow. Shale / siltstone and sandstone bedrock, where present is classified as 'LI', a Locally important aquifer which is moderately productive only in local zones, as presented in Figure 3.

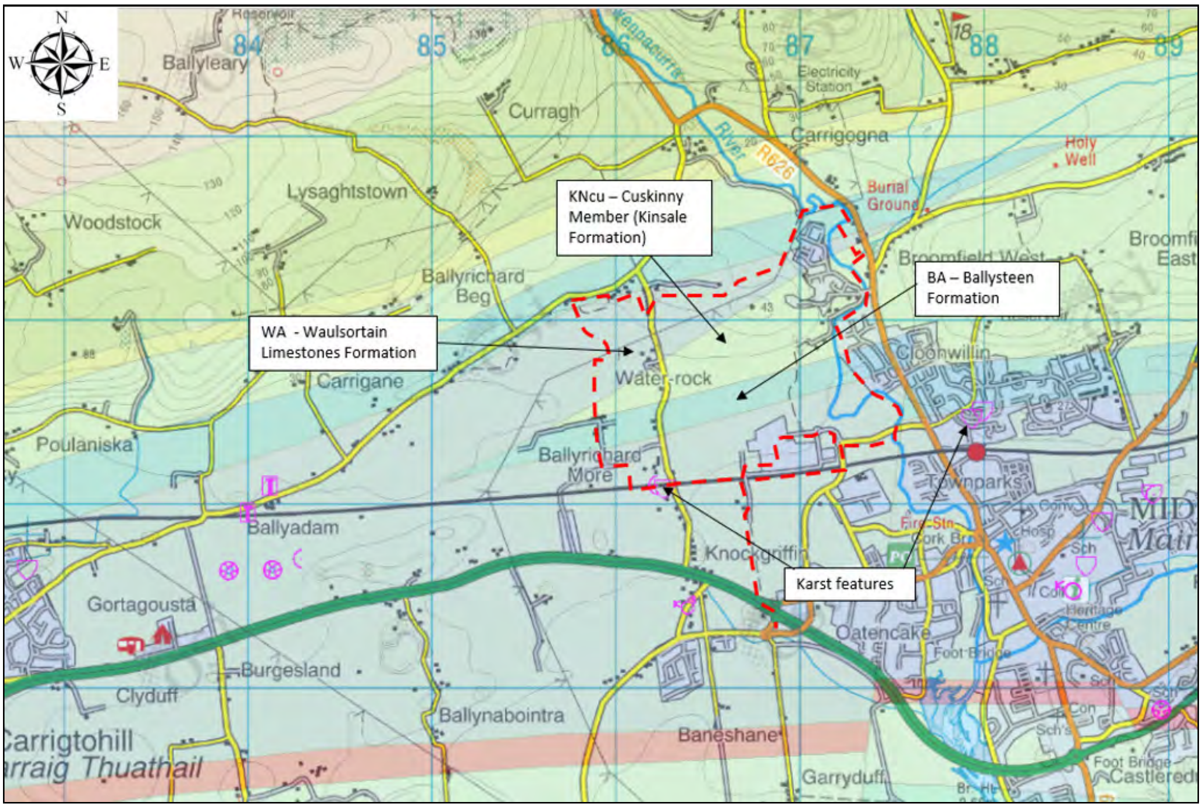


Figure 3: *Regional Bedrock Geology in the vicinity of the Study Area (Source; GSI 2018).*

2no. known karst features are present within the vicinity of the UEA: (1) a swallow hole and cave system, located adjacent to Water-Rock House, and (2) Baneshane Spring, located further south, as presented in Figure 2 and Figure 3. Taking account of the general topography and flow direction of Water-Rock Stream, it was considered plausible that the stream would continue to flow in a southerly direction underground from the point at which it enters Water-Rock swallow hole / cave system, before emerging at surface at Baneshane Spring, albeit this was subject to verification.

Groundwater vulnerability rating beneath the southern, eastern and central portions of the UEA is '*high*' while the rating beneath the western portion is '*moderate*'. Localised sections in northern and south western portions are rated as '*extreme*', with minor areas of '*Rock at or near the surface or karst*' (including the Water-Rock cave system). Groundwater is likely to be encountered at shallow depths, within two key zones:

- Shallow groundwater associated with the gravel aquifer (anticipated within several metres); and,
- Groundwater associated with the shallow karst limestone bedrock aquifer (anticipated within 10m).

Inferred groundwater flow beneath the western portion of the UEA is assumed to follow topography in a southerly, south-easterly and south-westerly direction, and discharge to Water-Rock Stream. Inferred groundwater flow to the east is assumed to follow topography in a southerly and south-easterly direction, and discharge to the Owenacurra River.

SITE ASSESSMENT

Flow Monitoring - During the monitoring period from 18th June to 19th July 2018, surface water flows of between 422 m^3/d and 1,157 m^3/d were recorded at the upstream monitoring locations on Water-Rock Stream (FM01 / FM02, prior to discharge to Water-Rock cave / swallow hole). Monitoring locations are presented in Figure 4.

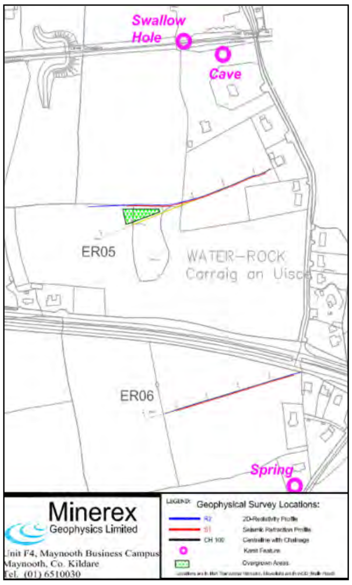
Plate 1: *Swallow hole at entrance to Water-Rock Cave System (Source: enva, 2018).*

Figure 4: *Flow monitoring locations.*

During the same period, surface water flows of between 0m^3/d and ca. 89m^3/d, and ca. 472m^3/d and 2,283m^3/d were recorded at the following respective downstream locations: private residence / Baneshane Spring (FM03); and a culvert at Baneshane Stream (FM04, downstream of Baneshane Spring). These flows were recorded during the 2018 drought period and so would be representative of low flow / drought conditions. During each monitoring event higher flows were recorded at the upstream monitoring location, compared to the immediate downstream location (FM-03, private residence / Baneshane Spring) which suggests that, under low flow conditions, the stream loses flow to ground within the cave system, or that Baneshane Spring only represents a portion of groundwater discharge, with other potential discharge points located in the wider area.

Tracer Testing - Dye was added at the two entrances of the Water-Rock cave system (cave and swallow hole). The stream at Baneshane was observed for three hours, however no colour change was noticed. On the 20th of June, approved, biodegradable floats were released into the cave system, and a trapping system was installed at Baneshane Stream (FM04). However, 48 hours later, none of the floats were recovered. Finally, on the 3rd of July, an ISCO composite sampler was set up at Baneshane Stream and programmed to take a grab sample (of 200ml) every 30 minutes for 24 hours. Dye was released to the cave system again. At the end of the monitoring period, all water samples were scanned by UV detecting lamps at a laboratory. However, dye was not detected in any of the samples. The results of the tracer testing between Water-Rock Cave and Baneshane Stream are therefore inconclusive, and do not verify karst connectivity between these two points.

2D-Resistivity Survey - The purpose of the geophysical survey was to qualitatively determine the nature and thickness of overburden at key locations, to assess the potential karst connectivity between Water-Rock cave/ swallow hole and Baneshane Spring, and to identify targeted areas for future intrusive investigation. 2no. sections (ER-05 and ER-06) were surveyed as part of the 2D-Resistivity survey at selected locations between the cave / swallow hole and the spring, as presented in Figure 5.



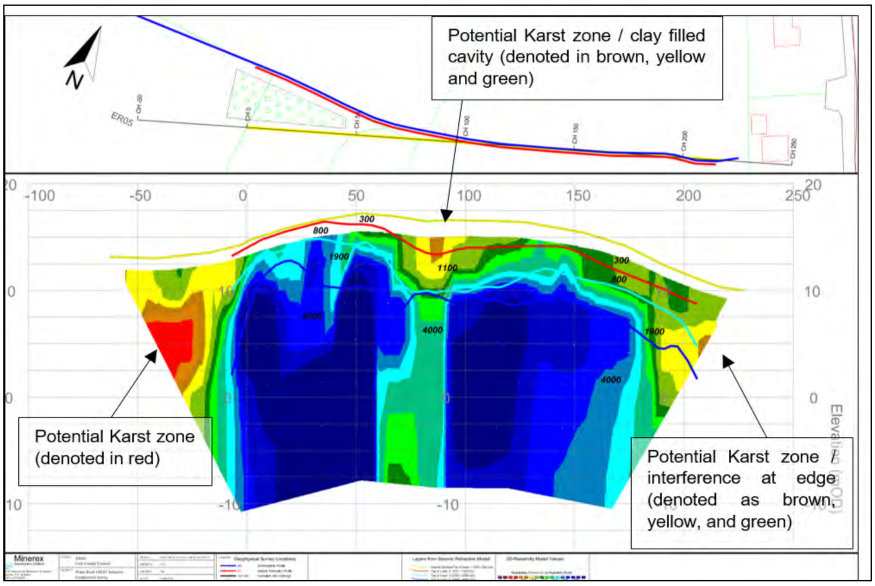


Figure 5: *Location of 2D Res. Surveys.* ***Figure 6:*** *ER05 Resistivity model output / cross section (Source; Minerex 2018 – amended).*

Model outputs, as presented in Figure 6 and Figure 7, suggest that ER05 (section immediately south of swallow hole / cave) appears to show a karst region at the western end of the section which may suggest hydraulic connectivity between the swallow hole and this area; however ER06 (section immediately north of Baneshane Spring) showed no evidence of karst.

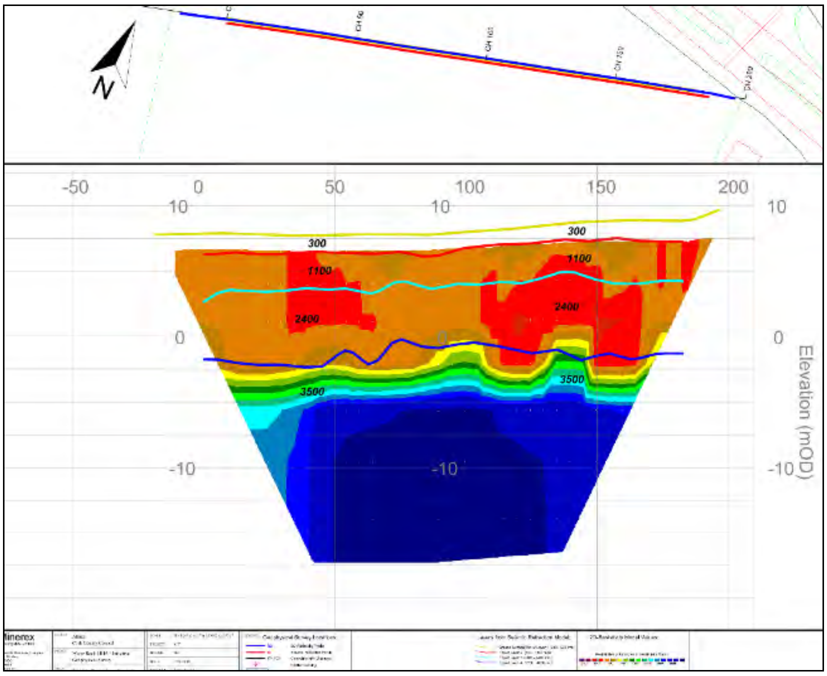


Figure 7: *ER06 Resistivity model output / cross section (Source; Minerex 2018 – amended).*

The geophysical survey findings, along with the results of the flow monitoring and tracer tests, do not suggest the Water-Rock Cave system is linked to Baneshane Spring via a single underground karst conduit. Hydraulic connectivity between these two points is inconclusive. Any potential connectivity is likely to be complex and may involve groundwater discharge to other karst features or surface water features in the wider area.

HYDROGEOLOGICAL CONCEPTUAL SITE MODEL

Taking account of all relevant data obtained from the desk-based review, site-specific monitoring programme and geophysical surveys, a hydrogeological conceptual model for the Water-Rock UEA (specifically for the relevant catchment areas to Water-Rock Stream) was developed as presented in Figure 8. The general conceptual understanding for the dynamic groundwater system beneath the Water-Rock UEA is summarised as follows:

- Subsoils (generally up to 10m thick) comprise low permeability '*Till derived from Devonian sandstones'* (GSI, 2018) and highly permeable gravels.
- Shallow groundwater is expected within 10m of the surface. Average annual groundwater level fluctuations of approximately 5m to 6m are likely.
- There are two key groundwater zones:
    - shallow saturated gravels (gravel aquifer); and,
    - underlying bedrock - karst limestone (Regionally important karstified aquifer dominated by diffuse flow) and sandstone / mudstone (Locally important aquifer).
- The gravel aquifer is hydraulically linked to Water-Rock Stream (at Ballyrichard More and Knockgriffin) and provides an important role in groundwater storage.
- Rainfall recharge to groundwater will be a function of infiltration capacity:
    - Areas of Till underlain by a Locally important aquifer will have high run-off rates and low potential for groundwater recharge. An estimated recharge cap of 200mm/yr applies.
    - Areas of Till underlain by a Regionally important karstified aquifer will have higher potential for groundwater recharge (estimated at ca. 400mm/yr), albeit infiltration rates are lower than for the exposed / shallow gravel aquifer.
    - Areas of exposed bedrock or shallow gravel have the highest infiltration rates, and potential for groundwater recharge (ca. 600mm/yr).

- Groundwater discharges to Water-Rock Stream via the gravel and bedrock aquifer, where hydrogeological linkages exist with the stream, as presented in Figure 8. These groundwater sources provide baseflow to the Water-Rock Stream, as recorded during the drought of summer 2018.

In terms of karst, the following conclusions were made:

- When the Water-Rock Stream is lost to ground at the swallow hole / cave, the underground stream enters a complex karst cave system which probably continues south, but not in a linear fashion directly to Baneshane spring, as had been previously thought.
- Based on available information including flow monitoring data, tracer test results and geophysical survey findings, it is clear that any hydraulic connectivity between the known karst features of the Water-Rock Cave and Baneshane Spring is complex. Potential scenarios could include the following:

    I. Groundwater from the cave system discharges directly to the Spring but with limited flow, with the bulk of groundwater flowing elsewhere within the cave system;
    II. Groundwater from the cave system discharges directly to the Spring but with limited flow, with the bulk of groundwater discharging diffusely along the shallow interface between the overburden and the highly weathered / karst limestone bedrock; and,
    III. Groundwater from the cave system does not discharge directly to the Spring. Other potential discharge locations include identified karst zones to the east and west of Water-Rock Cave.

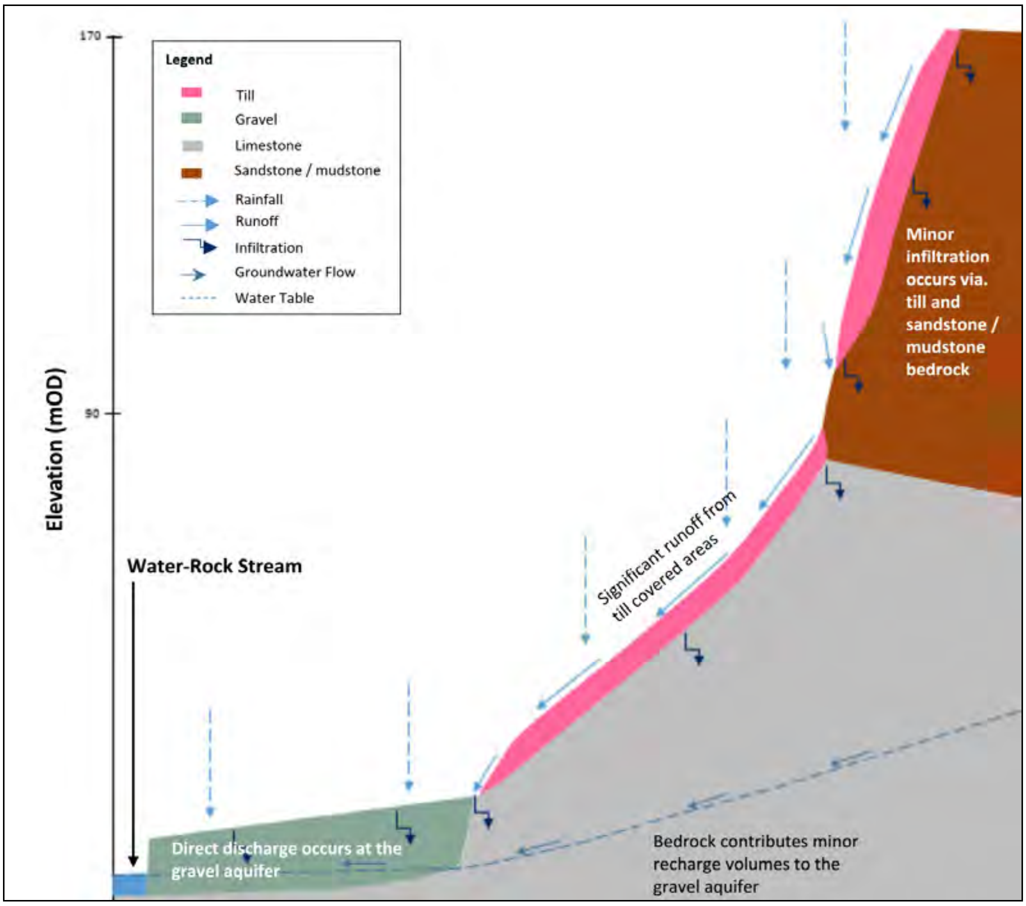


Figure 8: *Hydrogeological Conceptual Site Model.*

To inform the project specific flood model the groundwater contribution to Water-Rock Stream, prior to being lost to ground at Water-Rock swallow hole / cave, was estimated. Groundwater calculations were based on estimated groundwater recharge rates in areas (measured using available mapping) for a range of hydrogeological settings within the relevant Water-Rock surface water catchments (Catchment A and Catchment B). Baseflows of ca. 280 m^3/d and ca. 4,200m^3/d were estimated for each catchment area (of 2,000,000m^2 and 3,100,000m^2 respectively).

Similarly, using calculated rainfall rates for flood events, groundwater flows during a range of flood return periods were calculated. The results are summarised in Table 1. Given the inherent uncertainty in assessing karst hydrogeological settings, and taking account of the apparent complex nature of the underground cave system south of Water-Rock swallow hole / cave, a conservative approach was adopted in the flood risk assessment and site-specific flood modelling. The UEA infrastructure was therefore designed to provide for sufficient capacity in a worst case scenario, a 1 in 1000 year flood event.

Parameter	**Return Period (Yr)**	**Effective Rainfall (mm/d)**	**Unit**	**Catchment A (Atkins, 2018)**	**Catchment B (Atkins, 2018)**
Q (flood)	**2**	42.7	m3/s	7.48E-02	9.93E-01
	5	60.8	m3/s	1.07E-01	1.41E+00
	10	72.1	m3/s	1.26E-01	1.68E+00
	20	83.7	m3/s	1.47E-01	1.95E+00
	30	90.2	m3/s	1.58E-01	2.10E+00
	50	99	m3/s	1.73E-01	2.30E+00
	100	110.1	m3/s	1.93E-01	2.56E+00

	200	124.1	m3/s	2.17E-01	2.89E+00
	500	139.1	m3/s	2.44E-01	3.24E+00
	1000	151	m3/s	2.65E-01	3.51E+00

Table 1: *Calculated Flood Groundwater Discharge Rates (for various Return Periods).*

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SESSION III

IRISH WATER'S NATIONAL WATER RESOURCES PLAN – THE FUTURE OF OUR WATER SUPPLIES

Miriam Grant BEng MEngSc

Irish Water, Colvill House 24-26 Talbot St Dublin 1

ABSTRACT

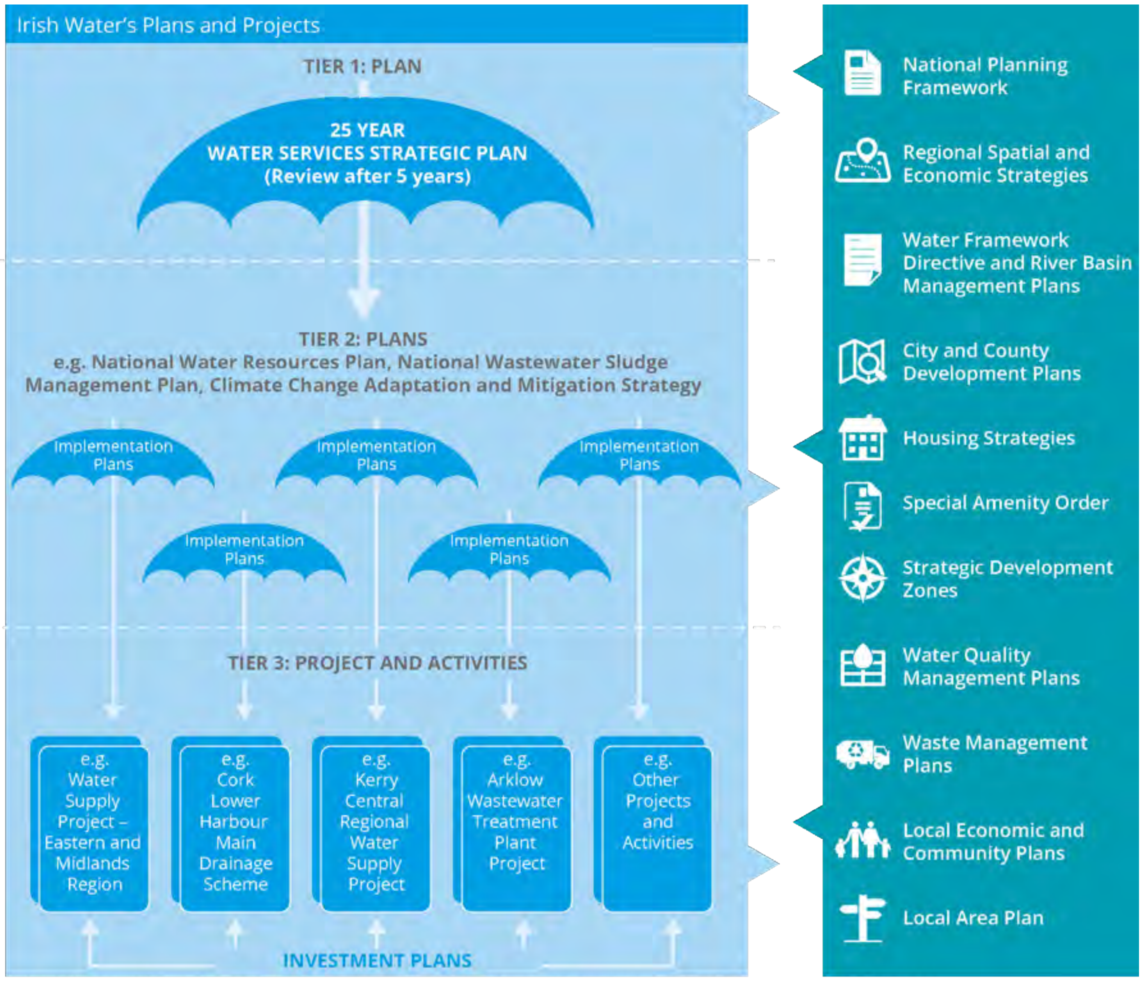
The National Water Resources Plan is a 25-year strategy that sets out how Irish Water will provide a safe, resilient and sustainable water supply for every scheme in the country. This plan will underpin all drinking water project investment from now and into the future and will ensure that all projects strive to achieve the same service levels and security of supply. This paper describes Irish Water's Planning Framework, focusing on the requirement for a National Water Resources Plan (NWRP). The methodology used for developing the plan will be described and a key focus will be on the interim groundwater assessment, the current challenges and the work currently being progressed by Irish Water to improve reliability and quality of our groundwater supplies.

Introduction to the NWRP

In 2015, Irish Water published its 'Water Services Strategic Plan (WSSP)', which set out a 25-year vision for Ireland's public water services, recognising substantial deficits in both its potable water and wastewater services. This plan formed the high-level framework within which the interim 5-year investment plans are developed, targeting priority issues and delivering improved outcomes. Today, Irish Water's capital investment programme has reached €750 million annually and is delivering a range of programmes covering:

- Drinking Water; Targeting leakage reduction, supply resilience, improved quality to meet statutory standards, capacity for new development as well as asset renewal programmes to maintain safety and serviceability of the existing systems, and
- Wastewater; targets untreated discharges, failing discharges, sewer overflows, system improvements and capacity upgrades for essential new development.

At the core of the WSSP is the objective to provide a compliant and cost-effective service to every business and household customer, regardless of where they are located on the network. While the major investment programs are delivering year on year improvements, the WSSP recognised the need for subsidiary (Tier 2) Plans, as illustrated in Figure 1, to form the basis for sustainable long-term service delivery, taking account of current legislation and regulation, EU Directives (notably the EU Water Framework Directive 'WFD'), growth in demands from demographic change (population growth and migration patterns), economic growth, developments in the networks and climate change, whose impact in this sector will be significant. These Tier 2 plans also allow us to align with the requirements of the Public Spending code.



It should be noted that the listing of the documents on the right of the graphic is not intended to show a hierarchy of plans or an alignment of the plans with the Irish Water Tier 1, Tier 2 and Tier 3 plans/ projects.

Figure 1: *Irish Water Planning Framework (Irish Water, 2015)*

The NWRP is one such Tier 2 Plan, currently under preparation and intended to set out a framework for establishing long term sustainable and resilient supplies for every community on the public network, taking account of these changing conditions. This Plan must take account of all relevant EU & National policy, national and regional planning objectives, environmental regulation and policy. Each draft plan is subject to Strategic Environmental Assessment (SEA), whereby all proposed outcomes are assessed at a strategic level for compliance with environmental and habitats objectives. This process includes multiple stages of stakeholder engagement, including the public, ensuring maximum transparency in the analysis of the issues and the development of strategic solutions.

The NWRP is being produced in four regional elements having regard to scale and the regional factors affecting water supplies across the country as shown in Figure 2. The four regions are:

Group 1; North-West region
Group 2; South West region (Cork & Kerry)
Group 3; South East region
Group 4; Eastern & Midlands region

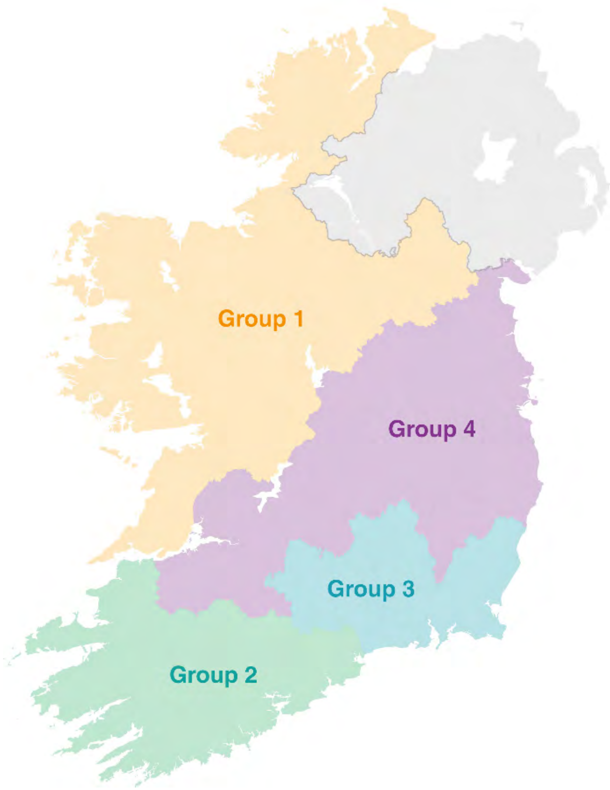


Figure 2: *NWRP Regional Groups (Irish Water, 2020)*

The challenge for the NWRP is to develop a robust and resilient Plan which is capable of being implemented at affordable cost to meet the needs of the communities it serves with a high degree of resilience (1 in 50 Level of Service). This requires that each scheme is examined from the point of view of the yield and quality of the source water, the available treatment and the nature of the distribution system.

The World Health Organisation (WHO) recognises that the first step in providing safe drinking water is that the source raw water is as clean as possible. Irish Water has adopted this ‘Source to tap’ principle and is committed to preparing ‘Drinking Water Safety Plans (DWSP) for each Water Supply Zone (WSZ). The WSZ is the smallest Management unit where all of the customers on a supply receive water from the same source or group of sources. Within this unit, the DWSP comprises an integrated approach to intrinsic safety of drinking water through managing the supply in terms of both quantity & quality from source, through abstraction, treatment, storage, transmission and distribution to the customer tap.

The process of preparing the DWSP is described in Figure 3, which requires a systematic approach to quality & quantity risk management. This covers sufficiency of raw water, together with effective leakage management, to meet volume needs, taking account of growth and security of supply. It provides for quality compliance through source protection in the first instance, combined with appropriate treatment barriers and integrity of the supply system. This Plan also addresses cost effective service with energy management as criteria guiding the capital & operational interventions

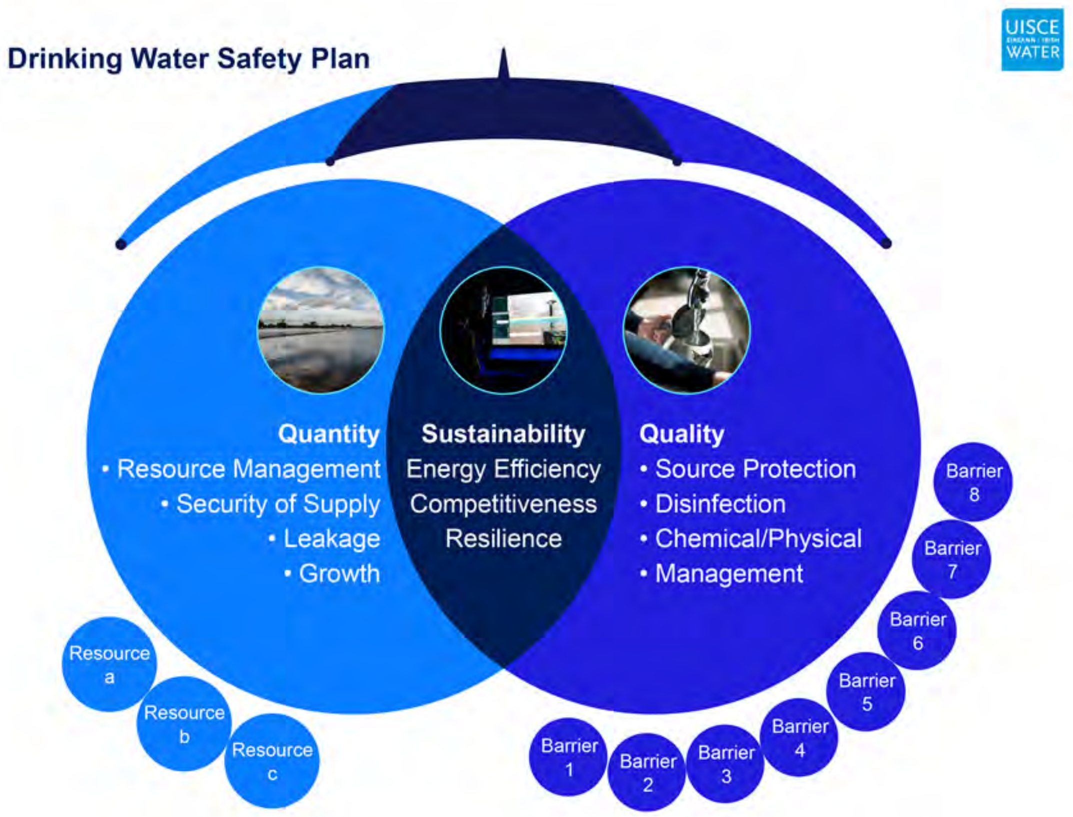


Figure 3: *DWSP Development for Public Water Supplies*

Approach to NWRP Development

Water Resource Zones (WRZs) are the management units at which Water Resource Planning is undertaken. Water Resource Zones represent an area where the supply and demand are largely self-contained. It is where the resources, supply infrastructure such as the water treatment plants (WTPs), and the customers are connected. The Supply-Demand Balance is calculated for each Water Resource Zone. The approach to development of the National Water Resource Plan requires that each Water Resource Zone is assessed in accordance with the process set out in Figure 4. This process takes a systematic approach beginning with an analysis of the performance and sustainability of the existing supply. This involves assembling all available scheme data to determine the following:

- Supply Forecast; water available for use from the existing source, whether surface or groundwater, to determine the sustainable output today and in the future, in accordance with the EU WFD.
- Demand Forecast; comprising the current demand estimates, looking at components of domestic & non-domestic usage, leakage and operational usage, allowing for headroom and required peaking factors. These values are projected into the future, taking account of a 25-year planning horizon.
- Water Quality Assessment; which considers the barriers in place to quality threats (disinfection, clarification / filtration, other) and where a WTP is currently meeting these standards.

These assessments enable the Supply Demand Balance to be developed which addresses normal and more extreme conditions, such as a drought period. These assessments define the resilience of the existing WRZ supply and its ability to meet future needs, within the available resources. The next step is the assessment of how the long-term 'Needs' will be met, beginning with managing the existing supplies optimally, followed by an Options Appraisal Methodology to select a preferred way of solving any deficit in sustainability, resilience or quality.

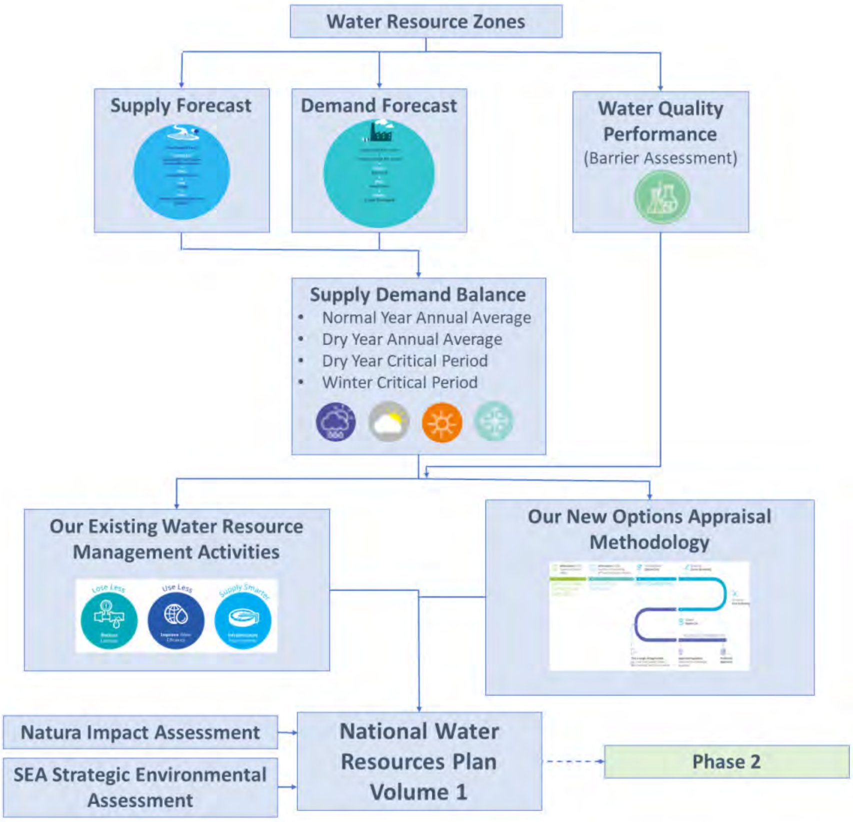


Figure 4: *Developing the NWRP at WRZ Level.*

In the development of the options, we start with a complete list of all possibilities or unconstrained options, including leakage reduction, demand management, new groundwater and surface water sources, linking up or rationalising existing supplies. These options are screened, first at a coarse level and then through a more rigorous fine screening assessment, on the criteria of resilience, deliverability, flexibility, progressibility, environmental and social acceptability, to eliminate those options which are infeasible and conflict with environmental objectives. This process results in a final list of options which are then assessed by testing a range of approaches to identify the preferred solution.

We recognise a number of uncertainties in the current process, including data gaps particularly with capacity modelling of sources, while we also await new abstraction legislation which Ireland has committed to introduce to meet the EU WFD requirements. This could involve new criteria for abstraction assessment which would impact our estimates of sustainable yield. This will require that the NWRP is reviewed as these deficits are identified. The Plan will be updated every 5 years to ensure that new data is incorporated as developed, to ensure robustness.

Assessing Hydrological Yield
The hydrological yield for our surface water sources is calculated by using the available storage, Flow Duration Curve, rainfall data and other information applying the Institute of Hydrology Report No.108 Low flow estimation in the United Kingdom Method. The Hydrological Yield is also based on maintaining a 1 in 50 Year Level of Service.

Due to the potential for large variations in sub-surface geology, even over short distances, producing robust desktop assessments of water availability from our existing groundwater abstractions is very difficult. Ideally, yield estimates would be based on a three-dimensional assessment of the geology within the vicinity of the supply, supplemented with long term records on pumping and drawdown of water levels over many years. Irish Water does not have this type of information available for most of our ground water assessments. It will also take many years to develop and roll out this type of analysis and monitoring at all of our groundwater sources.

For the purposes of the Plan, a simple methodology has been developed for assessing the Hydrological Yield of our groundwater sites, in the interim. This is carried out by:

- Defining the Zone of Contribution (ZOC), or the land area that contributes water to the well or spring; and
- Calculating a water balance for the source using the abstraction rate and the recharge rate as estimated from the Geological Survey Ireland (GSI) recharge maps.

The water balance shows the area needed to supply the yield and is compared to the delineated Zone of Contribution. The water balance needs to be larger than the Zone of Contribution for a safe yield, which would not be expected to impact the ecological status.

Irish Water recognises the work being carried out by other organisations, including regional assessments of groundwater availability being developed by the GSI, and that over time this work will become available and can be incorporated into future iterations of the Plan.

The Role of Groundwater in our Water Supplies

Groundwater plays an important role in Ireland's public water supplies. We currently have 1,090 sources supported by 725 Water Treatment Plants supplying 533 WRZ's. These WRZ's vary from the smallest schemes serving as few as 30 people to the largest Greater Dublin Area (GDA) supply serving 1.6 million.

The majority of Irish Water sources are based on groundwater supply, by number of schemes, but these represent the smaller schemes, with the bulk of larger supplies based on surface water sources. Historically, many rural water supplies were developed based on what were considered good quality groundwater sources, with limited treatment, primarily chlorine disinfection.

Given that limestone is the predominant rock type in the midlands, south and west of the country, the bulk of groundwater sources are served from limestone aquifers. These include:

- Boreholes; generally fairly shallow, drilled through boulder clay overburden. Borehole quality varies and Irish Water has developed a specification for proper borehole construction to protect the well from surface water impacts in its vicinity. Significant work has been carried out to create Source Protection Zones at sources and the Irish Water Disinfection programme has been upgrading chlorination plants on a priority basis
- Shallow wells; these are often older supplies based on historic high quality source wells, for example Millstreet, regarded as a holy well, with the public abstraction on the outlet of the well
- Sources fed fully or partly from groundwater recharge; most notably Lough Owel, which supplies the Mullingar Water Resource Zone as well as providing the headwaters for the Royal Canal.

While the bulk of groundwater schemes are small based often on a single borehole, a number of larger schemes depend on groundwater. Among the more significant are:

- Portlaoise, Mountmellick & the Central Area of Laois, where significant drought pressures were experienced in both 2018 and spring 2020

- South Kilkenny which supplies the eastern area of Waterford City. The Dungarvan Supply is also met from boreholes in limestone, recently extended to Ring/Helvic, while the whole of west Waterford is supplied from local boreholes
- Clonmel is largely supplied from Groundwater, supplementing the original 'soft' water source from the Comeraghs. This is one of the limestone aquifer supplies where complaints of hard water and limescale are common
- Castlecomer in north Kilkenny have given rise to issues with extreme levels of iron & manganese requiring recent interventions to address them
- In the Greater Dublin Area, a groundwater scheme was developed at Bog of the Ring in the north of Fingal to supply the Balbriggan area. Initially thought to have potential for up to 20 Ml/day, it has struggled to supply more than 3 Ml/day on a sustained basis.

Improving Reliability and Quality of our Groundwater Supplies

Irish Water is committed to improving the reliability and quality of all of our supplies. Limestone aquifers, in particular, have been found to be vulnerable to pollution requiring enhanced treatment, often after quality failures leading to prolonged Boil Water Notices in some cases. Examples are:

- Castlerea & Williamstown in Roscommon, where intermittent contamination especially after rainfall has led to the need for higher levels of treatment (DAF & Filtration) to meet quality standards consistently
- The Millstreet supply failed in recent years and needed enhanced treatment for cryptosporidium risk. The notice was lifted following installation of a new ultraviolet (UV) disinfection system
- Whitegate in east Cork was initially fitted with UV treatment, but this had to be supplemented by filtration due to occasional surface flood contamination leading to excess turbidity
- The Lough Owel Supply required only chlorination for decades, but ultimately succumbed to algal blooms from surface inflows requiring membrane pre-treatment more recently. Following this upgrade, it was removed from the EPA's Remedial Action List.

The Challenges facing the Future of our Water Supplies

Irish Water is facing a number of key challenges over the coming years, which have the potential to exacerbate the current problems with our water supplies. These include:

- Planned Abstraction Legislation which might reduce the amount of water we are able to abstract from some of our sources in the future
- Population Growth which will significantly increase demand with the country's population expected to increase by 21% or 1.2 million people over the next 25 years
- Water Quality with increasing pressure on raw water quality, and
- Climate Change which is expected to lead to drier summers and reduce the amount of water which can be abstracted. It is also predicted to increase the frequency of droughts and other extreme weather events that can interrupt supply.

Undoubtedly, groundwater will continue to play an important part in public and private water supply in Ireland. However, its use requires consideration of the following factors;

- Environmental sustainability; rigorous testing and hydrogeological assessment to verify sustainability of the source for the projected abstraction. All future abstractions will be regulated under the planned Abstraction legislation to bring Ireland into line with the EU WFD

- Detailed quality risk assessment and provision of the required source protection and treatment barriers, to meet the National & EU Regulatory standards at all times.
- Consideration will have to be given to control of carbonate hardness, having regard to the impact of limescale on hot water appliances and its economic effects (failure of appliances, heat exchange inefficiencies). Currently there is no requirement in the Regulations to limit hardness / alkalinity.
- There is a need to strictly monitor for Nitrate concentrations, which have been rising in some supplies in areas of intensive agriculture, while increasing evidence of pesticides in supplies generally are also noted.

Summary

The National Water Resources Plan is Irish Water's strategy to provide a sustainable, resilient and safe water supply to all of our customers, over the next 25 years. This ensures that we mobilise secure raw water sources, capable of meeting the volumetric and water quality needs, while maintaining sufficient ecological resources to support WFD objectives in our waterbodies. Groundwater must continue to play an important role in meeting these water supply objectives, now and in the future. Recent drought periods have highlighted vulnerabilities in many of our supplies, indicating the importance of good long term strategic planning, ensuring we are investing in sustainable sources in the right places. For groundwater, this emphasised the need to develop a much better understanding of aquifer capacity, requiring better modelling supported by field verification and validation as well as collaborative work with other organisations. From a quality perspective, our experience has been that limestone aquifers are vulnerable to surface pollution sources, while high natural hardness leads to objection on aesthetic grounds. From a safety perspective, this underlines the importance of Water Safety Plans, incorporating source protection, recognising risks not only from organic and bacterial contamination but also micro-pollutants such as pesticides and other diffuse pollutants.

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A FRAMEWORK FOR DRINKING WATER SOURCE PROTECTION

Barry Deane

National Federation of Group Water Schemes

ABSTRACT

Source protection, as a means of providing safe and secure drinking water, is a priority for the National Federation of Group Water Schemes (NFGWS). Since 2010, the NFGWS have undertaken projects, assisted by Dundalk IT and the Geological Survey of Ireland, as a means of making progress in the implementation of source protection across the GWS sector. In undertaking these projects, it became clear that some rethinking of the approaches to source protection was needed based on the lessons learned in recent years in undertaking source protection reports and Water Framework Directive (WFD) characterisation, and the necessity to link source protection scientific assessments effectively with appropriate and relevant protection and mitigation actions 'on the ground'. It was concluded that an overarching framework was needed to guide future NFGWS source protection work. This paper summarises the Framework which is now providing the basis for protection of all groundwater and surface water group schemes drinking water sources. Full details of the Framework are given in NFGWS (2019).

INTRODUCTION

Protecting our drinking water sources from contaminants is a major national priority in safeguarding public health through ensuring a clean, safe and secure drinking water supply. This is achievable by developing and using a framework that is founded on structured, systems-based, risk-based, holistic and integrated approaches. Integrated catchment management (ICM) is now providing the overarching framework for the implementation of the Water Framework Directive in Ireland and the philosophy for water management, including drinking water source protection. The multiple-barrier approach, which is an integrated system of procedures, processes and tools that collectively prevent or reduce the contamination of drinking water from source to tap, is recognised internationally as an effective and transparent means of achieving the provision of 'safe and secure' drinking water. The NFGWS use both the ICM and multiple barrier approaches to help achieve safe and secure drinking water supplies.

The NFGWS is the representative organisation for the community-owned group water scheme (GWS) sector in Ireland. Since its establishment in 1998, the organisation has worked in partnership with government departments, local authorities and other state and non-state stakeholders to ensure that the services provided by our GWS members achieves the highest standards in terms of water quality and customer service. The organisation recognises the importance of protecting drinking water sources as the first line of defence in a multi-barrier approach towards supplying quality drinking water.

The National Rural Water Services Committee established the National Source Protection Pilot Project from 2005 – 2010 on the Churchill & Oram GWS County Monaghan in partnership with the NFGWS and Dundalk Institute of Technology. Subsequently the NFGWS embarked on a pilot project with the Geological Survey of Ireland with 5 GWSs in the south of the country, to delineate groundwater Zone of Contributions (ZOC) for each source using the Groundwater Protection Scheme model DELG/EPA/GSI (1999). These projects formed the basis of the NFGWS 2012 Strategy for implementing source protection across the GWS sector. From 2012 to 2018, the NFGWS focused its source protection efforts on the delineation of drinking water catchments. To successfully identify and implement source protection measures within these catchment areas requires a truly collaborative Integrated Catchment Management (ICM) approach. The National Source Protection Pilot Project - Phase II was successfully established by the NFGWS in 2018, bringing together a range of stakeholders to oversee the development and implementation of ICM source protection plans on nine GWS drinking water catchments.

The work on surface water sources is undertaken with the assistance of Dundalk IT, and on groundwater sources with the assistance of the Geological Survey of Ireland (GSI) and Tobin Consulting Engineers. It became clear at an early stage in this process that an overarching framework was required to successfully achieve the projects objectives. Therefore, as a component of this work, a framework entitled ‘A Framework for Drinking Water Source Protection’ has been developed as generic guidance for the catchment component of drinking water source protection. It is based not only on the ICM and multiple-barrier approaches but is also influenced by, and builds on the progress made in the area of source protection in recent years and the new information and maps produced by the Environmental Protection Agency (EPA).

The main objectives of the Framework are to:

- Provide a high level vision and structure for the catchment components of the multiple-barrier approach for source protection.
- Integrate and link groundwater and surface water source protection approaches.
- Connect with the characterisation approaches used by the EPA and the Local Authority Waters Programme (LAWPRO) as part of WFD implementation.
- Encourage targeting of the main issues and pressures, and the most appropriate and cost-effective protection/mitigation measures and actions that need to be dealt with in any given source catchment.
- Provide a narrative that will be understandable and effective in public consultation and collaboration.

The guidance provided by the Framework is not meant to be prescriptive and can be adapted in a flexible manner to suit the particular circumstances or needs in a source catchment.

SUMMARY OF FRAMEWORK

The Framework consists of a number of steps and components. These vary depending on the quality of the untreated source water. The process is outlined in the flowchart in Figure 1 and is summarised below.

1. Evaluation of the quality of the untreated source water.
2. Delineation of the catchment area of a surface water source or the zone of contribution (ZOC) of a groundwater source.
3. Initial characterisation involving a desk-based compilation and evaluation of relevant information and maps for the catchment area/ZOC.
4. An interim ‘story’ of the source catchment area.
5. Further characterisation, involving fieldwork and catchment walks.
6. Analysis and conclusions on the potential mitigation strategies and activities needed.
7. Implementation of specific targeted and appropriate mitigation activities.
8. Monitoring progress and making adjustments, if necessary, as this is an iterative process.

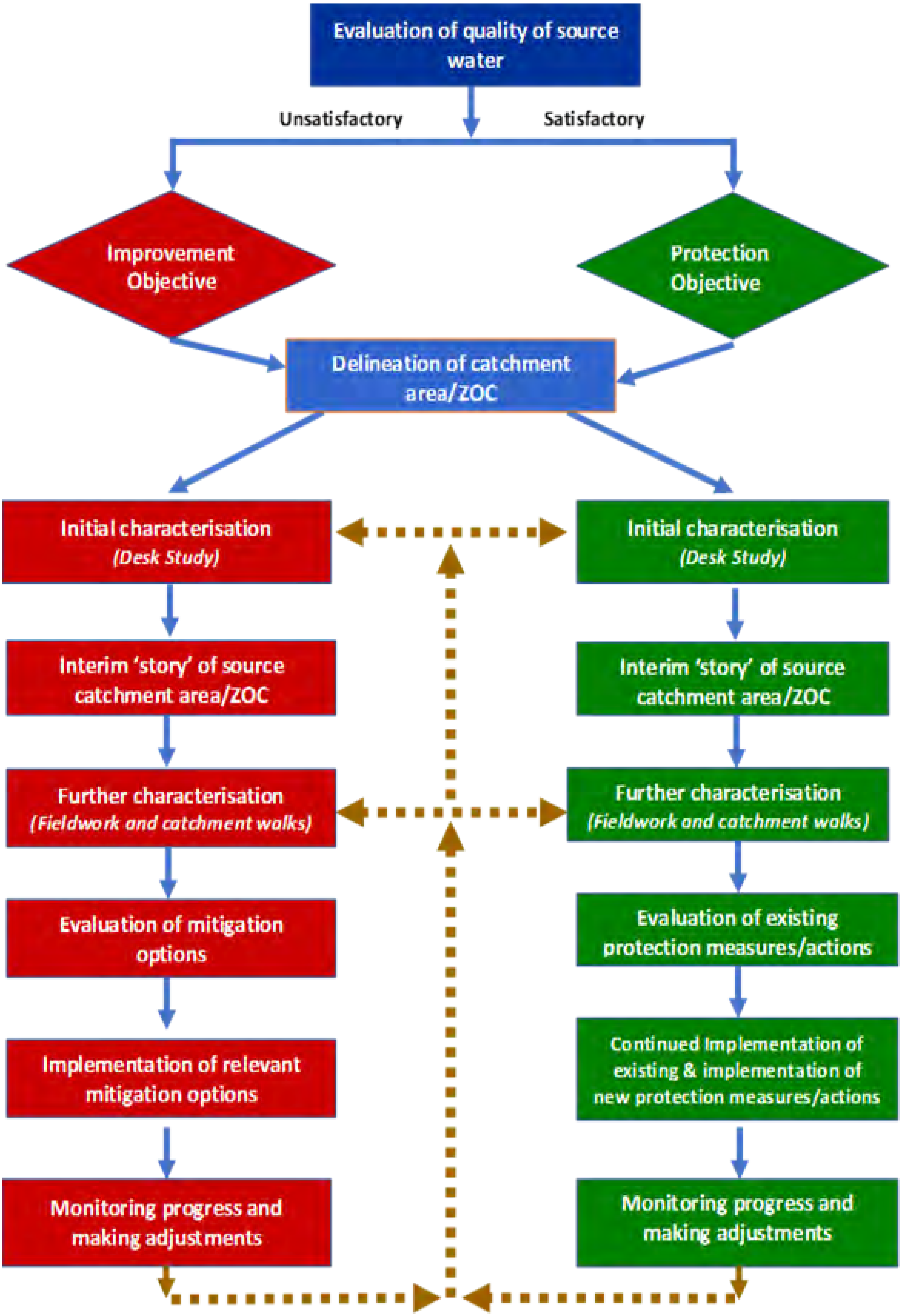

Figure 1: Summary of Source Protection Framework

EVALUATION OF THE QUALITY OF UNTREATED SOURCE WATER

The requirement is to provide drinking water users with water that complies with the Drinking Water Directive and related regulations. Treatment is an essential element in the multiple-barrier approach. Therefore, the objective of the catchment component of source protection is not necessarily to provide water to a potable standard, although that would be a good outcome, but to reduce the risks from human activities in source catchments, lessen dependence on treatment processes, reduce the costs of treatment and desludging, and enable compliance with Article 7.3 of the WFD. In addition, the word 'protection' in source protection can be nebulous unless targets are set that measures/activities are designed to achieve and are achievable in practice. Therefore, **'guide values'** have been determined that provide a target, as a metric for different pollutants, that can realistically be set as the objective for the catchment component of source protection. Where concentrations in the untreated source water are above the guide values, mitigation activities are needed to reduce the concentrations caused by the significant pressures. Where concentrations are below the guide values, while there will be pressures, none are significant and therefore, there are none that need to be dealt with by specific mitigation measures/activities, although general protection practices need to be maintained. The outcome is a decision as to whether the objective for a source is **'improvement'** or **'protection'**, with the improvement scenario requiring a greater resource input generally.

DELINEATION OF THE SOURCE CATCHMENT AREA/ZOC

The area providing the water needs to be known. For groundwater sources in particular, this generally involves investigations and analysis, with associated time and resource requirements. Figure 2 shows an example of a ZOC. For large catchments upstream of a surface water source, delineation of sub-catchments is likely to be necessary.

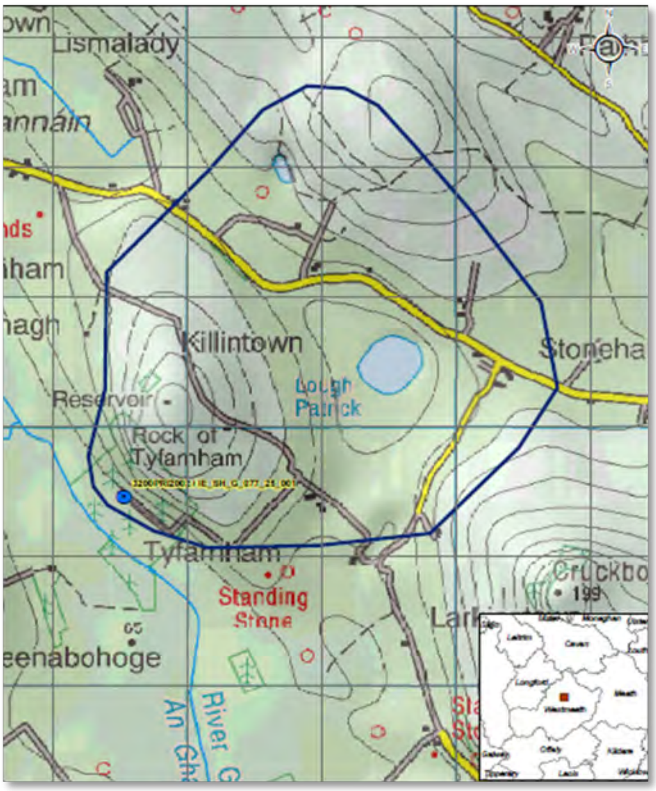

Figure 2: Multyfarnham GWS County Westmeath Groundwater ZOC

INITIAL CHARACTERISATION

In circumstances where improvement of untreated water quality is needed, the initial characterisation process enables the significant issues and significant pressures to be determined and, where diffuse sources are posing a threat to water quality, the location of the critical source areas (CSAs) (see Figure 3). Where protection is the objective, initial characterisation enables an understanding of the reasons for the satisfactory water quality as well as an evaluation of possible areas with associated pressures that are susceptible to impacts from present or future activities.

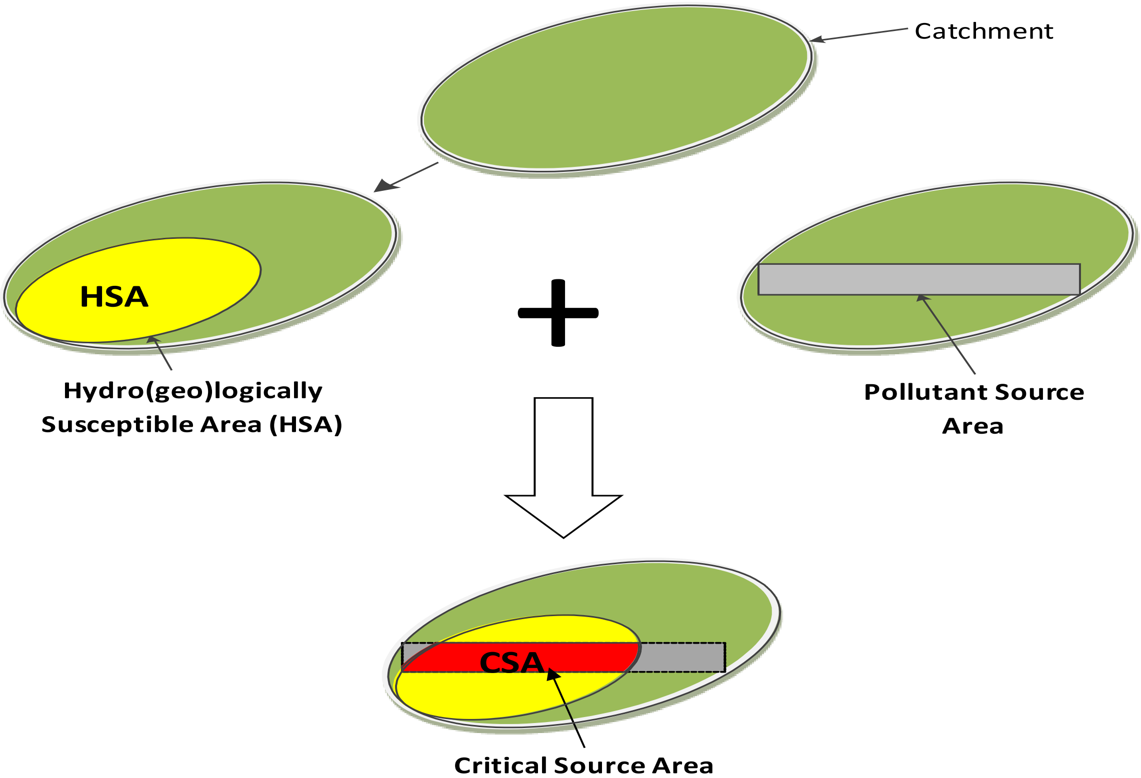

Figure 3: Diagrammatic representation of the components of CSAs

INTERIM 'STORY' OF SOURCE CATCHMENT AREA

This is a critical section in the desk study, as it summarises and integrates all of the information and then provides a basis for the work plan and for the consideration of possible mitigation options. It is based on an integration of all the relevant components of the source-pathway-receptor model for environmental management. If one of these components is missing, the continuum is broken. It is recommended that a three-dimensional 'mental model', aided by the pathways conceptual model (illustrated in Figure 4), is developed as an ongoing process while the information/evidence is being collected and assessed in relation to 'significant' issues in the catchment area/ZOC, the 'significant' pressures and the main relevant pathways.

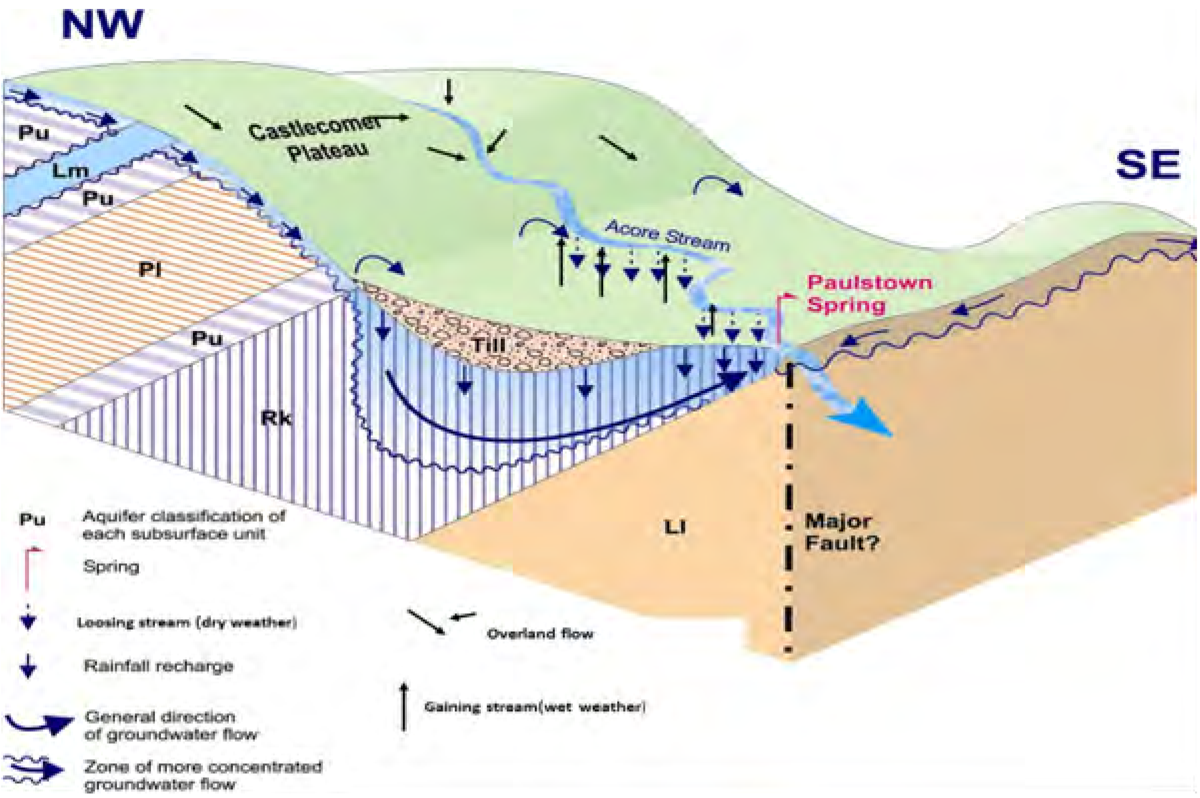

Figure 4: Schematic diagram drawn by the Groundwater Section, GSI, for the Paulstown Source Protection Report.

FURTHER CHARACTERISATION OF THE SOURCE CATCHMENT AREA

Field or street scale assessments, involving fieldwork and catchment walks, are an essential component of the source protection framework. They should focus on the issues, pressures and CSAs provided by the interim ‘story’, as well as on data gaps. For larger surface water catchments, a focus on sub-catchments may be necessary. For both groundwater and surface water sources, further sampling and analysis of untreated water may be needed. The work required and the resources needed for sources with an improvement objective will generally be greater than for sources with a protection objective.

MITIGATION AND PROTECTION STRATEGIES AND ACTIVITIES

Details on the recommended approach to the selection of management practices and on possible mitigation options for all the main issues and pressures (both point and diffuse) are given in the framework document. A key goal is to ensure that decisions are targeted to achieving the required objectives, and therefore are efficient and effective in terms of water quality outcomes, resources required including staffing and costs, and acceptability among stakeholders.
Once the characterisation process has been undertaken, management strategies and practices can be assessed as a means of achieving the source objectives. The approach being used when considering management practices are summarised in the steps in Table 1.

Table 1: Recommended steps in selection of management practices.

1	Undertake a brief inventory of existing management efforts, including quality assurance implementation.	
2	Evaluate their effectiveness.	
	Where the objective is Improvement	***Where the objective is Protection***
3	Note ‘significant’ issues and ‘significant’ pressures.	Check if there are point or diffuse pressures in susceptible areas that have the potential to pose a future threat to source water quality.
4	Take account of whether they are point source and/or diffuse source pressures.	Evaluate whether or not existing measures and actions are adequate and if consideration should be given to checking that the measures are being undertaken satisfactorily and/or whether some additional actions are needed.
5	If feasible, undertake an analysis of the pollutant reduction that is required.	Where additional actions would be beneficial, identify them and evaluate for cost, acceptability and achievability.
6	Identify the measures and actions that have the potential to achieve the objectives for the particular issues and pressures in question.	Consult with relevant public bodies (e.g. planning authorities).
7	Evaluate the likely effectiveness of these measures and actions in terms of, for instance, pollutant reduction and usage in the relevant critical source areas.	Select those additional actions that are recommended to be undertaken. Consider giving priority to those that have more than one environmental benefit.
8	Assess their cost, if feasible, and do a comparison between options.	-
9	Consult with relevant public bodies (e.g. planning authorities).	-
10	Assess whether they are likely to be acceptable and assess the constraints.	-
11	Note any co-benefits, and consider giving preference to those with more than one benefit.	-
12	Decide on the preferred mitigation measures and recommended voluntary actions, and in the process, take account of the regulatory nature of the ‘measures’ and the voluntary nature of the ‘actions’.	-

In addition to meeting water quality objectives, consideration of the additional benefits from the mitigation options for related environmental objectives – biodiversity, carbon sequestration and flood mitigation – is recommended as a means of achieving optimal outcomes for the environment and, perhaps, public acceptance for the activities.

IMPLEMENTING MITIGATION AND PROTECTION STRATEGIES

While all the components described above are necessary, the most critical factor in achieving the objective of ‘safe and secure’ drinking water supplies is the undertaking of targeted and appropriate mitigation activities, based on an implementation plan and measurable outcomes.

MONITORING PROGRESS AND MAKING ADJUSTMENTS

Monitoring and tracking progress needs to be undertaken at appropriate intervals, with consideration given, in particular, to learning lessons as part of an evolving and iterative process.

CONCLUSIONS

This is a high level, overarching framework that is intended to encourage an integrated and targeted approach to source protection. It builds on the groundwater protection scheme model and the understandings provided by the catchment characterisation work undertaken in recent years. It is influenced by and benefits from international approaches. It links intentionally with the WFD implementation and catchment management approaches being undertaken by the EPA and LAWPRO, and, in the process, with the physical settings, issues and pressures relevant to Ireland.

While a framework such as this is beneficial, the work 'on the ground' by scientists and engineers, in collaboration with GWSs and local communities, is essential for success. By combining the Framework with work specific to each source, this approach will become an exemplar for drinking water source protection in Ireland and internationally.

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WFD GROUNDWATER STATUS: THE WHOLE TRUTH AND NOTHING BUT THE TRUTH?

Philip Maher

Hydrometric & Groundwater Section, Environmental Protection Agency, Richview, Dublin

ABSTRACT

The role that the Water Framework Directive (WFD) status assessment plays in groundwater management is considered in this paper. The ecological and chemical quality of water in Ireland has deteriorated since 2013, after a period of relative stability and improvement. The overall concentration of nitrate in groundwater, and surface water, has also increased during this time. Reductions in groundwater flow, or in groundwater quality can directly affect drinking water supplies, surface water quality, and, associated ecosystems. Management of groundwater quality and quantity is therefore an important tool in protecting our environment and health.

In general terms, the main threats to groundwater can be divided into nutrient enrichment, chemical contamination and unsustainable abstraction. These threats are addressed by the WFD and related Directives. In Ireland, the Groundwater Regulations aim to give effect to the measures needed to achieve the environmental objectives established for groundwater by the WFD and the Groundwater Directive. The overall goal of European and National water policy is to restore the quality of polluted waters, and ensure clean waters are kept clean.

The groundwater status assessment procedure addresses threats to water quality and quantity by determining both the chemical status and the quantitative status of each groundwater body. Groundwater status is assessed using monitoring data from the past six years, which is applied to five chemical and four quantitative status tests. Overall, there has been an improvement in groundwater status since it was first assessed in 2009. In the most recent status assessment, 92% of groundwater bodies met their good chemical and good quantitative status objectives.

However, do the results of the status assessment give us the full picture on water quality? Does the status assessment provide "the whole truth and nothing but the truth"? Clearly the status assessment results in isolation don't tell the full story as water quality has deteriorated during a time when status has improved. Therefore, decision makers (e.g. regulators, consultants and public bodies) should not rely on status alone as the only source of information in water management. A holistic approach to water assessment and management is encouraged, where groundwater status results are viewed together with national water quality and quantity data, risk characterisation information on pressures and in conjunction with surface water and receptor data.

Key words: *WFD, status assessment, classification, water quality, abstractions, water resources.*

WHY IS GROUNDWATER IMPORTANT?

Groundwater plays an important role in overall water quality, it provides the source for many drinking water supplies, and, as part of the hydrological cycle, it provides the base flows to our surface waters and associated ecosystems.

The ecological and chemical quality of all water types in Ireland has deteriorated since 2013, after a period of relative stability and improvement (EPA, 2019a). Positive trends reported previously by the EPA have reversed. Since 2013, the population of Ireland has increased, as have cattle numbers and fertilizer use. These pressures have caused an increase in nutrient concentrations (phosphorus and nitrogen) in our water bodies, which continues to be the most widespread concern for water quality in Ireland. In the period 2013-2018, over a quarter of river sites monitored had increasing nutrient levels, and nutrient loads to the marine environment have also increased during this time. The overall concentration of nitrate in groundwater has also increased in this period. Increased concentrations of nitrate in groundwater may be impacting on the quality of surface water, particularly where there are free draining soils and where the ecology of those rivers, lakes or estuaries is sensitive to inputs of nitrogen.

Elevated nitrate levels in groundwater are also a concern for drinking water supplies and have the potential to be harmful to human health. Several drinking water supplies have had exceedances of the nitrate drinking water limit in recent years. Groundwater is an important source of drinking water in Ireland, on regional and local scales. Groundwater sources (springs and boreholes) supply 17% (by volume) of public water supplies (EPA, 2020a), and household wells provide around 500,000 people with water in Ireland (EPA, 2016a).

Recent droughts and periods of low rainfall have reminded many of the importance of groundwater in supplying baseflows to rivers and lakes. During extended low flow periods, most of the flow in rivers is supplied by groundwater.

Reductions in groundwater flow and deterioration in groundwater quality can directly affect drinking water supplies, surface water quality and associated ecosystems. It is therefore important to consider groundwater as both a receptor and as a pathway to surface water. Holistically managing groundwater quality and quantity, together with our surface water resources, is therefore vital to protect both our environment and health.

Under the WFD, status is the current metric by which Ireland is gauged by policy makers and this acts as a driver for prioritised action. For groundwater, improvements in status have occurred since groundwater was first classified in 2009. However, status is a reflection or look-back at the past, and the WFD always intended it to be used in combination with forward looking trend projections and the implementation of control measures to prevent or limit further pollution. These latter aspects of the WFD form part of risk characterisation. Characterisation is the critical step that drives actions to ensure that the status of water bodies is not compromised in the future. While it is important to improve any groundwater bodies at poor status, it is equally, if not more, important to ensure that water bodies do not deteriorate in status.

MANAGEMENT OF GROUNDWATER THROUGH THE WFD

LEGISLATIVE BACKGROUND TO GROUNDWATER MANAGEMENT

Management of the groundwater issues outlined above is achieved through the EU Water Framework Directive (WFD) (2000/60/EC[1]), and the National River Basin Management Plan 2018-2021 (DHPLG, 2018). The WFD requires all member states to protect and improve water quality in all waters so that they achieve good ecological status by 2015 or, at the latest, by 2027. The WFD was given legal effect in Ireland by the European Communities (Water Policy) Regulations 2003 (S.I. No. 722 of 2003[2]). The overall goal of European and national water policy is to restore the quality of polluted waters, and ensure clean waters are kept clean. The WFD was agreed by all individual EU Member States in 2000. The Directive runs across three river basin planning cycles, 2009-2015, 2016-

[1] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32000L0060&from=EN

[2] http://www.irishstatutebook.ie/eli/2003/si/722/made/en/print

2021 and 2022-2027[3]. A key part of the WFD is public engagement and the involvement of local communities in the management and decision making of their water resources. The WFD is a powerful tool to help communities protect and improve their waterways[4].

The Groundwater Directive (GWD) (2006/118/EC), a daughter directive to the WFD, was introduced in 2006 to improve groundwater quality and resources (EC, 2008). In Ireland, the Groundwater Regulations[5,6] aim to give effect to the measures needed to achieve the environmental objectives established for groundwater by the WFD and the GWD. They include the following overarching requirements to manage groundwater.

- To protect, enhance and restore all bodies of groundwater and to ensure a balance between abstraction and recharge of groundwater, with the aim of achieving good groundwater status by not later than 2015 (this deadline was subsequently extended to 2027).
- To prevent (in the case of hazardous substances[7]) or limit (in the case of non-hazardous substances) the input of pollutants into groundwater and to prevent the deterioration of the status of all bodies of groundwater.
- The reversal of any significant and sustained upward trend in the concentration of any pollutant resulting from the impact of human activity in order to progressively reduce pollution of groundwater.

Gathering data for the WFD assessments is an important part of the overall process. Article 8 of the WFD requires the establishment of programmes of monitoring for groundwater (EPA, 2006). The EPA manages national groundwater monitoring programmes for the collection of water quality and quantity data. Water quantity data is gathered for the WFD and to support the requirements of Section 64 of the EPA Act, 1992[8].

WHAT IS STATUS AND WHAT IS THE INFORMATION USED FOR?

The Groundwater Regulations provide the legislative framework under which groundwater status assessment is undertaken. Status assessment, or classification, is a backwards looking ‘audit’ of water quality in the current cycle and provides a six-yearly review of the condition of water bodies. All water types (rivers, lakes, groundwaters, estuaries and coastal water) are assessed and, following completion of the assessment, the water quality information is reported by the EPA, most recently in 2019 (EPA, 2019a). Status is used by the European Commission to assess Member States’ water quality, and to assess their progress with the goals of the WFD.

The status information from the previous cycle acts as a starting point that feeds into the next step of the process, risk characterisation. Characterisation is the critical step that drives future actions to ensure that the status of water bodies is not compromised in the future. In characterisation, status is used in combination with forward looking trend projections and the implementation of control measures to prevent or limit further pollution. Characterisation involves establishing where the water quality and quantity issues are, identifying the source of these issues, determining why they are occurring, and, having appropriate measures to address the pressures. Detailed guidance on the characterisation process has been published by the EPA (EPA, 2016b), and in previous IAH Proceedings (Daly et al, 2016). Characterisation is a forward-looking assessment to plan for the next

[3] A summary of the data and information gathered up to the first cycle is presented in Hunter-Williams et al (2009).

[4] See www.catchments.ie for more information.

[5] S.I. No. 9/2010 - European Communities Environmental Objectives (Groundwater) Regulations 2010. http://www.irishstatutebook.ie/eli/2010/si/9/made/en/print

[6] S.I. No. 366/2016 - European Union Environmental Objectives (Groundwater) (Amendment) Regulations 2016. http://www.irishstatutebook.ie/eli/2016/si/366/made/en/print

[7] Refer to EPA, 2010b, Classification of Hazardous and Non-Hazardous Substances in Groundwater

[8] http://www.irishstatutebook.ie/eli/1992/act/7/section/64/enacted/en/html

cycle, and it is currently underway for the third 2022-2027 cycle. Where problems are identified through characterisation, measures can be planned to address these potential issues, through the next River Basin Management Plan (RBMP). In 2020, planning started for the third cycle RMBP 2022-2027, with a public consultation on the significant water management issues undertaken by the Department of Planning Housing and Local Government (DHPLG, 2020). A draft third cycle RMBP is due to be published in December 2020, with the finalised RBMP due to be published in December 2021. In theory, all water bodies should achieve good status by 2027, and therefore the 2022-2027 RBMP should include an explanation, plus any proposed or agreed alternative objective for water bodies that are unlikely to achieve good status by that date.

HOW IS STATUS ASSESSED?
In general terms, the main threats to groundwater can be divided into nutrient enrichment, chemical contamination and unsustainable abstraction. The groundwater status assessment procedure addresses these threats by determining both the chemical status and the quantitative status of each groundwater body. The groundwater body (GWB) is the groundwater management unit under the WFD (WGG, 2005). GWBs are used for status assessment, characterisation and reporting purposes. There are 514 GWBs in the second WFD cycle. Both chemical and quantitative status are classed as either 'good' or 'poor'. GWBs that are reported as 'not at risk' are automatically classed as 'good' status in the concurrent RBMP cycle. The WFD sets out a series of criteria that must be met for a GWB to be classed as good chemical and quantitative status. The criteria for good chemical status are further elaborated in the GWD and are summarised in the following section.

Threshold Values (TVs) are groundwater quality standards that are to be established by each member state for the purpose of assessing the chemical status of GWBs and are also used when undertaking trend assessments. TVs have been developed for Irish groundwater bodies by the EPA for substances that are leading to (or likely to lead to) chemical and/or ecological status failures (EPA, 2010a).

There is a degree of uncertainty in the status assessment process, based on the assumptions in the status tests, variabilities in monitoring data, and the uncertainties in our understanding of groundwater flow and quality. Thus, a weight of evidence approach, with monitoring data, complemented by conceptual understanding and other available data sources, is applied to the assessments.

Input Data for Status Assessment
The national groundwater monitoring programmes managed by the EPA provide most of the input data for the status assessment. The groundwater quality assessment also considers information from the surface water WFD status assessments, GWB conceptual site models, pollution impact potential maps, and assessment of licenced sites from the EPA's Office of Environmental Enforcement. The quantity assessment water balance test considers GSI's groundwater recharge data and abstractions data from the EPA's Water Abstractions Register. The impact of groundwater abstractions on surface waters and wetlands considers depletion in the flow (and level) in and to those receptors. Timely and accurate abstraction registration and deregistration (once abstractions have ceased), are essential to accurately assess the impact of abstractions on the water environment. Practitioners are encouraged to engage with water abstractors to remind them of their requirement to register any abstraction 25 cubic meters or more with the EPA[9]. Any changes to existing registrations should also be updated on the register.

Status Tests
Groundwater status is determined using five chemical and four quantitative tests. The overall chemical status of the GWB is the worst-case classification from the chemical status tests. The overall quantitative status for the GWB is the worst-case classification from the quantitative tests. The overall status is the worst-case classification from the quality and quantity tests, referred to as the 'one out, all

[9] Refer to the EPA website for information on how to register an abstraction https://www.epa.ie/licensing/watwaste/watabs/

out' principle. The tests determine if the WFD objectives are met for a GWB. The tests are outlined in Table 1 below and are set out in detail in EPA guidance (EPA, 2010a), the Groundwater Regulations, and in previous IAH Proceedings (Daly & Craig, 2009).

Table 1: Summary of Groundwater Status Assessment Tests

Chemical Test	**What the test looks to establish.**
Saline (or other) Intrusions	Is there evidence of saline or other intrusions in the GWB?
Impact of Groundwater on Surface Water Ecology	Are pollutant(s) in the GWB (typically phosphate) impacting on an associated surface water body (SWB) sufficient to threaten the WFD objectives for the SWB?
Groundwater Dependent Terrestrial Ecosystems (GWDTE)	Are pollutant(s) in the GWB acting on an associated GWDTE sufficient to threaten the WFD objectives for the GWDTE? Evidence for this test is provided by the National Parks and Wildlife Service (NPWS).
Drinking Water Protected Area	Is there a deterioration in groundwater quality from anthropogenic influences that could lead to an increase in drinking water treatment at an abstraction in the GWB?
General Chemical Assessment	Is there a widespread deterioration in groundwater quality that has, or will compromise the strategic use of groundwater in the GWB?
Quantitative Test	**What the test looks to establish.**
Saline (or other) Intrusions	Is there evidence of saline or other intrusions in the GWB induced by groundwater abstraction?
Impact of Groundwater on Surface Water Ecology	Could groundwater abstraction impact on the flow required to support surface water ecology in an associated SWB?
Groundwater Dependent Terrestrial Ecosystems (GWDTE)	Is groundwater abstraction affecting an associated GWDTE such that it could threaten the WFD objectives for the GWDTE? Evidence for this test is provided by NPWS.
Water Balance	Are the abstractions in the GWB in excess of the recharge to the GWB, such that there is insufficient water available to support the ecology of surface water bodies and wetlands, or falling groundwater levels?

Large Point Sources (Licensed Sites)

Status, trends and prevent or limit objectives are used by the EPA to determine which industrial and waste licensed sites are deemed to be significant pressures[10]. Between 2010 and 2013, reviews of each industrial and waste licensed facility, in the context of the prevent or limit objective of the Groundwater Regulations, were undertaken by the Office of Environmental Enforcement of the EPA. As set out in the EPA guidance (EPA, 2014), the three main criteria for the establishment of a site to be a significant pressure are listed below (this assumes that the site is already in breach of the prevent or limit objective, and that groundwater concentrations exceed generic assessment criteria, which would generally be the case for licensed sites with any appreciable existing or historical contamination).

- Is there evidence that there is an expanding plume? Is the estimated or known area of the plume greater than 2 km^2?
- Is there known or potential impact on groundwater-related receptors? For example, drinking water, GWDTE or receiving surface water receptors.
- Do contaminant concentrations exceed 100 times the TV / related value at any groundwater monitoring point?

[10] Significant pressures are those pressures that are having a significant impact on ecological status and need to be addressed before the status will improve.

The third point above (i.e. concentrations in excess of 100 times the TV) is the main trigger for industrial or waste sites in Ireland being assigned as significant pressures, and therefore assigned 'poor' status. Measures to manage the contamination form part of the conditions of the licences for these sites. These sites are 'clipped out' from the parent GWB based on hydrogeological information local to the facility, following the general GWB delineation principles.

GROUNDWATER STATUS RESULTS, 2013-2018

There has been a gradual improvement in groundwater status since the first assessment in 2009 (Table 2). This has been accompanied by an improvement in knowledge on pressures, which has resulted in many "point source pressure" groundwater bodies being found to present little risk to the status objective being met and subsequently has seen them become subsumed into their parent groundwater body. The number of groundwater bodies failing to meet their status objective reduced from 103 in 2003-2008, to 45 in 2010-2015, and most recently, to 40 in 2013-2018. In the 2013-2018 status assessment, of the 514 groundwater bodies, 474 (92%) met their good chemical and good quantitative status objectives, accounting for 98% of the country by area. (EPA, 2019a). Maps displaying GWB status and water quality data are available on the EPA website (EPA, 2020b).

Table 2: Summary of the 2013-2018 status results, and comparison with previous results.

Groundwater Assessment Test	**2013-2018 (514 GWB)**		**2010-2015 (513 GWB)**		**2003-2008 (757 GWB)**	
	Good status	**Poor status**	**Good status**	**Poor status**	**Good status**	**Poor status**
Surface Water Quality	510	4	504	9	662	95
GWDTE Chemical	512	2	511	2	757	0
Drinking Water	512	2	513	0	757	0
General Chemical	481	33	477	36	749	8
Intrusions	514	0	513	0	757	0
Overall Chemical	**476**	**38**	**469**	**44**	**654**	**103**
Surface Water Quantity	514	0	513	0	757	0
GWDTE Quantity	513	1	512	1	755	2
Water Balance	513	1	513	0	756	1
Intrusions	514	0	513	0	757	0
Overall Quantitative	**512**	**2**	**512**	**1**	**754**	**3**

Of the 40 poor status groundwater bodies, 38 were assigned poor chemical status and two were assigned poor quantitative status. Most of the poor chemical status GWBs relate to contamination from historic mines, industrial and waste licensed sites. A summary of the tests is provided below.

- For the Surface Water Quality Test, due to improved conceptual understanding of how groundwater is contributing phosphorus to rivers that are at less than good status, there was a reduction of five in the number of poor status GWBs. Three of the remaining poor status GWBs are associated with groundwater contributing metals to less than good status rivers in historic mining areas and, the fourth is a cross border GWB with Northern Ireland.
- In the GWDTE Chemical Test, the GWBs relating to the Caherglassaun and Tullynafrankagh turloughs remain at poor status based on an assessment by NPWS.
- For the Drinking Water Test, poor chemical status was assigned to the Durrow and Mitchelstown GWBs that supply drinking water because the average nitrate concentrations exceeded the nitrate threshold value and are continuing to increase.
- In the General Chemical Test, 32 of the 33 poor chemical status GWBs relate to contamination from historic mines, industrial and waste licensed sites. Improvements in groundwater quality at four licensed sites lead to a reduction in the number of poor status GWBs. An additional poor status GWB was created following review of historic contamination at a licensed industrial site.

- In relation to quantitative status, the Bettystown GWB is at poor status due to failure of the Water Balance Test, as a result of abstraction pressures. The Clara Bog GWTDE GWB remains at poor status as the NPWS have indicated the bog is not meeting its conservation objective because the ecology is impacted by historical regional and local drainage schemes.

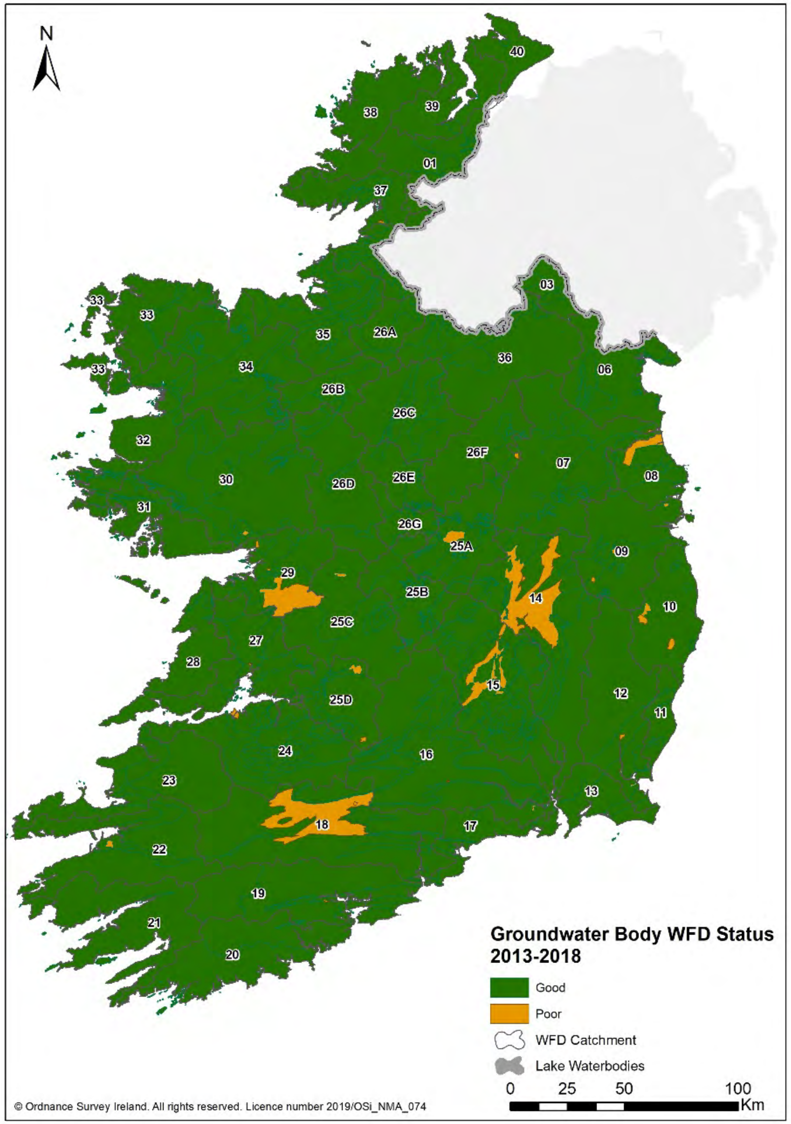
The picture from the status assessment alone indicates an improvement in groundwater quality, with poor status accounting for only a small area (2%) of the country. This picture contrasts with the water quality assessment, which shows that water quality, including in groundwater, is declining. This contrast is apparent when comparing the status results from 2013-2018 (Map 1 below, EPA, 2019a) with the differences in nitrate concentration 2013-2018 (Map 2 below., EPA, 2019b). Map 2 shows an increase in nitrate concentrations across the country.

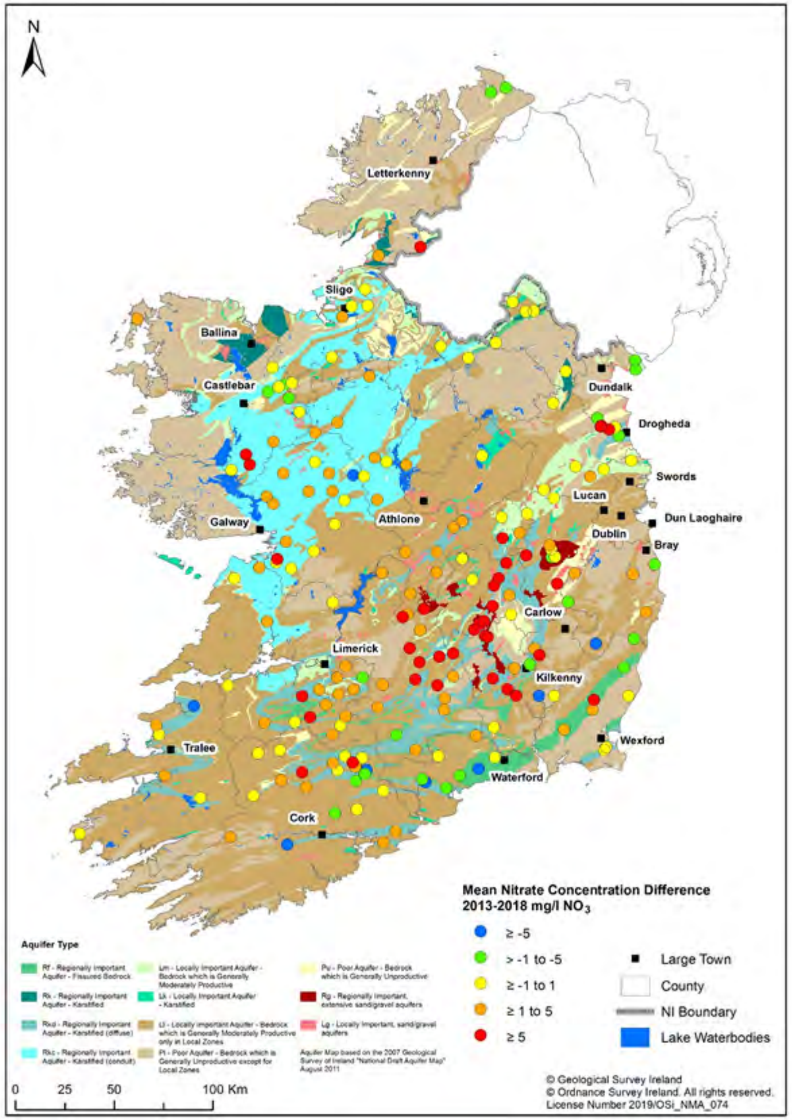
DOES WFD STATUS PROVIDE "THE WHOLE TRUTH AND NOTHING BUT THE TRUTH" IN RELATION TO WATER QUALITY IN IRELAND?

Do the results of the status assessment give us the full picture on water quality in Ireland? Does the status assessment provide "the whole truth and nothing but the truth"? Status assessment provides a framework for high level regional assessment of groundwater quality and for providing information for the next planning cycle i.e. characterisation and catchment management planning. However, the status assessment results in isolation don't tell the full story, as water quality has deteriorated during a time when status has improved.

There are some limitations to status, based on the way it has been structured / designed. Status is a backwards looking snapshot of the past condition of water quality, it does not take account of projected changes to water quality and quantity over time. In addition, the status assessment result is broad and is based on the 'one out all out rule'. GWBs failing one test may still have reasonable water quality or quantity under the other tests. In addition, two GWBs could have the same status results, but the story behind them, i.e. the condition of water quality and quantity in them, could be quite different, and therefore the management approach to these GWBs could also be different. Status shouldn't be the only criteria used for groundwater management.

Status is limited in its practical application to water management, but it is the means by which the European Commission assess water quality in Member States. Therefore, status tends to get overly focused on in the water quality narrative. However, status alone doesn't give the full picture of water quality and so cannot be relied upon as the only source of information in water management. A holistic approach to water assessment and management is encouraged, where groundwater status results are viewed together with national water quality and quantity data, risk characterisation information on pressures and in conjunction with surface water and receptor data, as discussed in more detail in the following section.





Map 1: Groundwater Status 2013-2018

Map 2: Change in groundwater nitrate concentrations 2013-2018

WATER QUALITY

Nutrients
Based on the status results alone, nutrients would not appear to be a significant groundwater quality issue, as only two GWBs were assigned poor status for the period 2013-2018, as a result of excess nutrients, from nitrate in drinking water. However, the assessment of national water quality data indicates that nutrients are the most significant groundwater quality issue.

Nitrate
The most recent assessment of water quality in Ireland, from the period 2013-2018 (EPA, 2019a), indicates that overall, the concentration of nitrate in groundwater is increasing, with the percentage of monitoring stations with average nitrate concentrations greater than 25 mg/l NO_3 having increased by 6.5% between 2013 and 2018. Generally, the south and south-east of the country continue to have the greatest proportion of monitoring stations with higher nitrate concentrations and, it is in this region where nitrate concentrations increased the most since 2013. Given the nature of activities that can give rise to increased nitrate in groundwater, this increase is attributed largely to the impact of diffuse nutrient losses from agricultural sources. These parts of the country are characterised by freely draining catchments with soils, subsoils and bedrock which are not favourable for denitrification, and excess nitrogen applied to the land through agriculture leaches to the groundwater, as nitrate is highly mobile. High levels of nitrate in groundwater are a source of contamination to drinking water supplies.

As well as affecting drinking water, nitrate in groundwater at concentrations below the TV can impact on the quality of surface water, leading to increases in river and estuarine nitrate concentrations. The nitrate TV's origins are in the Nitrates Directive and Drinking Water Directive water quality standards, yet ecological impact in rivers, estuaries, coastal waters and wetlands is observed in Ireland at much lower nitrate concentrations, with ecological effects being seen at around 1 mg/l and above. However, nutrient enrichment is a complicated process, with phosphorus often the more critical nutrient when nitrogen concentrations are lower. As nitrogen concentrations increase, they may have an increased influence on enrichment and the ecological health of the surface water and wetland receptors. The relationship in saline water is also more complex as the interaction with other nutrient sources from adjacent seawater becomes important.

Groundwater acts as a pathway for nutrients to discharge to surface waters, impacting on the quality and ecology of these waters. This effect also highlights why trend assessments and an assessment of the nutrient losses to water are important. Nitrate levels in groundwater have not significantly affected groundwater status results as few drinking water sources have reported exceedances, and the surface water receptors have not yet reached a tipping point where nitrogen becomes as critical a parameter as phosphorus for their ecological health. However, if we were to rely on status alone to take action on nitrate levels in groundwater, it would be too late, as the impact would already have happened, ecological deterioration would have already occurred and it would be difficult to address. Therefore, water management needs to consider not only status, but also the forward-looking aspect of the WFD, i.e. characterisation, to predict these negative impacts before they occur.

Phosphate
Phosphate concentrations in groundwater are generally stable (EPA, 2019a). The average phosphate concentration in groundwater was below the threshold value (0.035 mg/l P) at 93% of the monitoring locations during 2013-2018. The highest groundwater concentrations of phosphate are generally in the karstified limestone aquifers, due to the vulnerable nature of the limestones, along with shallow soils and subsoils, and sinking streams, often resulting in little time for attenuation, and therefore high phosphate concentrations in groundwater. In these areas, groundwater can be an important pathway for the movement of phosphorus from diffuse and small point sources to water ecosystems, due to these high concentrations in groundwater, combined with the high groundwater flow contribution to surface water, of the order of 70% (EPA, 2010a). The Impact of Groundwater on Surface Water

Ecology status test assess the impact of phosphate in groundwater on receiving surface waters. No GWBs were assigned poor status based on this test in 2013-2018. In addition, the main regions of concern where phosphate is elevated in surface water are areas with heavy soils and/or with steep slopes and, these regions generally do not coincide with the karstified limestone aquifers overlain by shallow soils. Therefore, groundwater status does not provide significant insights on water quality with respect to phosphorus. A conceptual understanding of the physical settings and breaking transport pathways is of greater importance than status or groundwater quality results when considering management options to prevent pollution of phosphate in surface water.

E. coli

Escherichia coli (E. coli) is a bacterium used as an indicator of faecal contamination of water. Its source is generally agriculture or septic tanks. Many private water supplies abstract from groundwater and may have limited or no treatment (EPA, 2016a). Approximately half of the 195 groundwater monitoring sites, which sample raw, untreated water, had a sample contaminated with one or more E. coli in 2017 (EPA, 2018). The high proportion of monitoring sites with E. coli detections reflects both the presence of pressures and the naturally vulnerable nature of groundwater in some parts of the country, for example the karst limestone aquifers in the west of Ireland. Fortunately, where these abstractions are also used to provide water supply, adequate disinfection treatment systems for E. coli are in place and should allow for safe delivery of water supply if maintained and operated correctly. E. coli are not WFD status criteria *per se*; but are useful when informing management strategies for water supplies, in particular private water supplies, and also may act as an indicator of raw water vulnerability where other substances, pathogens and viruses may utilise the same pathways to get to a water treatment plant. These factors highlight the need for testing of drinking water supplies from groundwater for microbial contamination and for the provision of adequate treatment. This is particularly relevant for households and other private supplies which may not have treatment in place for microbial contaminants. The EPA recommends that all drinking water supplies be monitored at least once a year for E. coli, with greater frequencies required for some supply types.

E. coli is a significant water quality issue, however pathogens (such as E. coli) are not a parameter considered by the WFD and therefore not reported on by the status assessment. The WFD indirectly considers E. coli in relation to the protection of drinking water with the recent inclusion of catchment based metrics in the revised Drinking Water Directive[11] reinforcing the alignment between these Directives.

Point Sources

Small point sources of contamination generally do not have an impact at a regional (GWB) scale, although they can cause issues to groundwater, surface water and wetlands at a local scale. Large point sources potentially affecting groundwater on a regional water body scale, such as EPA licensed sites, are assessed on site specific data submitted to the Office of Environmental Enforcement of the EPA.

For GWBs associated with licensed industrial sites, the status result gives an indication of the scale of contamination in the GWB. Where the spatial extent or magnitude of the contamination is known to be significant, then smaller groundwater bodies have been delineated to reflect and allow management of these point sources. It is important to note that GWBs associated with licensed industrial sites that are currently at good status may still have contamination issues, but the contamination may not have significant spatial extent or magnitude, but still represents a failure to prevent or limit pollution. This highlights that pollution can still be evident in good status groundwater bodies, and may come from either or both point (and diffuse) sources. There may breaches of quality standards that are more localised in nature, but are not picked up in the status assessment because their spatial extent is localised.

[11] https://ec.europa.eu/environment/water/water-drink/review_en.html

Hazardous Substances and Pesticides

The EPA has conducted screening analyses for a wide suite of hazardous substances and pesticides in groundwater from 2007-2009 and in 2014. The results have shown that very few of these substances are found in groundwater and, where they are found, they are typically at low concentrations. The national screening analysis is completed once per six-year WFD cycle, and the planned screening analysis for the current (second) cycle is currently underway in 2020. Additional monitoring to be completed in 2020 includes certain pharmaceutical compounds and per- and polyfluoroalkyl substances (PFAS), based on the Common Implementation Strategy Groundwater Working Group[12] Voluntary Groundwater Watch List. Widespread status failures are not expected as a result of these types of chemicals outside of historic mining areas or licensed industrial or waste sites, but there may still be local impacts that are not of sufficient scale or extent to be picked up in the status assessment.

WATER QUANTITY

Abstractions

The abstraction of high volumes of groundwater from, for example, large wells, or mine dewatering, could affect surface water ecosystems by reducing the flow of water to them. The quantitative status assessment water balance test is a regional scale assessment and localised abstraction impacts may be masked by the scale of the assessment. For example, there may be a decrease in groundwater levels around a well field suppling drinking water, but these local issues may not be apparent in the GWB assessment due to the scale of the GWB i.e. there may be enough unimpacted area in the GWB to offset the impacted GWB area. However, as part of the assessment of abstraction pressures on surface water, such a groundwater abstraction may be identified as a significant pressure, and measures would be required to reduce its impact on the water environment. Determining whether abstractions are a significant pressure on our water resources is the subject of a paper in these Proceedings by Janka Nitsche, EPA. The management of groundwater abstractions by hydrogeologists in Ireland should be considered in conjunction with surface water as they are fundamentally linked, and surface and groundwater will be assessed together by the EPA from now on.

In the most recent status assessment, only one major GWB (Bettystown) was at poor status due to abstraction pressures (the smaller Clara Bog GWDTE GWB was also assigned poor quantitative status in 2013-2018, due to regional drainage). However, the characterisation risk assessment highlights that many other groundwater abstractions may be having an impact on surface waters and further investigation is required to determine if these groundwater abstractions are impacting on the supporting conditions for the associated surface water bodies. Therefore, the large scale of the status assessment water balance test means that local impacts may not be captured by the assessment. Localised impacts may still be occurring in a good quantitative status GWB.

Climate and Increased Seasonality

The WFD status assessment is based on an assessment of annual or six-year averages and it is not a good method of identifying changes such as increases in the range between winter and summer groundwater levels, i.e. more pronounced seasonality, as these changes would be masked by annual averaging. As climate change is expected to lead to an increase in the occurrence of such water level changes, along with their associated ecological impacts, the WFD is likely to require alteration to take account of these impacts. Such changes to technical assessments as well as the integration of climate change monitoring into the national monitoring networks are currently being considered at a European level.

CONCLUSIONS

The ecological and chemical quality of water in Ireland has deteriorated since 2013, after a period of relative stability and improvement. The overall concentration of nitrate in groundwater has also increased during this time, particularly in the south and south-east of the country, and is attributed

[12] https://ec.europa.eu/environment/water/water-framework/groundwater/activities.htm

largely to the impact of nutrient losses from agricultural sources. Phosphate concentrations in groundwater are generally stable. Nutrient affected groundwater acts as both a source of chemical contamination, and as a pathway for nutrients to discharge to surface waters, impacting on the quality and ecology of these waters.

Management of water resources is undertaken through the WFD and related directives, and the National River Basin Management Plan 2018-2021. Status assessment provides a framework for high level regional assessment of groundwater quality and for providing information for the next planning cycle i.e. characterisation and catchment management planning. There has been a gradual improvement in groundwater status since the first assessment in 2009. In the 2013-2018 status assessment, 92% of GWBs met their good chemical and good quantitative status objectives accounting for 98% of the country by area.

Status does not give “the whole truth and nothing but the truth” when it comes to water resources assessment. The status assessment results in isolation don’t tell the full story as water quality has deteriorated during a time when status has improved. Limitations of the status assessment results include the following:

- Status is a backwards looking snapshot of the past condition of water quality, it does not project changes to water quality and quantity over time into the future. For a forward-looking assessment of water quality, characterisation results should be used.
- Status results are broad and are based on the ‘one out all out rule’. A GWB failing one test can still have reasonable water quality or quantity under the other tests.
- Status assessment is conducted at the regional (GWB) scale. Thus, the assessment results may not capture local contamination or over abstraction issues. Investigations are needed at a local scale to assess these issues. Assessments of groundwater should be considered in conjunction with associated surface water bodies, and vice versa.
- Status alone does not capture the impact of nutrients in groundwater on surface water and associated ecological receptors. The additional information provided by characterisation results and a conceptual understanding of nutrient transport are needed to manage and improve water quality.
- E. coli is a significant water quality issue, however pathogens (such as E. coli) are not reported on by the status assessment. The WFD indirectly considers E. coli in the revised Drinking Water Directive.
- The status assessment is not a good method for capturing changes in water level patterns resulting from climate change. Alteration of the WFD guidance to take account of these impacts is currently under consideration at a European level.

Decision makers (e.g. regulators, consultants and public bodies) should not rely on status alone as the only source of information in water management. A holistic approach to water assessment and management is encouraged, where groundwater status results are viewed together with national water quality and quantity data, risk characterisation information on pressures and in conjunction with surface water and receptor data.

Looking to the future, the changing policy landscape at EU level (such as CAP revisions, Nitrates Derogation, climate action, EU Green Deal, Biodiversity Strategy and Farm to Fork Strategy) may provide increased urgency to address water quality issues. Closer to home, the effect of Brexit on the transboundary management of GWBs shared between Northern Ireland and the Republic of Ireland is uncertain at this time.

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SESSION IV

PRACTICAL ISSUES WHEN DRILLING BOREHOLES IN IRISH LIMESTONES

David Ball (Hydrogeologist)

28, New Bride Street, Dublin 8

ABSTRACT

Drilling boreholes in the limestones in Ireland is important because the breaks or karst solution conduits running through the limestones can form the framework for the most productive groundwater flow systems in the country. For an experienced hydrogeologist each new borehole provides further learning and surprises. The practical aspects usually seem daunting for less experienced hydrogeologists. The following paper aims to provide some practical tips and a description of a realistic context that may help hydrogeologists and groundwater engineers when working in Irish limestones.

1. INTRODUCTION

My attitude to drilling limestones has come full circle. In my naive youth, when I hoped to drill into the Jurassic, Cretaceous and Tertiary soft porous limestones described in my text books, I looked forward with excitement, until I realised that text book conditions seldom materialised. In middle age, when faced with utterly barren, massive dolomitised Carboniferous age limestones in the Midlands of Ireland, I used to contemplate the work with dread. In the last 25 years, with the help of others, and since getting my head around structural geology and deep palaeo-karst development, the excitement and enthusiasm is back, and continues.

I have written and spoken about drilling in limestones in Ireland in the past. For these papers I had assumed that most of the readers or audience had first hand experience of drilling, in particular water well drilling, in Ireland.

My approach to this paper is different from the past papers, because I have realised over the last two decades that many hydrogeologists have had few opportunities to drill and develop new water supply boreholes in limestones. Therefore, my approach to this paper is to write with them in mind.

To give myself a context, I have asked myself "If I had a hydrogeological training but little experience, what would I like to know before I started to drill a water supply borehole, or any borehole, in limestone in Ireland?" and, "What am I likely to encounter, what am I looking for, how do I react to what I find, what does it mean, and what should I do, or ask the driller to do, under certain circumstances?"

My objective is to try to provide tips, guidance and realism that might help quieten the understandable anxieties that all people feel when setting up and directing a borehole drilling programme in limestones.

Tip: Take comfort that it is normal to be anxious when given the responsibility of spending someone else's money to hopefully find what your client thinks they want, in any ground that has never before been explored.

2. GENERAL PRACTICAL TIPS

Tip 1. Setting Expectations with the Client

At the start of any drilling work, it is important to clarify expectations with the client and the drilling contractor. If expectations and objectives are not clear and realistic at the outset, then probably it will not be possible to put into practice many of the practical tips described later in this paper. In other words, you can't deal with the multitude of issues that may arise and do a good job, if the foundations of the project are not realistic.

Clients will often wonder whether they need a hydrogeologist for the work; a common attitude with inexperienced clients is “Why get a hydrogeologist? Why not just get a driller and a water diviner?“.

If the inexperienced client is required, or have been convinced that they need, to employ a hydrogeologist, they will often assume, or project onto the hydrogeologist, a naïve expectation, that ‘their expert’ will get them the result they need.

Sometimes, ‘the expert’ will not challenge their client’s expectations, perhaps through fear of not getting the work, or because they don’t think the client will accept the uncertainty of drilling in limestones in Ireland. Leaving the client’s naïve assumptions unchallenged is a recipe for future disappointment, all round anxiety and stress.

It is vital to spell out and explain several truisms before planning and agreeing to carry out a drilling project in limestones in Ireland.

The first truism is that hydrogeologists are not omniscient. A hydrogeologist cannot know, nor ever should be expected to know, whether open fractures or karst conduits will be encountered below a particular site, chosen by the client. Often, clients or their advisors will specify that a borehole must be drilled at a particular point because the rest of the site has been committed for other purposes in the plans. Just because they have ‘marked the spot’ does not mean that Nature has provided an open karst conduit at 60 metres below ‘the spot’.

Under these circumstances it is important for the hydrogeologist to remind themselves, and to make sure that the client understands, the following:-

1. A borehole is always a ‘voyage of discovery’; no one has ever made such a hole into the subsurface below this precise point, therefore no one knows what will be encountered, in the very narrow diameter sample of the subsurface that will be excavated by the drilling tools.
2. All unweathered or unaltered bedrock below the 26 counties on this island, is not porous or permeable, because, with the exception of the Triassic age Kingscourt inlier, all bedrock is over 300million years old and all primary pore spaces in the original sediment matrix have been flattened by the compression of lithification and tectonic forces.
3. Therefore, groundwater can only exist and flow through secondary spaces created where the solid rock has been broken, or altered by weathering.
4. Whether there are any gaps in the solid rock is not known, but the work of a hydrogeologist is to identify, and make the best of any evidence during drilling that the hole has encountered a break in the limestone or weathering that might yield water.
5. The driller’s job is to operate the drilling equipment, and discus their observations and ideas with the hydrogeologist. The hydrogeologist’s job is to develop and communicate a conceptual hydrogeological model of what might be found and a variety of potential construction designs that might be used, with the driller, and then observe the work full time, interpret the findings and direct the work.
6. The overall objective of the drilling is not just to make a hole. Instead the objective is to explore, develop, appropriately design and construct a hydraulically efficient, properly protected water supply source. Making the distinction absolutely clear between ‘a borehole’ and ‘a water supply source’, to both the client and the driller, is essential.

In short; all limestones in Ireland are heterogeneous and anisotropic. No matter the ‘Aquifer Classification’, there is no way anyone can predict precisely that a narrow diameter hole will encounter open breaks in the rock that will yield water below a particular site.

If you can get the client and the driller to understand and retain realistic expectations, then your work and your relationship with them will be comfortable, and there will be less disappointment and greater acknowledgement of success.

Tip 2. Setting up the right Drilling Contract

Drillers and engineers like to look at groundwater supply work through the lens of construction; with a focus on parameters that are man-made, for example, borehole depth, diameter, casing wall thickness, wellscreen slot size and cement grout viscosity. These parameters are items of measurement and control. However, anyone with on-the-ground experience creating a groundwater supply in limestones, would realise that the design, construction and development of the water source depends upon natural characteristics of the subsurface revealed **as** the hole is being excavated, and **not** on some predetermined scope of work and Bill of Quantities. Most of the specific characteristics of the rock and the breaks in the rock are not known before the start, therefore it is vital that the contract with the driller allows for flexibility of design and construction, in the light of the **findings as they arise**.

Engineers and drillers are used to working on, what I loosely call, a "footage and diameter basis"; where there are different prices for drilling a metre, at different diameters, in different depth ranges, and with different rates for a range of other activities guessed in advance. These prices and rates are put into the Bill of Quantities and a total price is calculated. The driller in their tender usually works out his prices in order to achieve a reasonable profit on each item, allowing for the perceived risks. If one or more items do not take place, or the borehole is less deep, or has a narrower diameter, then the driller sees that they are not making the profit that they had anticipated at the start. This can be disheartening for the driller and lead to tension on site. The diminution of anticipated profit can lead to drillers resisting design changes that arise in the light of the findings during the work, or lead to spurious justifications by the driller for additional work that will help restore their profits.

Tip: 'footage and diameter' contract is not warranted, and ill-advised, when drilling into unpredictable limestones in Ireland.

Instead, there is an easier and much more appropriate contractual arrangement for constructing a groundwater source in limestones.

I insist on a driller being engaged on a "Day Rate basis".

This consists of an agreed 'working day rate' for the rig, and all the crew, fuel, ancillary equipment, and insurances. This rate is based on an eight hour working day, with the fundamental understanding that the driller will be paid this rate (or an equivalent hourly rate) for all work, as required by the hydrogeologist, to achieve the ultimate objective; in this case, the construction of a proper water supply borehole that makes the best use of the potential offered by the characteristics of the ground encountered below the specific site.

The driller is not paid if the machine is not capable of working (i.e. it needs repairs), or if previously agreed equipment is not available on site, or for lunch breaks or tea breaks. This arrangement encourages drillers to turn up on site on time, with well maintained clean equipment, ready to do what ever is required to achieve the overall objective. They know that they will be paid, even if, for example, they are asked to stop drilling and turn off the airflow so that the recovery of water levels can be measured, or stop drilling downwards, and instead flush the hole with air to see whether the yield from a fracture develops further. Such time and activity are all part of the design, construction and development of a proper water supply borehole in limestones.

Outside the day rate, the only other costs are materials. The arrangement for materials is that they will be paid for if they are used, at cost, plus 5% for ordering and delivery. In other words, the driller does not make a profit by installing materials in the hole. Yet, the driller is fairly paid for the work involved in installing or using these materials. The driller is expected to have agreed materials either on site or quickly available. So, for example, bagged cement is available at a nearby builder's providers, whereas heavy mild steel plain casing of various diameters is available on the trailer on site. It is expected that the driller will have PVC plain casing of standard sizes and wall thickness in stock in their yard, and this can be brought to site before it is required. However, when a hydrogeologist specifies an unusual PVC casing diameter or wall thickness, for example to provide sufficient collapse resistance for a possible grouting operation, it may be necessary for the hydrogeologist to explain to the client that they should pay for the full shipment of casing whether it is used or not. The hydrogeologist should try to work with the materials that are readily available or in common use.

Limestones in Ireland are heterogeneous and results are unpredictable, therefore it is essential that the hydrogeologist or groundwater engineer, the client and the drilling contractor all have realistic expectations and there is sufficient flexibility in relationships and contracts.

Tip: My final question to a driller before signing a contract or agreement is,

“Are you confident that there is enough profit for you in this way of working, and at this day rate?”

They are sometimes surprised by the question. My question is driven by my awareness that the driller may have underestimated their own costs. It is also driven by a selfish motive; which is, when there are problems and it is dark, cold and the rain is seeping into our clothing, I do not want a driller feeling that he’s not making any money, and losing the will to continue through the hardship.

When working in tricky limestones the driller has to know that there is something in it for him, and the hydrogeologist needs to feel confident that he can ask the driller to do whatever is reasonable to complete the job successfully.

So, a practical essential tip for drilling boreholes in limestones is ‘get the foundations of the work right before you start’.

Tip 3. Sensible Scope and Phasing of the Work

The client usually will start with the assumption that the hydrogeologist or groundwater engineer simply will design and cost a final production borehole, award the contract on behalf of the client, then supervise the drilling, well development and testing of the production borehole, and then write a report.

This is not correct.

It defies common sense, to embark on carefully constructing an expensive final production borehole without having previously proven that a hole drilled below this precise site will provide the water required.

The scope and phasing instead should always be:-

1. Site walk over, gather and assess existing information with particular emphasis on structural geology.
2. Choose one or more sites (sometimes this is not possible because the client has a restricted site).

   Don’t bother with a geophysical survey unless you have a very large rural site and there are several structural geology/ karst geomorphology targets that you want to check out.

3. Construct and supervise one (or more) narrow diameter exploration boreholes.
4. Determine the yield either with the rig during drilling, or with a separate airlift pumping assembly, or with a test pump.
5. If the yield appears to be adequate; design a production borehole based on the findings in phases 3. and 4., and work out, with the driller, the scope and phases of work and the materials necessary to convert the exploration borehole into the production borehole.
6. Convert the exploration borehole into the production borehole.
7. Test the borehole to establish its hydraulic efficiency, and test it for long enough to determine the sustainable yield from the groundwater flow system running through the limestone that feeds water to the borehole. (Tip: It is very likely that the borehole will be highly efficient at letting water flow into it, but the groundwater flow system some distance from the borehole may restrict flow to the borehole. There is nothing that you can do about this, but it is important to find this out before you recommend a pump and a pumping regime.)

For the purpose of this paper, I will restrict myself to describing practical tips relating to Phases 3, 4, 5, and 6 above.

3. PHASE 3 EXPLORATION DRILLING

This consists of relatively inexpensive and quick, narrow diameter drilling, but always with final production borehole construction in mind.

The objective is to drill down through the overburden and explore the limestone below, for evidence of groundwater movement in open joints, fractures, faults and / or karst solution conduits.

Always remember that this exploration borehole is not a borehole that has to succeed. The objective is exploration.

Start off with the frame of mind that you have no idea what you will find, and that you and the driller will work together to make the best of any potential that you encounter.

Do not be afraid to stop drilling short of your initial conceptual design target depth if your observations indicate that there is no point in continuing. There is no point in going on and wasting your client's money, if you have no reason to think that you will encounter a break in the rock that will give you the water you require. Tips on how to judge this are given below.

The exploration drilling may seem relatively quick and easy but, because it is very important, it demands full-time concentration, attention to detail and care.

It is essential that you are on site next to the rig and the driller, for every moment of the working day, and that the driller and his crew understand that they must never carry out any work if you are not on the site.

Exploration Borehole Tips

Ask the driller to bring 6inch and 8inch steel casing to the site.

Ask the driller to bring 10inch, 8inch and 6inch drill bits and appropriate hammers to the site.

The first step in an exploration borehole is to get through the overburden and into the top of the limestone rock.

In the Midlands, South and East, there is usually a greater thickness of overburden above limestones than in the west. The overburden consists of boulder clay, and or sand gravel clay peat or marl. This overburden is often unstable and requires support by casing.

The ideal economical start is to drill 8inch through the overburden and into the top of solid rock, and line this upper section with 6inch internal diameter steel casing. Drilling into clean, light grey limestones such as the Waulsortian, Dartry or Edenderry Oolite, the top of the rock may have a thin epikarst followed by solid rock. By contrast, the top of shaley limestones, such as the Ballysteen or the Dublin Calp, may be difficult to recognise because the limestone and shale have been softened and partially rotted by weathering.

It is often difficult to distinguish between the base of black boulder clay and the top of the rotten shaley limestone. Sometimes, in the Dublin Basin and the Ballysteen elsewhere, the black boulder clay and the rotten black shaley limestone can extend to depths of 30-40 metres.

Tip: Do not give up if you encounter soft rotten black shaley limestone.

The process of rotting of the limestone and shale means that water must have passed through the rock in order to weather it to such a state of decomposition. If water has passed through the rock to rot it, then the water was probably flowing to somewhere else. It is possible that there is a fracture/joint/conduit system of open joints or fractures that form a collector zone in the hard rock below the rotten upper layer.

The overburden and the upper rotten rock zone require support. Therefore insert 6inch steel casing into the 8inch hole but

Tip: Do not let the driller hammer the 6 inch steel casing into the 8inch hole, because you may need to take this steel casing back out later in order to convert the exploration borehole into a proper production borehole.

Tip: Wrap and stuff a textile or plastic seal into the gap between the 6inch steel casing and the 8inch open hole wall at ground level, in order to stop drill cuttings from washing down between the casing and the hole wall. Cuttings in this annulus can make it more difficult to remove the 6inch casing later, if required.

Once the upper part of the exploration borehole has been supported to the necessary depth, change hammer bits and drill on down through the rock.

This is the critical phase.

What you and the driller are looking out for are signs that water has moved through breaks in the rock.

Listen, sample and look out for the following:-

1. **Tip:** Look for signs of iron staining on edges or faces of the larger drill cuttings. This iron staining, particularly in the dark shaley limestones but also the clean limestones, indicates that water has flowed along joints in the rock at some time in the past. Therefore, there is or has been a groundwater flow system in the breaks in the rock

2. **Tip:** Listen for a change in the beat of the hammer.

A change in the sound of the hammer beat means a change in the rock.

Below are **Tips** on how to interpret the sounds and vibrations from the down the hole hammer whilst it is drilling:-

a. An aggressive, rapid, monotonous hammer beat with a slight 'ringing' sound from the drill rods means that the rock is hard unbroken and unchanging.
b. A sudden stuttering or erratic change in tempo of the hammer beat combined with a softer sound may indicate either a change from a hard to a soft limestone, or shale layer, or rock just above the top of a large cavity in the rock. In the former case, a black shale can be distinguished from a soft black limestone layer by the sudden appearance of a very thin layer of black carbon floating on the surface of the water flowing away from the wellhead. Do not worry if you see this. It is not an oil leak from the rig. If you suspect that the drill bit is about to break in through the top of a significant cavity, immediately signal to the driller to stop drilling and lift the hammer by about 10cms. Then, tell the driller what you think may be about to happen, and agree with him to drill on slowly with very little weight on the bit. It is often a false dawn, and there is no big cavity, but by proceeding slowly in a controlled manner, you will be able to observe and assess any slight colour change or increase in the volume of water, and then decide whether to 'work over' the zone to try to increase the yield.
c. A sudden missed beat, or missed series of beats, means that the hammer bit has gone into a space in the rock. This space could be empty (i.e. containing just water) or it could contain something very soft that provides no resistance to the hammer bit pressing down on it. When the hammer misses several beats, it is important to observe intently the water coming out of the hole, even if it is water that had been injected by the driller to cool the bit, suppress dust and bring up cuttings.
d. Look out for a change in water colour from the previous greys to a light or dark brown, bright orange yellow or even a pink or purple.
    i. A medium brown is usually a sign of iron oxide deposits on the side walls of a fracture or series of open joints.
    ii. A bright orange yellow is a cause for optimism and momentary celebration, because these colours usually are representative of soft residual clays from the weathering of clean limestones deposited in a cavity. These clays may indicate that the borehole has encountered a well developed, karst 'plumbing system' that has taken large flows at some stage in the geological history of the rock at this depth. The plumbing system may contain clay now, but it may be possible to clean out the clays and reactivate significant groundwater flow.
    iii. Pinks, purples, russets and chocolate browns are unusual. They seem to come from hard, thin clays clogging small cavities in clean limestones that have been subjected to slow deep weathering. These exotic colours are commonly found in rocks that have been subjected to weathering under humid or arid tropical conditions where a laterite has developed above the rock. Some clays found, down to 120 metres, in a borehole under the Bog of Allen were identified as early Tertiary in age.
e. Do not drill on when you encounter a sudden colour change. Instead work over the zone. Stop drilling, raise the bit about 10cm and just let air out of the hammer. Observe whether the colour change persists. Observe whether the flow of water increases.
f. If the colour persists and the flow of water definitely increases, then keep on circulating air out of the hammer bit until the water flow contains less colour or clay sediment. Measure the flow of water by constructing a dam around the back of the rig and placing an appropriately sized pipe in the dam. Excavate a sump below the outlet of the pipe so that a bucket can be put under the flow from the pipe. A simple bucket, of a known volume, and a stop watch are all that is required to estimate the flow from the borehole.

g. If the flow remains significant but does not increase and also the colour remains intense, then turn off the airflow to the hammer for, say 5-10 minutes and let the water level in the borehole rise. Then, lower the hammer to the level of the gap in the rock, and only then turn on the air fully. The sudden blast of air will drive a shock of water inside the gap in the rock as well as blowing all the water up out of the borehole. The blast will probably disturb or breakdown clay in the gap in the rock and make it easier for water to flow along gaps/fractures/conduits in the rock and into the borehole. To avoid the hammer bit becoming trapped, pull the drill tools back about 50cm whilst continuing to circulate air. The flow of water from the borehole will increase and the water will have a heavy clay load. Do not be dismayed by the increase in clay in the water. It is a positive sign. It means that the shock of the surge of air is working. The clay is being disturbed and the subsequent turbulent increase in flow of water along the break in the rock is eroding the loosened clay. Keep circulating air and observing the flow rate.
h. When the flow rate remains stable and the colour in the water decreases, then repeat the procedure in step (g.) above. Keep on doing this until there is no further increase in the flow rate and the water is relatively clear of clay and other sediment.
i. It is important not to continue drilling deeper until the productive gap in the rock has been cleaned, and the maximum yield has been obtained. It is important to deal with each gap or conduit in the rock in turn, so that you can focus the impact of the air surge on the conduit that you have just encountered. When you have encountered several productive gaps in the rock the impact of the air surge is dissipated.
j. If you have encountered a large karst conduit (say, 20cm plus in height) it may be necessary to spend an hour or even half a day cleaning out the clay and developing the yield by airlift pumping and surging. You may come under pressure from the driller or the client to press on deeper into the rock. Resist this pressure, by reminding them that the objective is to explore and determine the water yielding characteristics of the subsurface, with a view to designing and constructing a proper production borehole. The objective is not to just drill a deep dry borehole.
k. If the gap in the rock does not provide water or the yield of the borehole does not increase after, say, two or three attempts at air surging, then be encouraged by the fact that water has passed through the rock at this point, and carry on drilling down further into the rock looking for something more productive.
l. Always look out for white, pale grey or pink, pure calcite crystals in the drill cuttings. Pay particular attention if the proportion of calcite crystals suddenly increases, and inspect them intently to see if there is iron staining, or signs of solution weathering on any of the fragments. Irregular hammer beats and a sudden increase in white or pink calcite with iron stained faces in the drill cuttings usually signifies that you are drilling through, down or next to a fault or breccia zone, and it is likely that imminently you will encounter a flow of water.
m. Deciding when to stop drilling is a normal dilemma for a hydrogeologist. Base your decision on existing information from mapping and other boreholes in the area, and the evidence that you have obtained so far in the new exploration borehole in the context of the yield required by the client. There is no ‘Golden Rule’ for when to stop.
    i. The decision is easy if many open fractures or several karst conduits have been encountered below 30 or 40 metres. In which case the 6inch hole provides the evidence necessary for the design and construction of a proper modern production borehole with a pump chamber casing fully surrounded by a cement grout filled annulus.
    ii. The decision is more difficult if, so far, there has been just a single small inflow of water from a transition zone or epikarst between the overburden and the top of solid limestone, and yet there is still evidence or iron staining on the faces of the drill cuttings deeper down. In this case, discount the shallow water, and drill on to 60, 70, 80 and 90metres with an expectation that open fractures or a karst conduit will be encountered. If nothing has been found, experience has shown that, for a cheap **first** exploration borehole, it is still worth drilling on to, say, 100 -130 metres below the top of the rock. If there is no evidence of any changes by 130 metres, stop, explain to your client that you have evidence that groundwater has penetrated to a significant depth in the limestone, therefore there is evidence of potential for an open conduit system somewhere deep in the bedrock, and ask permission to drill a second exploration borehole at a second location on the site. Choose a site for a second exploration borehole some distance from the first. Drill it quickly but with full attention.

You may find that drilling becomes slower at depths beyond 80-90 metres because the upward airflow in the hole from the 6inch hammer does not clear the cuttings efficiently and the penetration rate decreases, and also the rig cannot carry more than 80-90 metres of rods and the driller has to carefully load extra drill rods from a trailer. In terms of efficiency, you may decide to stop the second hole at, say, 90metres (or a depth corresponding to the number of drill rods on the rig) if the findings are the same as the first hole.

iii. If the second exploration borehole does not provide either a significant yield or new evidence, then it is time to pull all the findings together and give the client two options; 1. There is no evidence to support a decision to carry on drilling, or 2. there is a justification for further exploration drilling.

4. TIP: PRELIMINARY ASSESSMENT OF THE YEILD FROM A 6INCH EXPLORATION BOREHOLE

The yield of water from an exploration borehole when air is being blown from the drill bit on the base of the hole usually gives an unrealistic result. More realistic results are obtained if several drill rods are removed and the hammer and drill bit are brought back to about 30-40 metres below either ground level or the top of the zone of saturation ('water table'). The water level in the hole will recover while the drill rods are being removed, but leave an extra 30 minutes for a fuller recovery before starting the airlift pumping. With the hammer and bit in this position, the airlift simulates a pump inside a pump chamber casing set at 30-40metres.

Do not be surprised if you find that the sustained flow rate with the hammer in this position is only 30% of the short term flow rate with the hammer at the bottom of the hole.

Continue airlift pumping using the drilling rig for at least two hours in order to get a rough idea of the yield, but discount the yield obtained from fractures or conduits encountered in the drilling down to 30-40 metres. (If you want to consider a production borehole design that allows in shallow water, then you need to assess the protection afforded by the nature and thickness of the overburden).

If the first exploration borehole appears to be very successful, it may be worthwhile to get more reliable information on the sustainable yield and the drawdown before designing the production borehole. In which case, release the driller and rig, and install either an airlift assembly to airlift pump the borehole, or an electric submersible pump and carry out proper step and constant rate pumping tests.

Tip: an airlift assembly of an eductor pipe with a 90° long radius elbow at the top, and a separate airline that can be moved up or down the centre of the eductor pipe is the best for pumping a new exploration borehole. The assembly can be used for airlift surging at different depths to clean out cavities or conduits, as well as for airlift pumping. The advantage of an airlift assembly for pumping is that, unlike a submersible pump, there are no moving parts that can be abraded or blocked by any sand or gravel washed out of the conduits. Though most of the sediment washed out of water bearing conduits is clay or silt, there can be sand and gravel. I once made the mistake of using a submersible pump to 'raw-hide' a borehole to clean out the conduits, and after a while the pump impellers were damaged.

5. CONVERSION OF A SUCCESSFUL EXPLORATION BOREHOLE INTO A PROPER PRODUCTION BOREHOLE

Tip: It is wise to dismantle a successful exploration borehole and convert it into a production borehole, rather than drill a new production borehole close to the exploration borehole.

There are two main reasons for not drilling a production borehole adjacent to a successful exploration borehole in limestones.

First, the production borehole may not encounter the same open fractures or conduits in the limestone as the successful exploration borehole.

Second, if the production borehole does encounter the same open fractures or conduits as the first hole, then cuttings, air and water will flow, often preferentially, from the new production hole, through the conduit in the limestone, into the exploration hole. Upward flow of air (air circulation) will be lost in the production hole, and hence drill cuttings that were on their way up the production hole will fall back with the loss of upward airflow, and can trap the hammer in the production hole. This can be a serious problem.

Though it is possible to avoid this problem by backfilling the adjacent exploration borehole with gravel prior to drilling the new production borehole, it is generally better and more certain to convert the original successful exploration borehole into a production borehole, in both clean and black shaley limestones.

The first step in the conversion is to assess all the information and draw up a design for the production borehole within the capability of the rig and the availability of materials. It is essential to draw up this design with the driller. The key considerations are:-

1. How to remove the 6inch steel casing?

2. The internal and external diameter of the pump chamber casing.

3. The expected drawdown during future production pumping and the length of the pump chamber casing.

If the 6inch casing is loose and not too deep, then usually, it can be pulled by the winch on the rig. If it is heavy or stuck, then either hydraulic casing clamps on the rig, or separate hydraulic casing clamps, must be used to jack the 6inch casing from the ground. The strain of the pull can be a test of the welds between the lengths of steel casing. **Tip:** It is a good idea to double weld 6inch casing joints if it is anticipated that the casing will be difficult to pull.

The PVC pump chamber casing should be flush coupled, screw threaded, water well grade blue PVC. There should be no wellscreen in a limestone production borehole, unless the limestone is a loose sugar-grain sized brown weathered dolomite that requires support.

The minimum internal diameter of the pump chamber casing is determined by the size of the proposed production pump. Leave sufficient annular space around the pump motor to permit water flow up the hole past the motor to the pump intake. For example, a nominal 6inch pump will fit easily into 180.8mm ID PVC casing with a 9.6mm wall thickness and a collapse resistance strength of 8.8 bar. The casing in this example has an outside diameter of 200mm (nominal 8inch OD).

The length of the pump chamber casing is worked out from the results of the yield test on the exploration borehole and expected drawdown at the required yield. For example, an end of dry summer depth to water level of 5 metres, and an expected drawdown of 20 metres, giving a yield of say 25m^3/h, would mean that the minimum length of the pump chamber casing should be at least 25 metres below ground level. However, the long term sustainable yield from production boreholes tapping into small karst conduits or fault zones usually decreases with long term pumping, because there may be restrictions in the size of the conduits some distance away from the borehole that restrict the groundwater flow through them to the borehole. Therefore, with this in mind, in the example above, it would be wise to install a longer pump chamber casing down to, say, 35-40 metres.

The external diameter of the chosen pump chamber casing is important, as is the drilled diameter of the existing exploration borehole.

The existing 8inch diameter hole in the overburden and the 6inch exploration hole in the bedrock must be reamed out (widened) in order to accommodate the pump chamber casing, with an annulus around the casing of roughly 2inches for the injected cement grout.

It is important to ream out an existing hole with a bit that is at least 4inches wider than the diameter of the existing hole. This is to provide a sufficient ‘lip’ of hard rock all round below the bit, in order to reduce the chance of the larger bit drilling on just one side, and moving off the alignment of the exploration borehole.

Therefore, taking as an example the production borehole pump chamber casing diameter and depth above, the exploration borehole should be reamed out using a 12inch drill bit down to, say, 35 metres. A length, or two, of 12inch ID steel ‘conductor’ casing probably need to be installed (driven in) in order to stabilise the upper over burden.

Tip: to make it easier to stabilise the overburden section of the exploration borehole once the 6 inch casing has been removed, and to ream out the hole at a wider diameter to 35metres, and to ensure that the cement grouting is successful, I have found that backfilling the exploration borehole with 2-5mm gravel/pebbles is both efficient and effective. Obviously, if the upper hole in the overburden is very unstable, then the last back fill of gravel is emplaced as the 6inch steel casing is being removed.

Tip: Contrary to common thinking; the 6inch diameter open hole formed during the drilling of the exploration borehole does not need to be reamed out at a wider diameter to permit an efficient flow of, say, $25m^3/h$ from the conduits in the limestone up the 6inch hole to the pump intake. The friction head loss at this pumping rate over a 70metre length of 6inch open hole is probably less than 1 metre. Using the 6inch open hole section as the producing section for the production borehole saves the time and cost of reaming the 6inch hole, at a minimum of 10inch diameter and then backfilling with gravel for a second time, to 35metres below ground level, before seating the 200mm pump chamber casing and grouting the annulus.

Cement grouting is a fundamental part of the construction of a limestone borehole. I have written before about borehole grouting in limestone in Ireland. I refer the reader to the following:- "How to construct a water supply borehole in Ireland" in the 2014 IAH – Irish Group Conference Proceedings, the Institute of Geologists in Ireland (IGI) "Water Well Guidelines" March 2007 and the EPA, Office of Environmental Enforcement, Drinking Water Advice Note 14 (2013) "Borehole Construction and Wellhead Protection". These documents describe the process.

Tip: In addition it is worth noting that there may be significant losses of cement grout into upper karst conduits and the epikarst outside the pump chamber casing. If this happens and the water above the injected grout is not rising up the annulus, an acceptable practical tip is to stop grouting, pull out and wash through the tremie pipes, let the grout in the annulus and conduit 'go off', pour by hand about 20 litres, or more depending on the size of the conduit, of gravel down the annulus, and then re-start injecting grout with the bottom end of the tremie pipe about one to two metres above the top of the gravel. The gravel has a sufficiently small grain size to sink down through the water in the annulus to form a heap in the entrance to the conduit. If the conduit is not too large, the gravel will eventually block the entrance to the cavity and further gravel will pile up inside the annulus around the casing above the conduit. The gravel in the narrow space confined between the rock and the casing will form a blockage to enable cement grouting to take place above it. Sometimes, the gravel slumps, the cement grout is lost again into the cavity, and the process has to be repeated with perhaps more gravel to bring the gravel level higher up inside the annulus above the cavity. There are numerous other additives and modifications to the density and viscosity of cement grout that can be used to overcome grout loss into cavities in limestones.

6. CONCLUSION

Water supply borehole exploration and development in limestones in Ireland requires the combination of an experienced good driller with powerful equipment and full time supervision by a hydrogeologist/groundwater engineer with a good conceptual model of the strong heterogeneity of groundwater flow systems in limestones, and an engaged client with realistic expectations. It is normal to be anxious about the uncertainty of drilling in limestones, but all the hydrogeologist and the driller can do, is use all their skill to make the best, for the client, of the opportunities in the subsurface, as they present themselves during the work. A lot is learned in every hole in limestone; each hole is always different. The voyage of discovery and learning can be rewarding – and fun.

HIDDEN LIMESTONE LANDSCAPES – GEOPHYSICAL SURVEYS ACROSS THE IRISH CARBONIFEROUS

Peter O'Connor, Tony Lombard, Yvonne O'Connell,

APEX Geophysics Ltd, 6 Knockmullen Business Park, Gorey, Co. Wexford.

ABSTRACT

Carboniferous limestone is the dominant rock type in approximately 50% of the Republic's land area and apart from the upland areas of Clare and Sligo/Leitrim/Roscommon, most of the limestones are in the low lying midlands and Munster valleys where they are covered by varying thicknesses of soil and subsoil, mostly of glacial origin. It is true therefore to say that most of the limestone landscape in Ireland is 'hidden' and only becomes 'visible' by excavation, by drilling through the soils into the underlying rock or indirectly through the use of geophysical methods.

The amount of excavation and drilling work is limited to very small areas and point sources whereas coverage by geophysical methods is more extensive. Geophysical surveying in limestone terranes has been in use since the 1960's for mineral exploration, since the 1980's for geotechnical, environmental and hydrogeological investigations and more recently airborne methods have been widely used in the national Tellus mapping program. This paper presents examples of surveys both with clear outcomes in terms of geological interpretation and also some where ambiguity or uncertainty exists. Integration of the geophysical results with geological and direct investigation data is critical to achieving a valid unified ground model.

Key words: *Geophysical, interpretation, ground model, integration, limestone.*

INTRODUCTION

This paper focuses on the authors' combined experience over almost 40 years of geophysical surveys for geotechnical, environmental and hydrogeological investigations and presents examples that illustrate 'hidden' limestone landscapes across a range of geological settings and geophysical techniques.

Commercial geophysical surveys for geotechnical, environmental and hydrogeological investigations benefit from the fact that they are usually part of live developmental projects and are often followed by drilling, physical property testing and excavation. This has allowed most geophysical surveys and accompanying interpretations to be confirmed by direct methods and the geophysical interpretation and techniques refined where necessary.

A discussion or tutorial on the geophysical methods commonly employed does not form part of this paper and the reader is referred elsewhere to the extensive texts on the subject. The main geophysical methods used, their typical depth range and the information they provide are summarised in Table 1 below. The resolution and depth range of geophysical methods are a function of sampling density or station spacing. Close spacings provide high resolution and limited depth penetration, wider spacings (and longer array or profile lengths) achieve greater depths but generally give a lower resolution. The choice of geophysical method(s) and station spacing is dependent on the objectives of the survey and the geological setting.

Table 1: *Main geophysical methods.*

Method	**Typical Range (m bgl)**	**Information Obtained**
Very Low Frequency Resistivity (VLF-R)	0 - 30	Lateral variation in bedrock type and depth, fault zones
Electromagnetic Conductivity (EM31)	0 - 6	Shallow variations in soils and depth to bedrock
Microgravity*	0 - 50	Maps density changes in the subsurface
Ground Probing Radar (GPR)	0 - 10	Soil and peat layers, cavities and bedding (in thin or absent soil cover)
Electrical Resistivity Tomography (ERT - also referred to as 2D Resistivity)	0 - 80	Lateral/depth variation in bedrock type and profile, fault/fissure zones
Seismic refraction	0 - 30	Bedrock profile and rock quality, weathered layers.

** The gravity method has an unlimited depth range but for practical purposes is taken as 0-50m.*

The case histories presented below are taken from surveys in limestone areas completed for development projects by APEX in the last 20 years. While some are public domain others are still subject to client confidentiality and for that reason specific details that could identify the site have been omitted. They include examples of buried channels, irregular bedrock topography, mapping of geological boundaries, karst features and fault zones.

CASE HISTORY 1 – BURIED CHANNEL

Background and geological setting
A survey was carried out over a harvested peat bog in Co. Kildare in an area underlain by Waulsortian and Allenwood limestones. The surface topography was flat with 1-2 m of peat cover remaining (Fig.1a).

Geophysical methods used
The methods consisted of VLF-Resistivity on a 50 x 100m grid with follow-up ERT (2D resistivity) and seismic refraction.

Figure 1a: *Setting and topography*

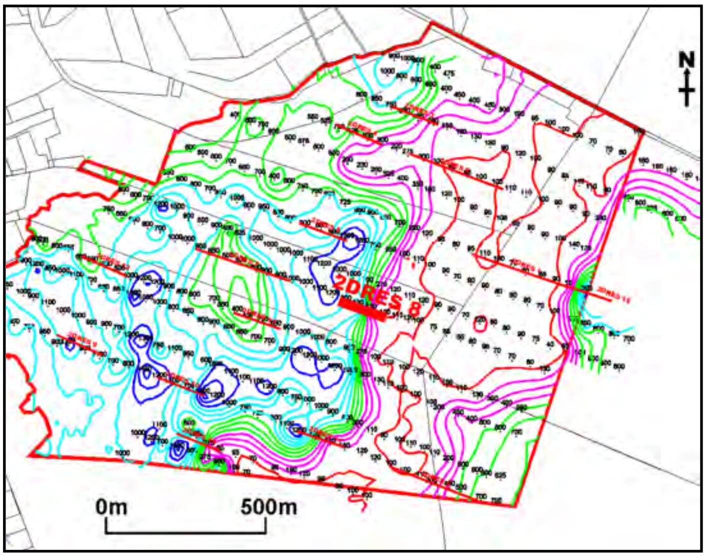


Figure 1b: *Contoured VLF-R data showing data points and resistivity values(black) and ERT locations (red lines). The NNE trending channel is outlined by the low resistivity contours (red, magenta) on the east of the site.*

Geological Interpretation

The resultant resistivity map outlined an extensive (1.4 km x 0.5 km) NNE trending sediment filled channel (Fig.1b). The transition from shallow (c. 6 m bgl) bedrock to depths in excess of 50 m is well illustrated on ERT profile 2DRES 8 (Fig. 3) and was confirmed by seismic profiles over the channel. This channel feature is open at both ends and is probably more extensive than outlined.

Follow-up cable percussive and rotary core drilling confirmed both the shallow bedrock depths and the existence of the channel. A borehole situated over the centre of the channel encountering bedrock at 123 m bgl with possible Tertiary soils at the base of the hole. These channel features are thought to be pre-glacial and associated with erosion of post-Carboniferous strata.

Open File mineral exploration boreholes in the wider area also encountered soil thicknesses in excess of 80 m separated by areas of shallow limestone bedrock. Features of such scale should be identifiable on the Tellus airborne EM data.

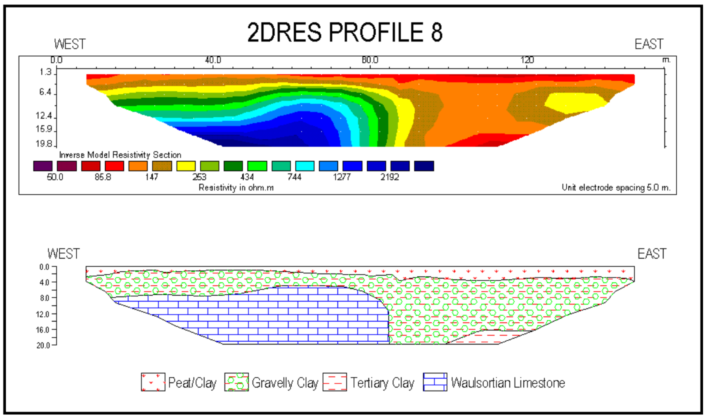


Figure 1c: *ERT profile 2DRES 8 running across edge of channel.*

Benefits and limitations -This example illustrates the benefits of reconnaissance surveying using a fast geophysical method such as VLF-R followed by targeted depth profiling using ERT and seismic refraction. Depth penetration using conventional ERT equipment is limited to around 50 – 80 m and therefore the bottom of the channel was not mapped in this case.

CASE HISTORY 2 – IRREGULAR BEDROCK TOPOGRAPHY

Background and geological setting

This case is an amalgam of examples taken from numerous surveys in the area around the Drogheda ‘graben’ underlain by the Crufty, Mornington, Tullyallen and Platin limestone formations. The surface topography is gently undulating and there is a moderate amount of outcrop across the area. Karst features are also present.

Geophysical methods used

The methods used consisted of VLF-Resistivity and EM Conductivity grids at 50 m or 100 m line spacings with follow up ERT (2D resistivity) and seismic refraction.

Geological Interpretation

The EM and VLF-Resistivity have outlined shallow limestone pinnacles or ridges separated by areas of thicker overburden. These have been investigated by ERT profiles and the presence of rock or soil confirmed by seismic refraction and boreholes. A feature of this area is the often rapid change in bedrock topography from outcrop or near surface to in excess of 30m over distances as short as 40 m (Fig. 2a-2c below). This suggests a buried irregular pre-glacial karstified limestone topography similar to the area around Dunamase, Co Laois.

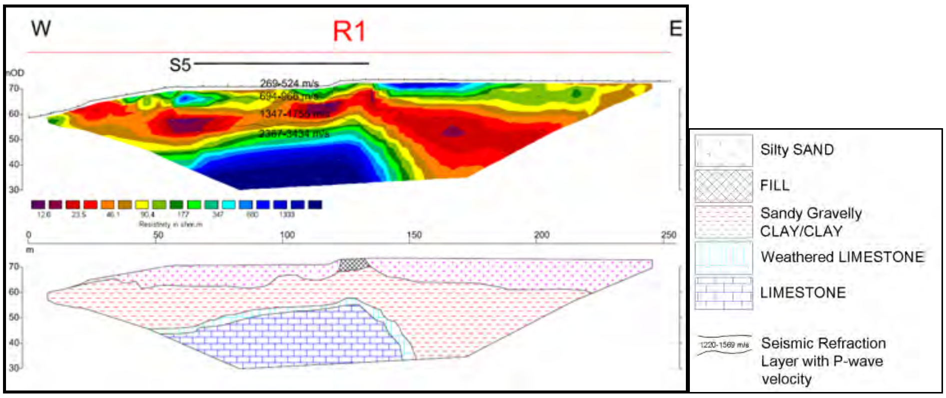


Figure 2a: *ERT and seismic profile showing soil layering over steeply dipping limestone bedrock.*

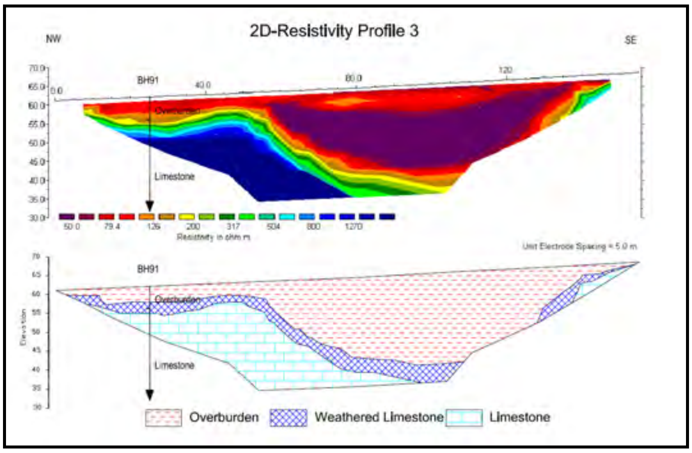


Figure 2b: *ERT profile with summary borehole log over steeply dipping limestone bedrock.*

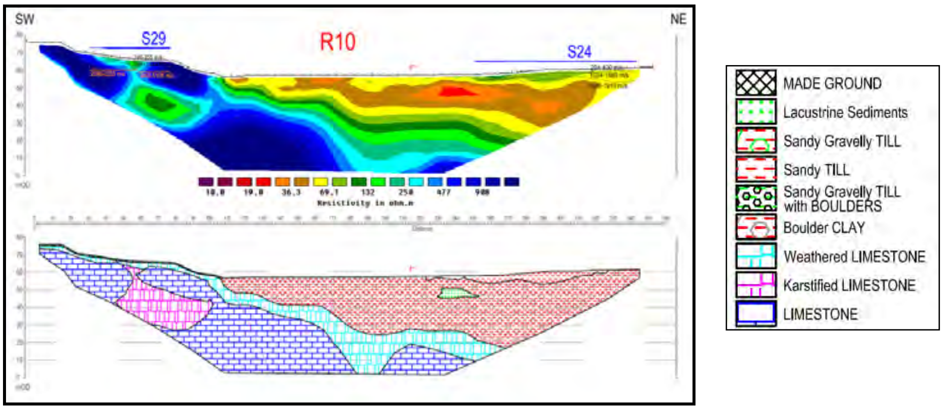


Figure 2c: *ERT and seismic profiles showing change in limestone bedrock depth from surface to greater than 40 m bgl (profile length 360m).*

Benefits and limitations

The examples from this area illustrate the need for a high density of ground investigation data in order to map the rapidly changing limestone topography. This need can be satisfied by geophysical surveying complemented by targeted direct investigation.

CASE HISTORY 3 – MAPPING GEOLOGICAL CONTACTS

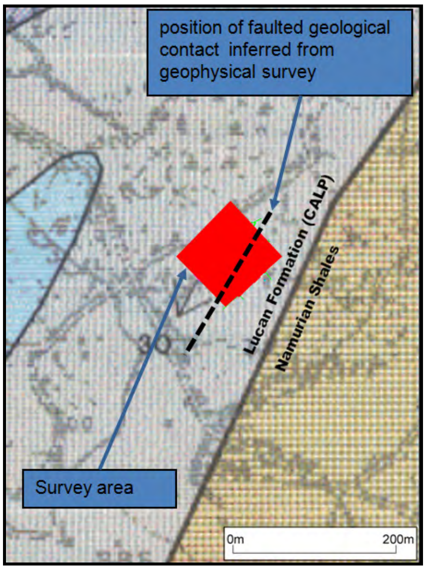
Due to the limited outcrop across most of the lowland limestones, geological maps of necessity involve interpolation and extrapolation of geological boundaries. Examples where geophysical surveying can be used to refine the location of the geological boundaries are shown below.

Background and geological setting

Fig. 3a is from a geophysical survey to map depth to bedrock over assumed Lucan Formation limestone. The geological map shows a faulted contact with Namurian shale to the east of the survey area. Fig. 3b is from a geophysical survey to map the bedrock profile along the route of a proposed bypass. The geological map shows where the route is expected to cross from reef and cherty limestone into shale.

Geophysical methods used

The methods used consisted of EM Conductivity with follow up ERT (2D resistivity) and seismic refraction. In Fig. 3a the survey area is overlain in red on the 1:100,000 geological map and the ERT and seismic profiles were recorded running SE-NW across strike. In Fig. 3b ERT and seismic profiles were recorded along the centreline of the proposed bypass.



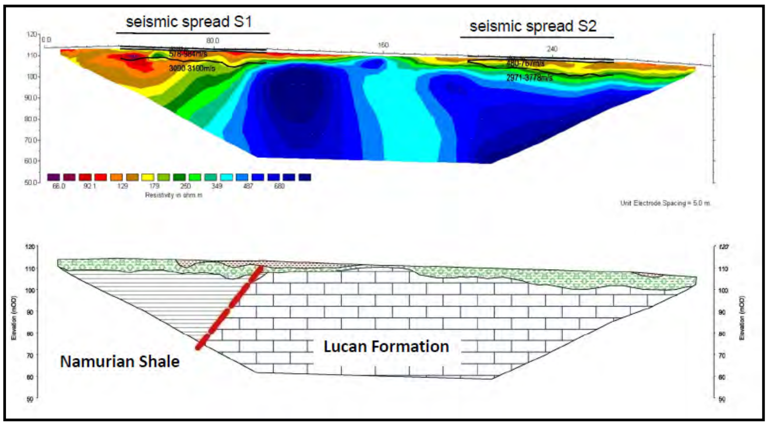


Figure 3a: *Survey area in red showing Lucan/Namurian contact from 1:100,000 geological map and inferred position from ERT and seismic survey (dashed line).*

Geological Interpretation

The ERT profile in Fig. 3a shows medium resistivity shallow limestone bedrock along most of the profile with a transition to lower resistivity shale at the south-western end (the seismic velocity of over 3,000 metres/second confirms that the low resistivity material is shale rather than soil which would have a lower velocity). The geophysical survey shows the new inferred boundary to be approximately 100 m northwest of the position indicated on the geological map. While the difference may be small in regional terms it is significant relative to the site extent.

The ERT profile in the top left panel of Fig. 3b shows high resistivity limestone bedrock along the southern part of the profile with a transition to lower resistivity shale just over the halfway point. The seismic velocity of the limestone (c. 4250 metres/sec) is also higher than the shale (3400 metres/sec) to the north. The geological boundary occurs approximately 75 m north of where shown on the 1:100,000 geology map.

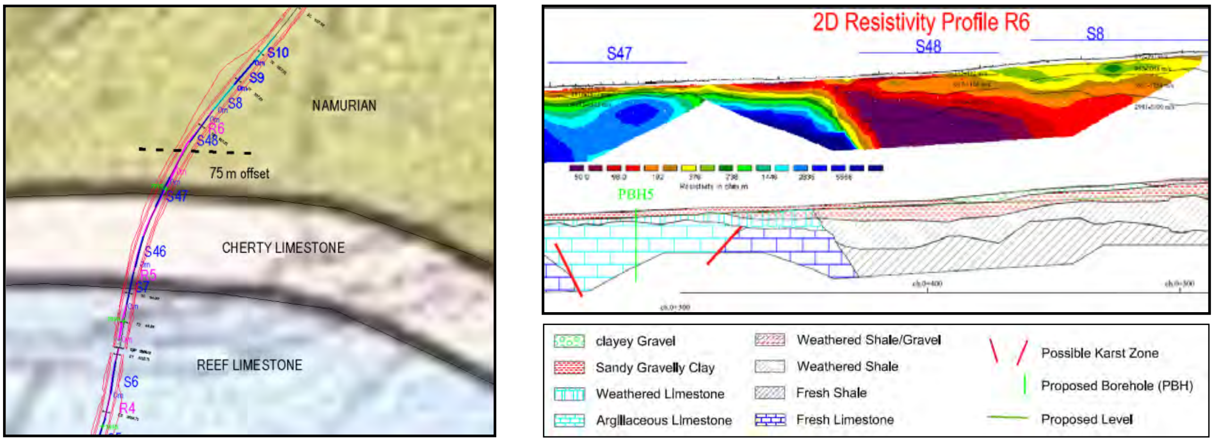


Figure 3b: *Geological map showing proposed route and geological boundaries. The contact with the shales taken from the ERT and seismic profiles is shown by the black dashed line.*

Benefits and limitations

These examples show how geological maps can be refined using geophysical methods and how they could complement interpretation of Tellus data. Vertical and sub-vertical contacts are usually readily apparent. Contacts between horizontal or sub-horizontal layers can be more ambiguous to interpret, e.g. between mudstone and gravelly clay where resistivity values are similar and may overlap (Fig. 3c).

This ambiguity can often be resolved by the recording a coincident seismic profile. Also it should be noted that while typical ranges of resistivity etc. are assigned to different limestone lithologies, these values can overlap due to weathering, fracturing or induration effects.

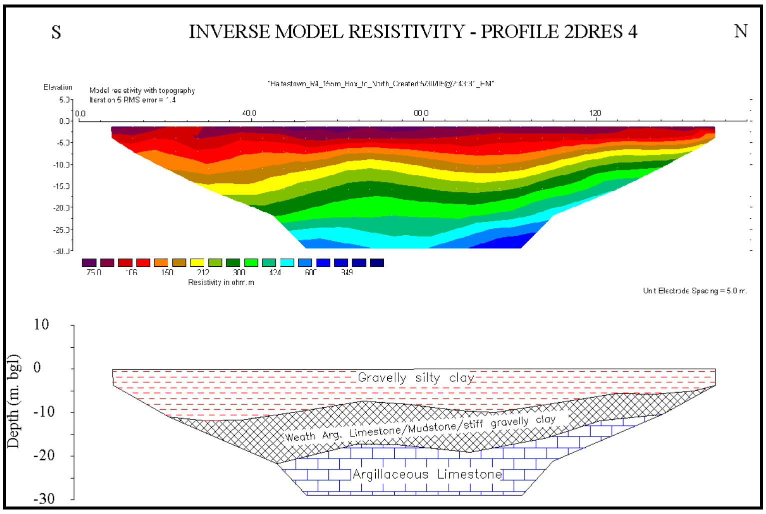


Figure 3c: *ERT profile showing gradational increase in resistivity and possible interpretations.*

CASE HISTORY 4 – BURIED KARST FEATURES

Background and geological setting

A geophysical survey was conducted on a site in Galway (Fig. 4a). The bedrock comprises undifferentiated Visean limestone known to be susceptible to karstification. Fig. 4b is from a geophysical survey in Clare. The Clare bedrock comprises Burren Formation limestone known which is known to be dolomitised in places. Overburden was thin or absent.

Geophysical methods used

On the Galway site a grid of microgravity readings was recorded followed by targeted ERT profiles and rotary core drilling. The contoured microgravity data (Bouguer anomaly) is shown in Fig. 4a. On the Clare site GPR profiles were recorded using a 250 MHZ antenna to screen for possible cavities. A processed GPR profile is shown in Fig. 4b.

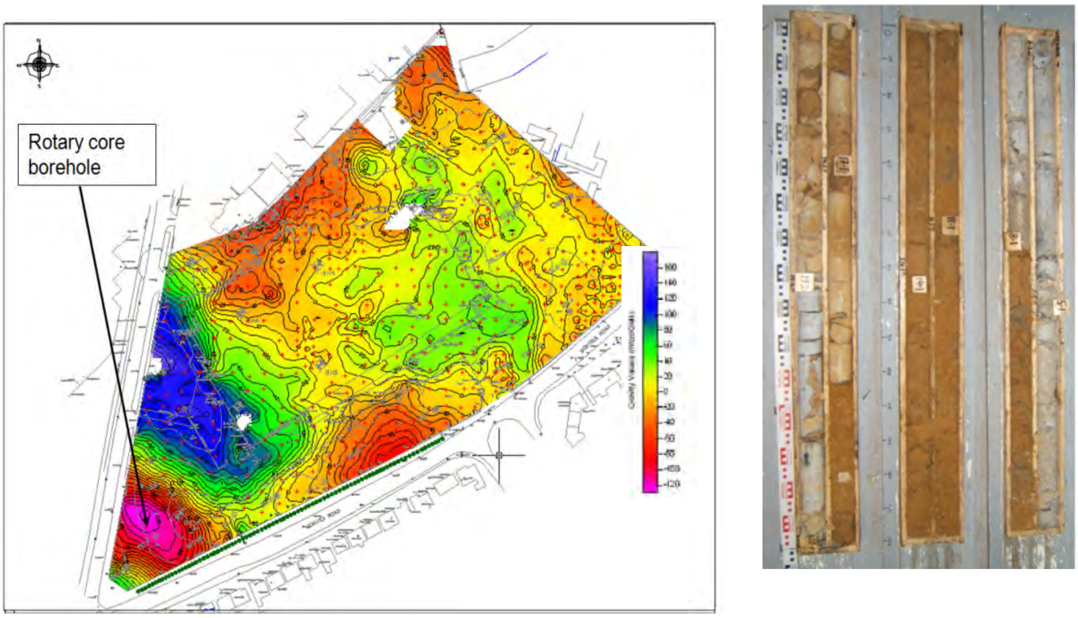


Figure 4a: *Contoured Bouguer Anomaly values in microgals with a photo of core from a borehole in a gravity low (magenta) showing limestone with cavities filled with silty sand (8.1 – 18.8 m bgl).*

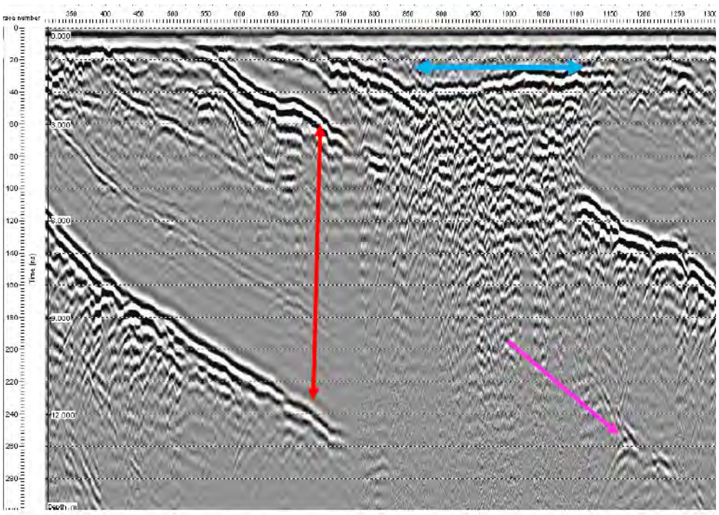


Figure 4b: *GPR record across exposed limestone showing dolomite bed (red), extent of fault/fracture zone (blue) and possible cavities (magenta). Profile length 90 m, depth range 15 m, vertical exaggeration x6.*

Geological Interpretation

In Fig. 4a the rotary core borehole drilled on the main microgravity low encountered a silty sand filled cavity from 8.1 to 18.8 m bgl. Boreholes drilled on other gravity lows encountered similar but less extensive cavities. In Fig. 4b a rotary core borehole encountered a dolomite bed with a thin shale marker bed at the top and bottom (shown by red arrow). A possible void is indicated by the magenta arrow in the bottom right hand corner. The lateral extent of a fault or fracture zone in the right centre of the profile is shown by the horizontal blue arrow.

Benefits and limitations

These examples show how gravity and GPR methods can yield useful information on karstic and other features within limestone. However the presence of even a small thickness (2m) of clay rich soil can severely limit the penetration of the GPR signal. Microgravity is the most direct measurement possible of voids as it depends on density variations but can be skewed by local changes in overburden thickness and density.

CASE HISTORY 5 – FAULTS AND GROUNDWATER

Background and geological setting

Both examples in this section were recorded for groundwater exploration in areas where faults were shown on the geological maps. Fig. 5a below shows a geophysical profile across a major regional fault in the south west where Waulsortian Limestone is faulted against Old Red Sandstone. Fig. 5b shows an ERT profile over the Lucan formation, an argillaceous limestone in the east midlands.

Geophysical methods used

ERT profiles were recorded at both locations with additional seismic profiles at the first site.

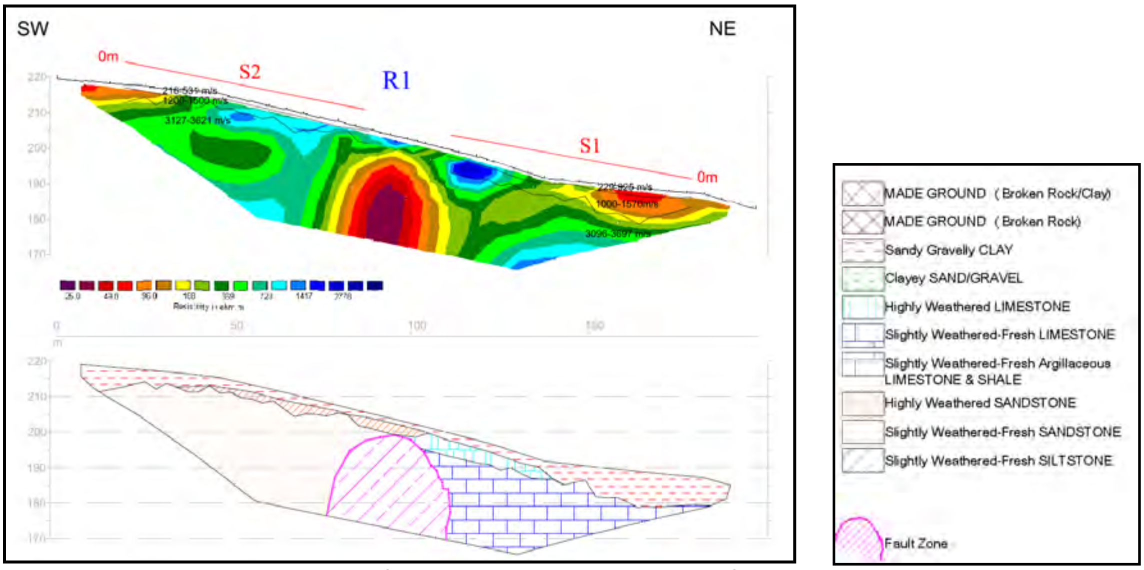


Figure 5a: *ERT and seismic profiles across a major regional fault in the south-west.*

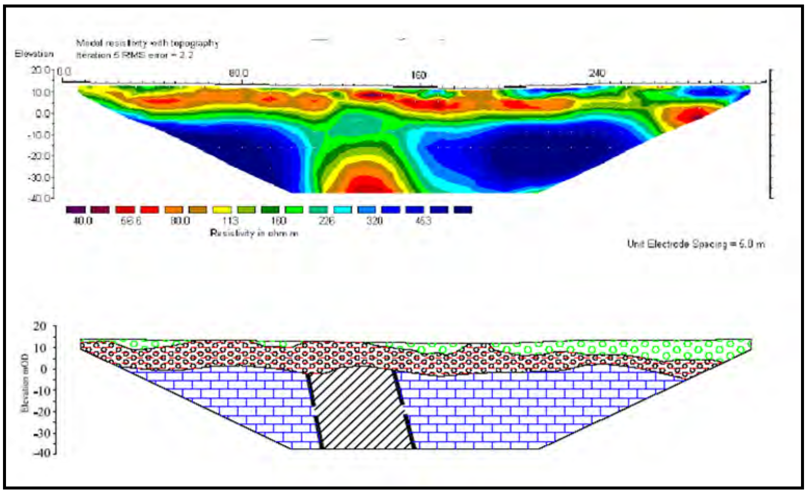


Figure 5b: *ERT profile for groundwater exploration in argillaceous limestone (blue) showing gravel (green hatch) and gravelly clay (red hatch) over bedrock. Mudstone bed in black hatch.*

Geological Interpretation

The fault zone stands out clearly on Fig. 5a as a low resistivity zone approximately 25 m in extent and covered by a thin layer of glacial material. A similar low resistivity zone in the argillaceous limestones on Fig. 5b was interpreted as a possible groundwater bearing fault but when drilled encountered a low permeability mudstone.

Benefits and limitations

These examples show how similar geophysical responses can be obtained in different geological settings and illustrate the need for each data set to be interpreted with reference to its own geological setting and supporting data.

SUMMARY AND CONCLUSIONS

A small selection of the various geological settings and features encountered during routine engineering and environmental geophysical surveys is presented in the above examples and gives some insight into what the Irish pre-glacial limestone landscape would have looked like. Erosional channels, limestone peaks, geological boundaries, karstic weathering and fault zones would all have been more readily apparent before the deposition of glacial material. Properly executed geophysical surveys are the most useful tool available to map these pre-glacial features to any extent.

Geophysical methods, while soundly based, repeatable and of proven value in ground investigation programs, are still indirect and always involve the interpretation of measurements taken at the ground surface to derive a ground model of the underlying soils and rock strata. In some cases, however, the interpretation may contain certain ambiguities, which should always be stated clearly in the accompanying report.

The accuracy of the interpretation is dependent on a number of factors chiefly the presence of a physical property contrast between the soil and rock layers, the acquisition of suitable good quality and properly focused geophysical data, and the involvement of geophysicists with relevant experience. When these factors are properly combined it is usually possible to make a reasonably accurate interpretation of the underlying limestone geology.

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BASEMENT CONSTRUCTION IN DUBLIN AND INTERACTION WITH THE UNDERLYING CALP LIMESTONE

Maurice Ryan

ByrneLooby, H5 Centrepoint Business Park, Oak Road, Dublin 12

ABSTRACT

City centre sites must maximise the available space for development. This has resulted in an increase in typical basement depths over the past 20 years. Double and triple level basements are now routine within residential and commercial developments. The shallow depth to bedrock in the southern part of Dublin city centre and the availability of modern piling equipment and construction plant has resulted in an increase in the number of basements which extend into the bedrock formation. Value engineering and efficiencies in rock drilling has led to bespoke embedded pile retaining wall solutions which combine secant arrangements through the overburden to cut off any shallow perched groundwater, with contiguous arrangements extended into the bedrock. Experience has shown that the groundwater productivity of the Calp Limestone is low, with groundwater ingress through the contiguous pile arrangement being relatively manageable via sump pumping from within the excavation. Future deep excavations associated with potential infrastructure developments require careful consideration and investigation to ensure robust groundwater management solutions are adopted.

Key words: *basements, Calp Limestone, groundwater*

INTRODUCTION

Substantial urban development has taken place in Dublin City Centre since the mid 1990's. Historically, the majority of basements constructed where relatively shallow with typical basements being single or possibly double level, between 3 to 6m deep. The sustained economic growth during the 2000's resulted in an increase in the use of underground space. As the scale of developments increased, the depth of basements increased accordingly, with depths in the range of 8 to 12m becoming typical.

The early basements were often constructed within lightly supported contiguous or secant piled retaining walls. The piled walls were generally constructed with Continuous Flight Auger (CFA) piling methods where rock socketing of piles was not required. On the occasion where bedrock was encountered, Rotary Bored Piling techniques were necessary. The capability of the available plant limited the potential for basement formation within the Calp Limestone, however modern piling plant and the desire to maximise the value of site footprints resulted in the construction of deep basements extending substantial depths into the bedrock formation.

This paper shall present details on how these deep basements are formed and how groundwater is managed.

GEOLOGY OF DUBLIN

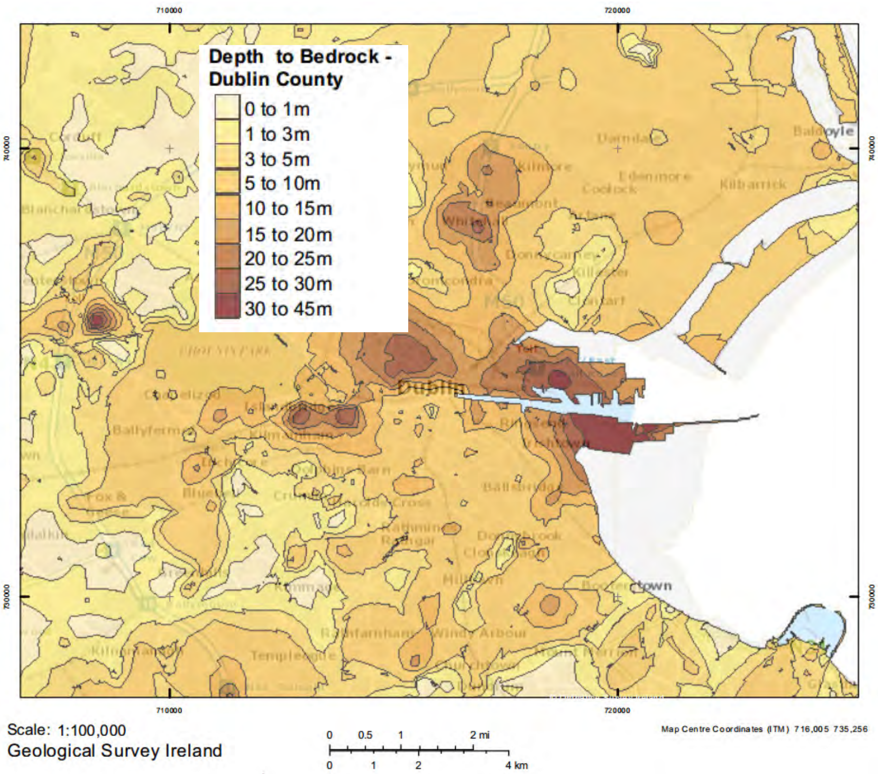
Substantial research has been carried out on the geology underlying Dublin city centre and the surrounding areas. Farrell and Wall (1990) presented a detailed summary of the underlying soils in the Dublin area, with additional studies and assessments provided by Skipper et al. (2005) and Long and Menkiti (2007).

Dublin city centre is underlain by bedrock which consists of an argillaceous Limestone of the Lower Carboniferous age, commonly known as 'Calp' (Skipper, et al., 2005). The Limestone bedrock is part of the Lucan Formation and has been estimated to be up to 800m thick in places (Nolan, 1985). Farrell & Wall (1990) note that the Limestone bedrock was formed in a shallow marine environment in the Lower

Carboniferous period approximately 330 to 360 million years ago. The Limestone typically consists of dark grey shaley Limestones and is often interbedded with Mudstones.

The bedrock in the city centre is covered by superficial deposits derived from the glacial and postglacial periods. A substantial infilled channel within the bedrock formation is present beneath the city centre, identified by Farrington (1929) as the former route of the River Liffey prior to the glacial period.

The Geological Survey of Ireland (GSI) GeoUrban Project (2007-2013) developed geological maps for Dublin. Map 1 presents the Depth to Bedrock map which presents the localised deeper zones and topography of the bedrock formation.



Map 1 *– Depth to Bedrock Map – Dublin (www.gsi.ie)*

The maximum depth to bedrock is approximately 45m below ground level at the mouth of the River Liffey. Sharp changes in level are encountered across the city centre, with one particular steep change noted close to O'Connell Street, where the depth to bedrock drops from 10m to 25m below ground level over a relatively short 500m distance (Long, et al., 2012a).

The main superficial deposit found overlying the bedrock in the Dublin area is the stiff glacial lodgement till, known commonly as Dublin Boulder Clay. This lodgement till was deposited under ice sheets more than 1km thick during the Pleistocene period (Long & Menkiti, 2007). The shearing and grinding mechanism of the ice sheet as it eroded the carboniferous limestone bedrock, in conjunction with the preconsolidation effect, formed a very dense to hard, low-permeability deposit (Lehane & Simpson, 2000). This deposit is widespread across the county.

Overlying the glacial deposits are thin layers of alluvium or estuarine deposits and Made Ground. Long et al. (2012b) notes that the recent estuarine or alluvium deposits are usually less than 2m thick and generally comprise soft organic, occasionally sandy, clayey silt with marine and estuarine shells.

The presence of Made Ground is widespread across the city centre area with this material noted to be highly variable in nature. The Made Ground is generally a clay and gravel matrix and may contain remnants of rubble, brick, plastic, glass, ceramics and ash.

ENGINEERING PROPERTIES OF DUBLIN LIMESTONE

McDonnell (2013) reports that Dublin geology consists of several Carboniferous formations, with the central region of the Dublin area dominated by Limestone of Dublin/Lucan formation. Other Carboniferous formations in Dublin area include the Malahide, Tober Colleen, Clondalkin and Waulsortian Formations. The latter is described as “more fossiliferous limestones” than the Lucan Formation by Friedman et al (2015).

The water depth variations during the formation of the Limestone led to depositional changes of the carbonate sediments which resulted in marked changes in the properties of the rock and its thickness. Farrell and Wall (1990) report that the above processes resulted in the formation of a variety of sedimentary rocks and a variation in sand and clay content of the limestone rocks and the inclusions of shale or mudstone layers which weathered to form clay in places. Farrell and Wall (1990) report that the variations in the rock properties affect the strength and weatherability of the rock and hence the engineering properties.

Skipper et al (2005) describe the rock based on the work of Marchant and Sevastopulo (1980) as dark grey, interbedded and laminated, fine-grained limestone and mudstone/shale in roughly equal proportions, intersected by calcite veins. Merchant and Sevastopulo describe the lithology and stratigraphy of the Calp Limestone shown on Figure 1 based on open faces from three quarries near Lucan/Palmerstown. Merchant and Sevastopulo distinguish three rock types: (1) fine grained, occasionally cherty limestones; (2) a rare dark coarser grained limestone which occurs as thin beds or at the base of the fine-grained bands; (3) a dark calcareous mudstone which ranges from blocky to fissile. Figure 1 also shows the relative thickness of the beds, the types of contacts between the beds and direction of the laminations within the limestones.

The limestone layers are described as a strong and argillaceous, while mudstones and shales are described as weaker by Long and Murphy (2003), whom also report on the typical Unconfined Compressive Strength values as “normally of the order of 100MPa in the limestone layers and 1 to 5MPa in the argillaceous zones”. Long and Murphy also report that the limestone generally dips at 5 to 30º and that the typical layer thickness ranges from 300 to 400 mm.

BASEMENT CONSTRUCTION SOLUTIONS IN DUBLIN

In order to maximise the available underground space, embedded retaining walls are routinely used to facilitate basement excavation and construction. The embedded retaining walls allow the proposed basement to be constructed tight to the site boundary. Where basements interface with the Calp Limestone, the piling plant must be capable of forming the necessary embedment depths within the bedrock formation. Rotary Bored or ODEX/Down-the-hole-Hammer (DTHH) techniques are typically used to form the embedded pile retaining walls. Figure 2 presents typical embedded pile retaining wall arrangements.

Contiguous pile retaining wall solutions are formed by installing piles with a 100 to 200mm space between each adjacent pile. All piles in the sequence are reinforced to form a structural element. Due to the gaps between the piles, such a solution will not form a groundwater cut off and should only typically be used where groundwater is not a concern, and where the ground conditions will not unravel through the gap.

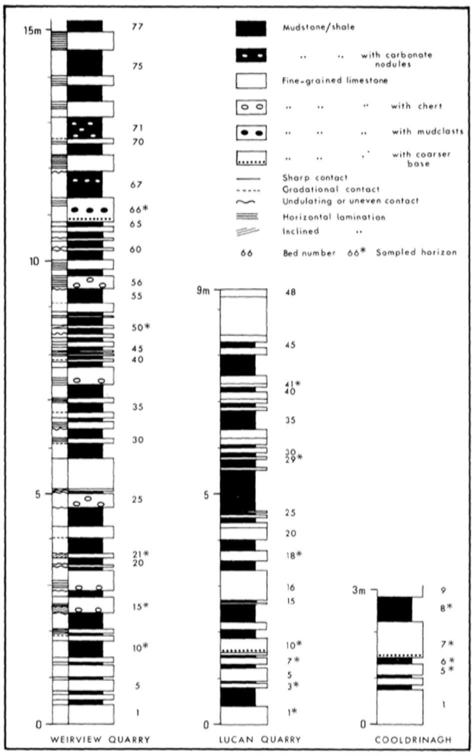


Figure 1 *– Nature of Strata of Calp Limestone, after Merchant and Sevastopulo (1980)*

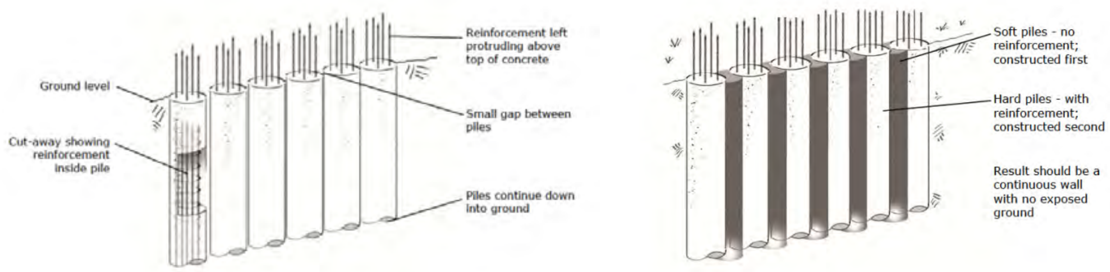


Figure 2 *– Contiguous Pile Retaining Wall (left) and Secant Pile Retaining wall (right)*

The secant pile arrangement involves the installation of primary and secondary piles. The primary piles are unreinforced concrete, varying between soft (~2N/mm^2) and firm (~10N/mm^2) depending on the design requirements of the scheme. The secondary piles are installed to intersect the primary piles, therefore forming an interlocking arrangement. The secondary piles are formed with reinforced concrete and act as the structural element of the retaining wall. The interlocking nature of the solution provides an effective groundwater cut off and will support all soil types given the continuous nature of the retaining wall. Figure 3 presents the relative cost of various embedded retaining wall solutions with reference to wall depth.

Diaphragm retaining walls may also be used when forming basements or deep excavations within the bedrock formation, however the mobilisation costs and space required to facilitate a diaphragm wall installation often preclude such solutions given the constrained nature of city centre sites in Dublin. More traditional retaining wall solutions such as sheet piles are also ruled out when interfacing with the Limestone as the sheet piles cannot extend into the rock formation without predrilling, therefore requiring the mobilisation of a rotary or DTHH rig.

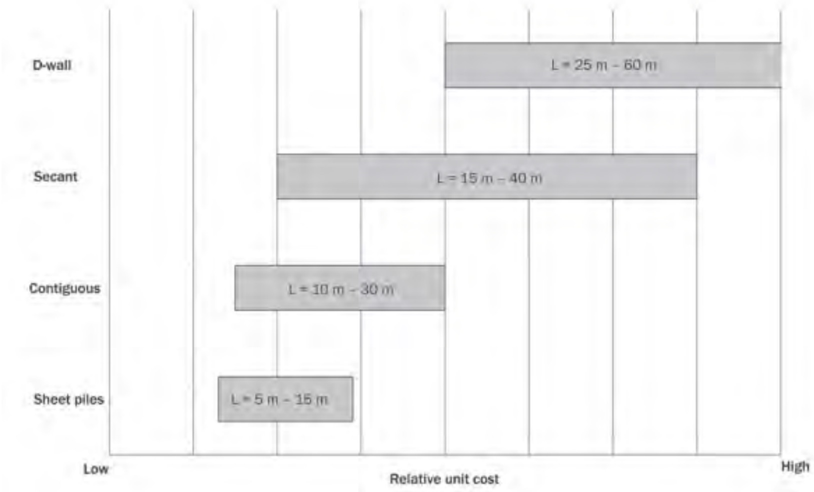


Figure 3 *– Relative cost of different wall types with reference to typical wall depths (CIRIA C760)*

The installation of rock socketed piles is more costly than piles installed through overburden only. As such, piling contractors have value engineered the installation of secant pile walls which interact with the Calp Limestone. Where basements extend into the bedrock formation, the secant arrangement is often installed through the overburden and the primary piles nominally socketed into the bedrock horizon. The secondary piles are then continued into the bedrock in a contiguous arrangement, below the toe levels of the primary piles. The bedding of the Calp Limestone typically ensures that the exposed rock face between the hard piles remains stable. Where needed, bolting or shotcreting can be locally applied to stabilise any unfavourable zones. Figure 4 presents a typical arrangement of such a solution, with the exposed rock face visible between the secondary piles.

Maintaining the secant arrangement through the overburden ensures any perched shallow groundwater is cut off and seepage into the excavation is limited. Control of groundwater through the rock formation needs greater consideration given the contiguous nature of the secondary piles within the bedrock formation.

CONTROL OF GROUNDWATER WITHIN THE CALP LIMESTONE

The majority of basements which interact with the bedrock are located to the south of the River Liffey, given the depth to bedrock is in the range of 5 to 15m bgl (below ground level) as illustrated in Map 1. The depth to bedrock immediately north of the River Liffey is substantially deeper, and therefore generally lower than the expected basement formation levels. To the south, the Calp Limestone is also generally overlain by the low permeability Dublin Boulder Clay.

The Lucan formation is classified by the GSI as a Locally Important aquifer which is moderately productive in local zones only. In general, permeability in the Lucan Formation is low (1m/day). The flow of groundwater in rock aquifers is dependent on the network of fractures and its properties such as density of fracture, direction, length, width and the connectivity between the network of fractures, fracture lengths can vary accordingly from a few metres to hundreds of metres (Comte, et al., 2012). When fractures are present in bedrock it will change the flow pattern of groundwater as the water is trapped inside the fractures and hence it moves along the direction of the fracture and also fractured rock aquifer characteristics such as transmissivity and storage will differ greatly depending on the length and width of the fracture. Higher yields can be obtained in fault disturbed zones. The limestones are generally recorded to be tight and dry, although experience suggests that individual fracture systems can give flows of between 5 and 20 litres/second (l/s).

Figure 4 *– Typical secant arrangement within rock formation (Murphy International Ltd. & PJ Edwards & Co. Ltd.)*

Groundwater flow in the bedrock is confined (artesian to semi-artesian) by the layer of low permeability clay present above it in the Dublin region. The boulder clay hence acts as a protective layer to the bedrock from surface activities and also limits the amount of rainfall that can end up recharging the groundwater in the bedrock (Misstear, et al., 2009).

Experience of basement excavations in the range of 12 to 16m deep, that intersect the bedrock horizon, have shown that groundwater ingress from the bedrock formation can be readily managed, with discharge rates typically in the range of 6 to 12l/s, which also accounts for any surface water discharge. Such volumes are generally managed by a series of sump pumps and groundwater collection trenches.

One of the deepest basements constructed in the manner outlined above is that of the Royal College of Surgeons development on York St. in Dublin City Centre, where a 19m deep basement was formed. A secant arrangement through the overburden was installed (8m deep), with every 4th secondary pile extended to below the basement formation level to cater for vertical loads from the superstructure and to offer some lateral support to the rock formation. Figure 5 below presents an image of the excavation on reaching formation level. Dewatering of the excavation was managed by sump pumping from below the formation level, with discharge rates of up to 20l/s recorded.

The horizontal bedding of the Calp Limestone allowed a vertical rock face to be formed, with minimal temporary lateral supported needed. The appetite for risk associated with this excavation and dewatering process was certainly more appealing to developers during that time than is currently the case.

FUTURE DEEP EXCAVATIONS AND GROUNDWATER CONTROL

Basement development in the city centre area will likely continue in accordance with the demand for development of commercial and residential properties, with double and triple level basements typically expected. Deeper excavations in the order to 20 to 30m bgl are expected to be required to facilitate the station box construction for the upcoming MetroLink infrastructure development.

Figure 5 *– York St. Basement Excavation (McNamara Construction)*

An upcoming commercial development in Dublin 2 which interfaces with a proposed MetroLink station box location facilitated an assessment of the productivity of the Calp Limestone, typical of the city centre. A pump test was carried out on site, within deep boreholes (30 to 38m deep) formed within the bedrock. The ground conditions across the site can be summarised as shallow deposits of made ground over a 7 to 8m thick layer of Dublin Boulder Clay, with the Calp Limestone encountered at an average depth of 9m bgl.

The pumping test comprised a three-stage step test at abstraction rates of 5.1 m^3/hour, 7.5 m^3/hour and 12.0 m^3/hour with a monitored recovery after the pump was shut off. This was followed from a 72-hour pumping test with the abstraction at a decreasing rate from 17.4 m^3/hour at the start of the test reducing to 8.7 m^3/hour at the end.

The transmissivity values fall in the range 46.32 – 101.91 m^3/day; the hydraulic conductivity in the range 2.29 – 4.73 m/day with an average of 3.18 m/day; and the range for storativity falls in the range 3.76×10^{-4} to 1.63×10^{-3}.

An assessment was carried out of the potential dewatering requirements for the proposed excavation if the a secant pile retaining wall was employed to support the excavation, with the primary piles embedded into the Limestone formation, and the secondary piles installed full depth. This arrangement would result in an approximate 20m high exposed rock face between the secondary piles. In addition to the dewatering assessment a review of the anticipated dewatering induced settlements was completed. Plaxis 2D was used to carry out finite element modelling of the excavation and dewatering phases. The model initially incorporated a transient flow analysis which considers the time dependent variable for the groundwater flow analysis. The predictions are considered a first order approximation of the problem as the deformational response of the ground model is not considered. To assess the potential for ground settlement, a fully coupled flow-deformation analysis was then completed. This type of analysis is required when it is necessary to analyse the simultaneous development of deformations and pore pressures in saturated and partially saturated soils as a result of time dependent changes of the groundwater conditions.

For the excavation and dewatering periods considered, there was good agreement between the transient flow and the fully coupled flow-deformation predictions. Both models suggested that for a dewatering period of up to 5 years after the commencement of pumping, the pheatric level in the soil overburden is only nominally reduced below its original level. Additionally, the predicted discharge rates (15 to 30l/s) and the zone of influence of the groundwater draw down (~500m radius) in the bedrock were in relatively good agreement with the hydrogeological assessment of the pump test. The expected pumping rates of 15 to 30l/s (+/- 50%), would be considered manageable discharge volumes from sump pumping within the excavation. Estimated settlements due to the dewatering were <5mm, which was deemed acceptable.

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CHARACTERISATION AND EVOLUTION OF A TCE PLUME IN FRACTURED LIMESTONE

Sean Needham, Marcus Ford, Gary Wealthall, Graham Webb, Andrew Morgan, Sonya O'Loughlin, Helen Haworth

Geosyntec Consultants, Innovation House, DCU Alpha, Old Finglas Road, Dublin D11 KXN4

ABSTRACT

This paper presents findings from field investigations undertaken to characterise trichloroethene (TCE) impacts to a Carboniferous Limestone aquifer, within the Dublin Basin. Investigations included coring, down-hole geophysical surveying, packer testing, pumping tests and tracer testing. The findings indicated an intensely fractured bedrock with three distinct fracture sets, the dominant set being bedding plane fractures with an approximate SSW - NNE strike, apparent ESE dip direction (105-125° direction), which is steep, typically between 50-70°. The dominant fracture set follows the major regional Carboniferous lineaments in the basin.

The limestone is unconfined, with groundwater being encountered at depths of between 5 and 7 metres below ground level (mbgl). Groundwater heads and inferred groundwater contours decline towards the east suggesting a predominantly easterly groundwater flow direction. However, this is not matched by TCE groundwater concentration data, which indicates a north-easterly plume migration direction following the strike of the dominant fracture set and cross-gradient to the inferred groundwater migration direction. Transient water level responses derived during three short-duration pumping tests indicated asymmetrical cones of depression that were also orientated in the direction of strike of the dominant fracture set and plume direction.

TCE depth profiling revealed groundwater concentrations that were indicative of the potential presence of dense non-aqueous phase liquids. Despite the presence of dense down-dip fractures sets, the source area appears to be restricted to the top 50m of the limestone.

Key words: *fractured limestone, structurally controlled groundwater flow, asymmetric drawdown.*

INTRODUCTION

Chlorinated hydrocarbon (CHC) impact (primarily TCE) to groundwater has been identified which is linked to former onsite degreasing activities that are understood to have occurred in the 1970s through to the late 1980s. Typical of similar TCE sites, no information is available on the quantities and volumes of solvents used at the site.

Investigations at the site commenced in the late 1990s and identified the presence of elevated TCE concentrations in groundwater at between 20 and 100 mg/l in near source zone monitoring wells. TCE concentrations have been relatively consistent although a gradual declining trend may be apparent, especially for data collected after 2010. However, the rate of depletion is slow. The inferred plume has been proven to a distance of approximately 150m down gradient from the source area and a program of investigation was designed to further delineate the plume and to design a groundwater remedy.

GEOLOGY

The bedrock geology comprises Upper Dinantian Carboniferous Limestone known as the Calp Formation (Lucan Formation: GSI Website 2019)[1], within the Dublin Basin. This formation is a dark grey, fine-grained argillaceous limestone typically containing interbedded shales in the more central basinal areas, while presenting more intermediate grade limestones along the basin margins. At the site, interbedded

[1] GSI website (https://www.gsi.ie/) accessed during Summer 2019.

shales are absent, and the limestone exhibits limited dolomitization or karstification, although some isolated proto-karst features have been encountered. The limestone was intensely fractured (refer to Figure 1) and beneath the site no change in lithology has been recorded to depths of 105 m bgl.

Optical down-hole geophysical logging undertaken on five boreholes to a maximum depth of 73 m bgl enabled the orientation and dip of natural joints and fractures at the borehole wall to be calculated. Example data are presented as Figure 1 and in Table 1. Three typically steeply dipping (40-60°) fracture sets have been identified, comprising two dominant sets and a minor (tertiary) set that is not present in all logged boreholes. These are presented conceptually as Figure 2. Overall, the fracture network appears triangular in nature, with steep intersects, which results in limestone matrix blocks with a prismatic/triangular geometry.

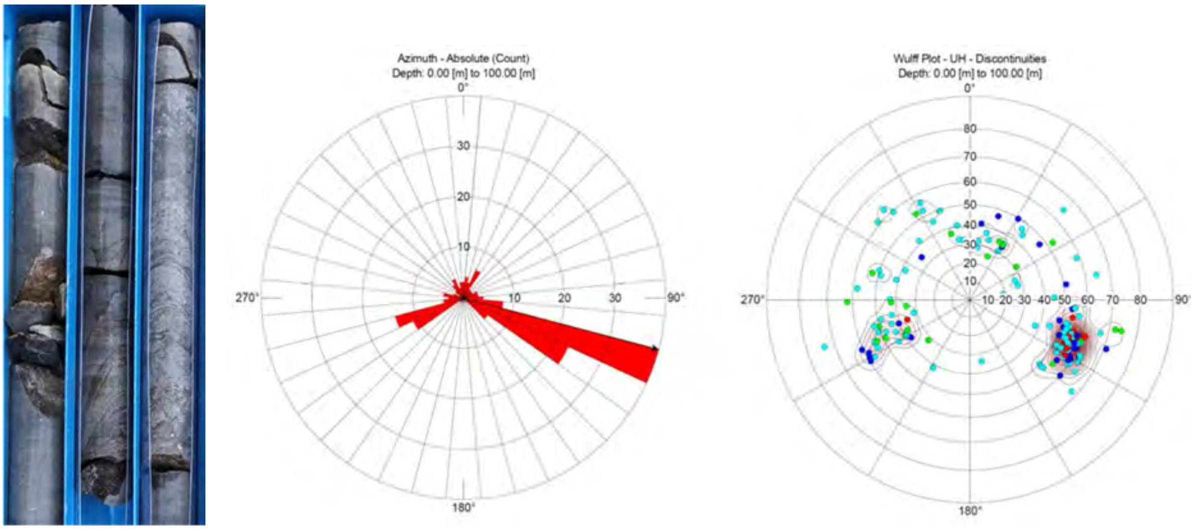


***Figure 1**: Example Rock Core, Rose Diagram and Wulff Plot (Upper Hemisphere)*

***Table 1**: Major Fracture Set Details*

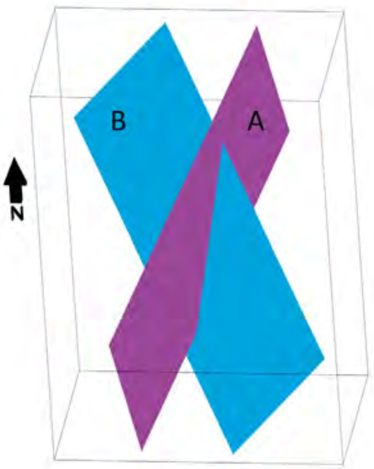
Fracture Group	**Dominant Fracture Group**	**Secondary Fracture Grouping**	**Tertiary (Minor) Fracture Grouping** Not present in all boreholes
Azimuth (direction) Range	Main: 105-125° (~E-SE). Overall: 90 - 140° (~E-SE) NNE Strike	220 - 270° (W-SW dip) SSE strike	30 - 90° (NE-E dip) WNW strike
Azimuth – Average	115°	240°	(weak) 60°
Dip	50 - 70°	40 - 60°	30 - 60°

The limestone was intensely fractured with relatively consistent distributions. Fracture counts and spacings are summarised as follows:

- Fracture counts: range 1.4 to 6.4 per metre.
- Spacings: averages per borehole 0.22 – 0.74 m (range min 0.02 m, max 2.45 m)

Accounting for the average dip of the fractures, true fracture spacings were estimated to average at between 0.11 m and 0.37 m, while maximum true spacings varied between 0.87m and 1.35m. No consistent or significant trends or changes in fracturing intensity were noted with depth or spatial position at the site.

Dominant (A: purple) & Secondary (B: blue) Fracture Sets



All Fracture Sets

(only seen in selected boreholes)

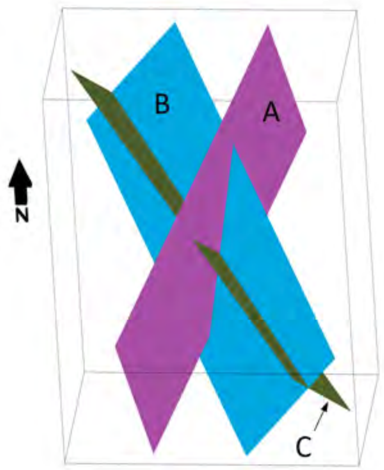


***Figure 2**: Conceptual Representation of Major and Minor Fracture Sets*

HYDROGEOLOGY

Regionally the Calp is classified by the GSI as a locally productive aquifer. In general, the Calp is considered to have low hydraulic conductivity in the order of 1 m/d (GSI 2019)[2]. Regionally, the majority of groundwater flow is considered to primarily occur within the upper 3 m (weathered bedrock), with limited groundwater flow in fractures below 10 m (GSI 2019). Specific yield is reported to range 0.001–0.01 and is mostly attributed to the fracture network, while the aquifer is typically poorly productive with well yields of less than 100 m^3/d.

No active groundwater abstractions within 1 km of the site are registered on the GSI groundwater data viewer website.

Groundwater within the unconfined limestone aquifer beneath the site is encountered at depths of between 5.5 m and 6.5 m bgl. Based on available information on the limestone in the region, the saturated thicknesses of the limestone at the site is expected to be in excess of 100 m (~95 m proven at the site).

Groundwater elevations, inferred equipotential contours and groundwater flow directions for September/October 2018 are presented as Figure 3. The inferred groundwater contours presented on Figure 3 are typical for the site and without accounting for any structural controls suggest a general easterly migration direction across the site is inferred.

Average hydraulic gradients (not including localised areas of steeper gradients) across the site are shallow and typically vary between 0.0014 and 0.0021 m/m. Areas where steeper hydraulic gradients are inferred (up to 0.004) may indicate the presence of barriers or zones where poorer fracture connectivity is present. In addition, an upward groundwater head gradient of between 0.0020 to 0.0032 (0.20 - 0.25 m over 85 m) is evident from multilevel well completions and adjacent traditional screened monitoring wells (refer to Figure 3). The inferred upward head gradient is similar to the horizontal gradient suggesting that TCE at depth will gradually rise upwards as down gradient groundwater migration occurs.

[2] GSI website (https://www.gsi.ie/) accessed during Summer 2019

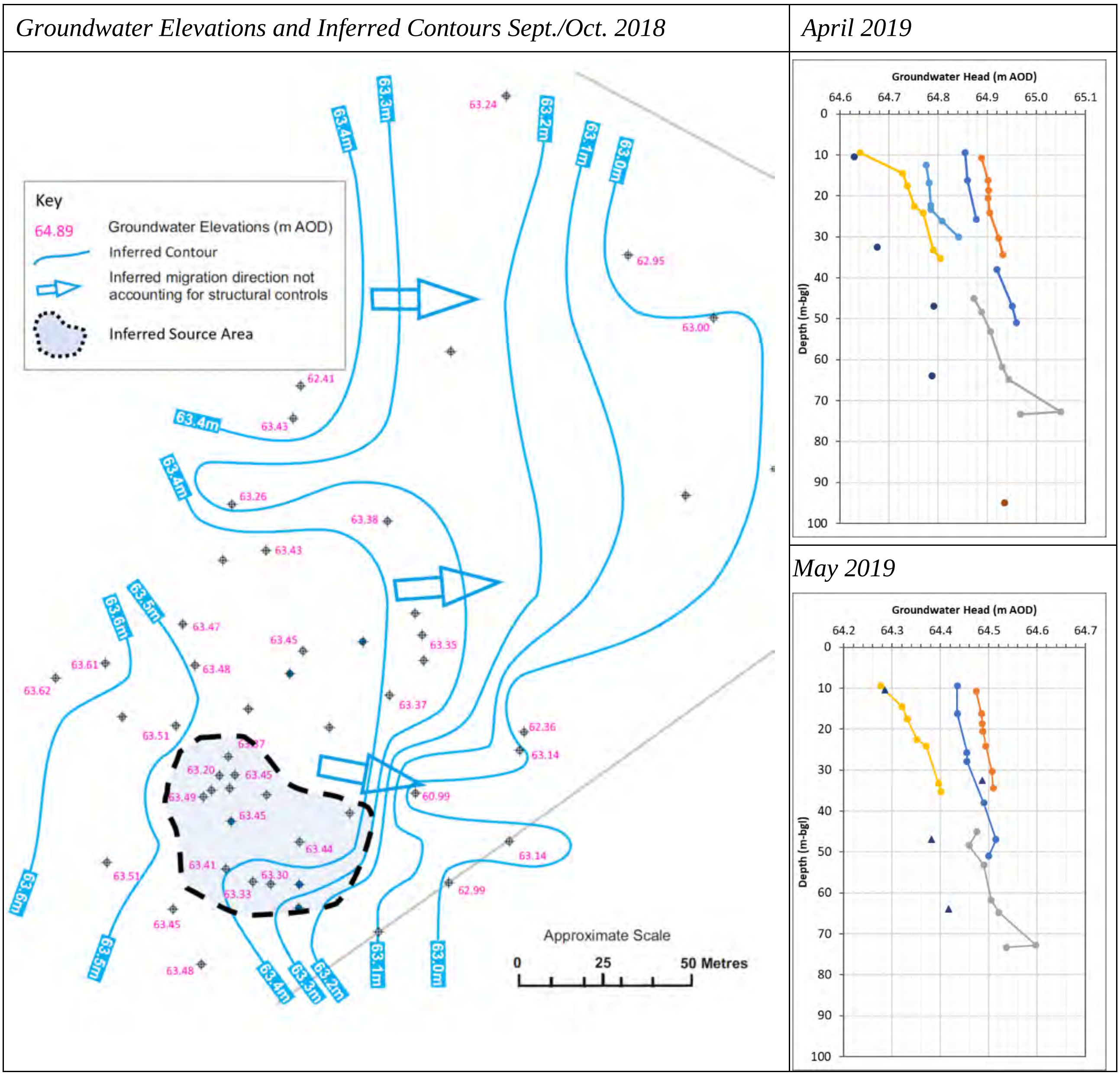


Figure 3: *Groundwater Elevations, Inferred Contours and Heads with Depth*

A total of 94 estimates of hydraulic conductivity (K) are available for the limestone at the site derived from a combination of single well tests (slug tests) and pumping tests are presented as Figure 4. A relatively narrow distribution in K is measured, with a bulk average of 1.06 m/d and a range 0.002 to 5.20 m/d (refer to Figure 4.a). Only seven K measurements of less than 0.1 m/d have been derived. Figure 4.b indicates minimal variation in K with depth, although values >2 m/d are only measured within the top 50m of the aquifer. The lack of any significant variation in K with depth appears to suggest an apparently open down-dip and down-strike fracture network system.

4a. Distribution of Hydraulic Conductivity Measurements *4b. Depth Profile*

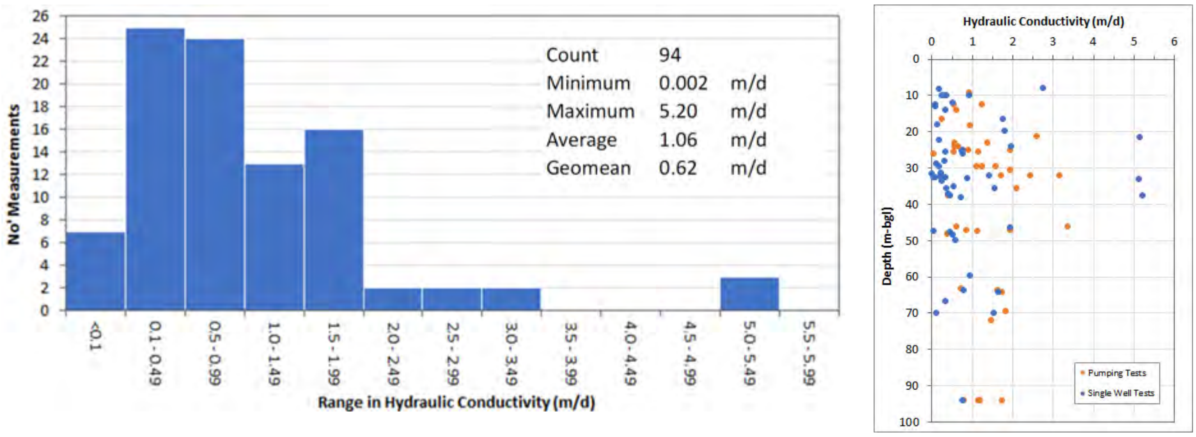


Figure 4: *Distribution of Hydraulic Conductivity Measurements*

TCE DISTRIBUTION

The inferred extent of the TCE plume is presented as Figure 5. The plume extent is seemingly controlled by structure and migrates to the north-east and cross gradient to the inferred groundwater flow direction. Groundwater sampling data are available from 1999 which consistently indicate non-detect CHC concentrations in six monitoring wells located down-dip and down hydraulic gradient to the east of the inferred source area.

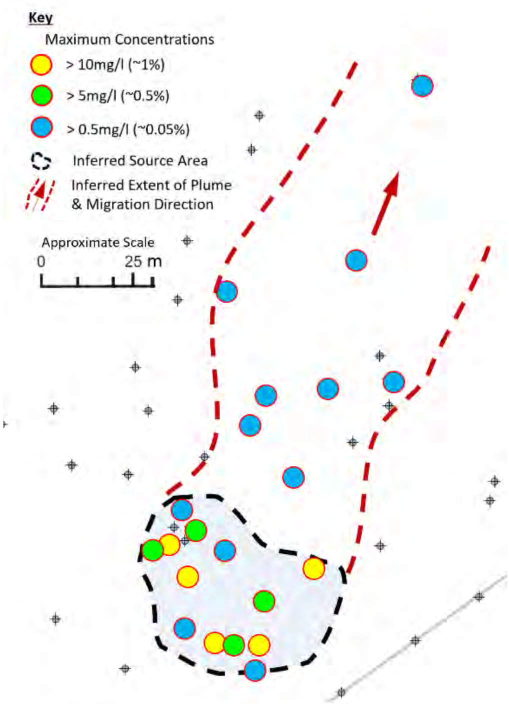


Figure 5: *2018-19 TCE Concentrations & Inferred Plume*

Figure 6a presents long-term TCE groundwater concentrations in near-source zone monitoring wells, which typically vary between 20 and 100 mg/l. It is generally accepted that groundwater concentrations at or above ~1% of aqueous solubility are indicative of the possible presence of dense non-aqueous phase liquid (DNAPL) (EA 2003[3]). Noting that the aqueous solubility of TCE is ~1,100 mg/l; >10 mg/l groundwater concentrations approximate to the 1% rule of thumb threshold. Based on peak groundwater concentrations, the following high concentration wells are identified:

- ~100 mg/l: two wells (>10% solubility)
- ~10 mg/l: nine wells (>1% solubility)
- ~5 mg/l: nine wells (>0.5% solubility)

Also evident from Figure 6a is an apparent gradual downward trend in concentrations, especially after 2010, which may suggest a gradual depletion of remaining TCE DNAPL in the source area within the fractured bedrock. The rate of depletion is slow and the Irish Groundwater Threshold Value (GTV) for TCE of 0.0075mg/l would not be achieved within a substantial period of time without intervention.

[3] Environment Agency (2003) An illustrated handbook of DNAPL transport and fate in the subsurface. R&D Publication 113, 64pp

TCE DNAPL has a density of 1,460 kg/m^3 and a relatively low viscosity of 0.56 cP. Due to these physical properties, TCE is considered to be a high mobility fluid in groundwater systems (EA 2003) and can readily penetrate to depth within fractured bedrock aquifers. Despite an apparently open fracture network at the site, depth profile sampling has identified that the primary source zone possibly still affected by DNAPL (as defined by >5mg/l TCE concentrations) is held up in the top 50m of the aquifer (refer to Figure 6b, which presents a composite of source zone monitoring well data). Figure 6b includes deep monitoring points that are positioned down dip and at a depth that would potentially intersect any down fracture dip migration of contamination from up-dip shallow high concentration source wells.

6a: Long-Term Source Zone TCE Groundwater Concentrations *6b: TCE Depth Profile 2018-19*

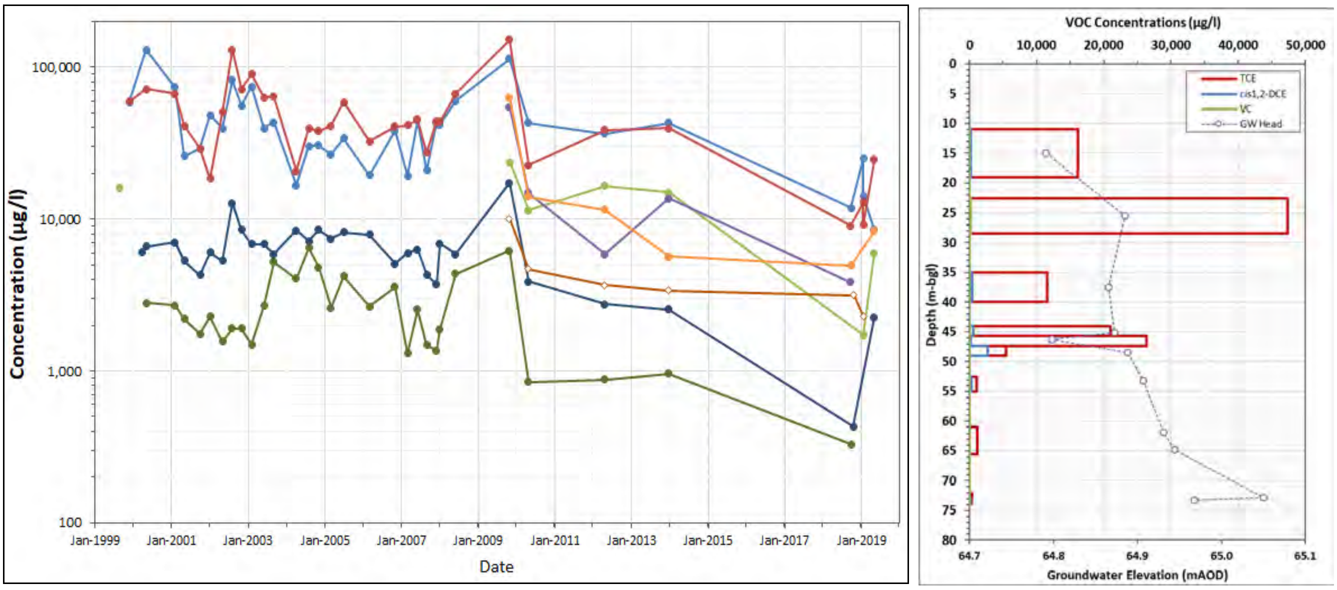


***Figure 6**: Long-Term Source Zone TCE Groundwater Concentrations and Depth Profile*

CONFIRMATION OF STRUCTURAL CONTROLS

TCE concentrations will act as a tracer for the migration of groundwater that passes through the source zone. Further confirmation of structural controls was derived from four short-duration (6 – 8 hr) pumping tests undertaken on selected long screened (5 to 8 m) monitoring wells at varying locations across the site. Measured drawdown responses from these tests have all shown asymmetrical cones of depression that align with the SW-NE trending major fracture sets. The drawdown cones from three tests are presented as Figure 7.

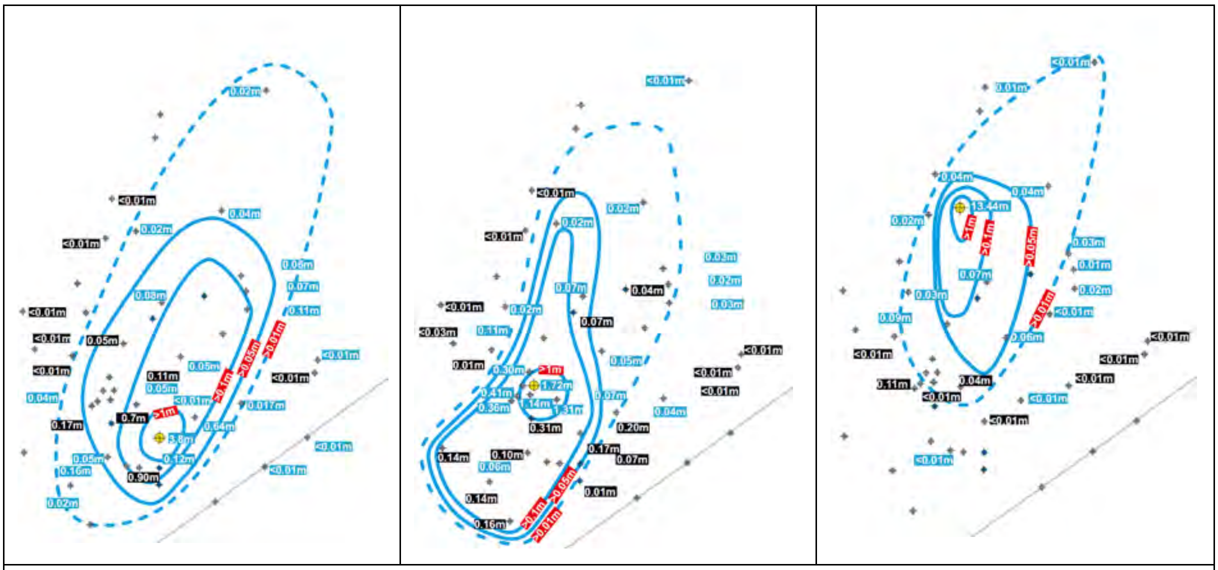


***Figure 7:** Inferred Drawdown Cones Highlighting Asymmetrical Shape*

The asymmetric drawdown and alignment with the dominant fracture orientations is conceptualised as **Figure 8**.

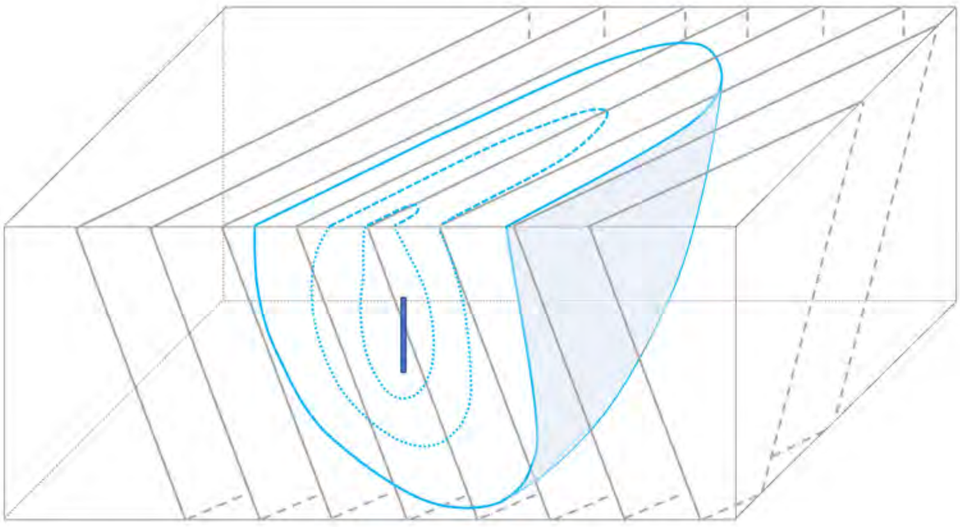


Figure 8: *Conceptual Inferred Drawdown Alignment with Major Fracture Sets*

The pumping test undertaken in the source area showed little or no drawdown to the east, which is significant, as generally lower groundwater levels are typically measured in this area suggesting an inferred easterly groundwater flow direction across the site. However, an easterly migration direction is not evident as non-detect CHC concentrations are measured in this area. The measured drawdown responses help confirm that some form of barrier or restriction to migration may be present. Given that no changes in geology or low permeability shale layers were recorded, it seems likely that restricted fracture connectivity may be playing an important role. Another feature of the pumping tests was the propagation of the drawdown signal with depth to (~90m) suggesting good down dip fracture connectivity with depth.

Figure 9a presents a conceptualised representation of the structurally controlled north-east (NE) groundwater flow direction along the orientation of the major fracture sets and upward head gradients within the limestone aquifer. The black lines representing the fracture sets do not indicate barriers, but rather zones where fracture connectivity is poor (or where fractures are sealed by calcite etc.). This results in a step-like feature to groundwater elevations between differing fracture sets. To enable groundwater contours to be drawn that indicate an easterly migration direction, the step feature would need to result in lower groundwater elevations with distance from west to east across the site. Figure 9a also shows hypothetical groundwater contours (pink) drawn when not accounting for structural controls and indicate an easterly flow direction.

Groundwater is still able to seep laterally across the rock matrix between fractures to enable a north-east to east groundwater migration direction, especially where fracture connectivity is greater or where intersecting sets of NW-SE trending Secondary (SW dip) and Tertiary (NE dip) fractures are present. The concept of an approximately north-east dominant groundwater flow direction at the fracture scale is explored further as Figure 9b, which highlights the influence of fracture connectivity on increased groundwater flow (blue arrows), plus secondary cross fracture set groundwater flow (small blue arrows) and their prevalence where Secondary (SW dip) fractures are present.

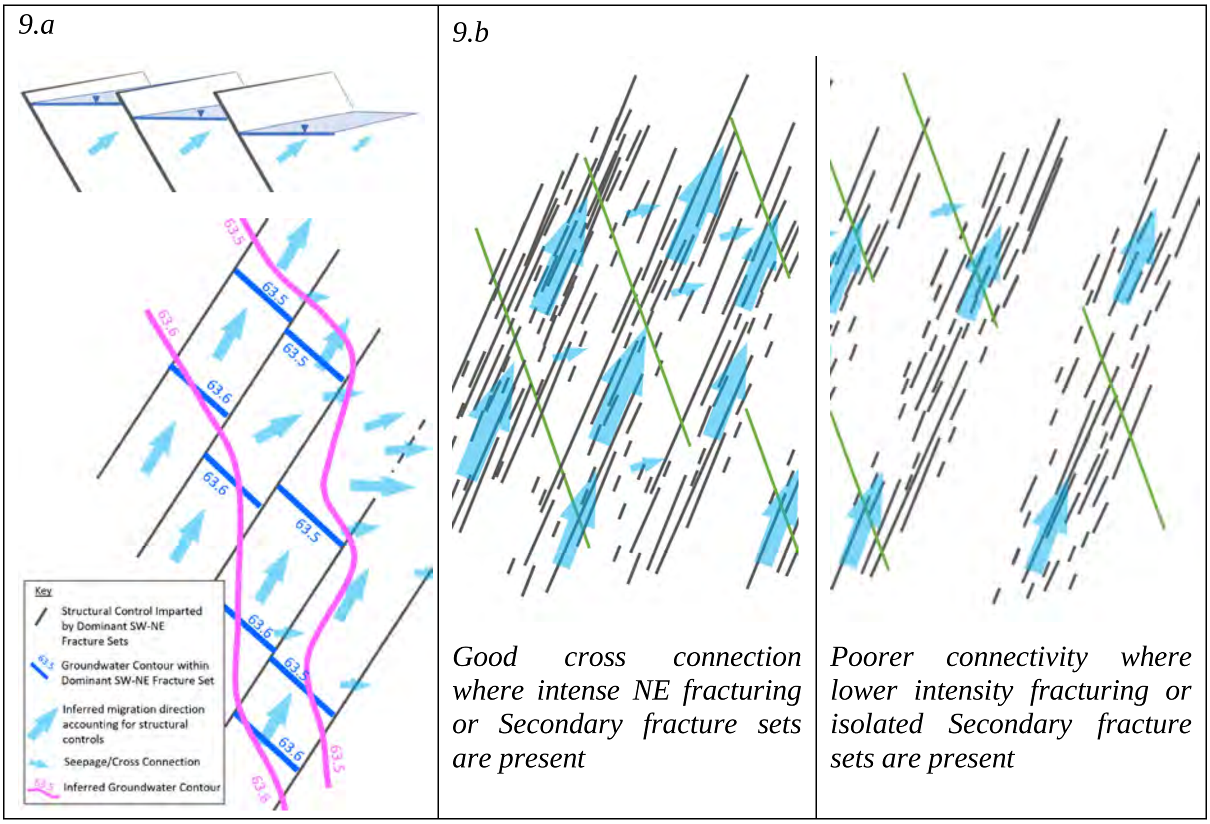


Figure 9: *Conceptual Representation of Structural Controlled Groundwater Flow within Fracture Sets at Study Site*

CONCLUSIONS

In summary, the investigations have identified:

- The presence of densely fractured limestone (average true spacings per borehole ~0.11 m and ~0.37 m with no changes in geology over a depth of 100m across the site. The primary fracture set has an approximate SSW - NNE strike, apparent ESE dip direction (105-125° direction), which is steep, typically between 50-70°. This set follows the major regional Carboniferous lineaments in the basin. Overall, the fracture network appears triangular in nature, with steep intersects, which results in limestone matrix blocks with a prismatic/triangular geometry.
- Structurally controlled groundwater and TCE migration along the strike of the major fracture set, which is cross gradient to the inferred hydraulic gradient. Confirmed by asymmetrical drawdown responses to short term pumping tests that also align with the major fracture set.
- Hydraulic testing indicates a bulk average K of 1.06m/d for the limestone with minimal variation with depth suggesting a relatively open connected down fracture dip and fracture strike fracture network.
- TCE depth profiling indicated that concentrations indicative of the potential presence of residual dense non aqueous phase liquids (source area) are restricted to the top 50m of the limestone. This is despite the presence of dense down-dip fractures sets. This characterisation has enabled remedial design to focus on preferentially targeting the top 50m of the limestone aquifer.

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