THE HYDROGEOLOGY OF EAST CENTRAL IRELAND

Field Guide

International Association of Hydrogeologists (IAH) Irish Group

2022

Cover page: ***The now famous photograph taken by Percy Foster on 20th February 2004 of steam rising on a frosty morning from St. Gorman's Warm Spring near Enfield, County Meath. A stop at this spring is one of our stops on Saturday morning, 22nd October.***

Contributors and Excursion Leaders.

Sarah Blake
Senior Hydrogeologist, Groundwater and Geothermal Unit, Geological Survey Ireland
Geological Survey Ireland, Department of the Environment, Climate and Communications, Block 1, Booterstown Hall, Booterstown, Blackrock, County Dublin

Peter Conroy
Director, Hidrigeolaíocht Uí Chonaire Teoranta
An tSeantsráid, Cill Dalua, Contae An Chláir, V94 DKX8

Natalie Duncan
Geoscientist, GW3D Project, Groundwater and Geothermal Unit, Geological Survey Ireland
Geological Survey Ireland, Department of the Environment, Climate and Communications, Block 1, Booterstown Hall, Booterstown, Blackrock, County Dublin

Patrick Morrissey
Martin Naughton Assistant Professor, Department of Civil, Structural and Environmental Engineering, Trinity College, Dublin
Trinity College Dublin, The University of Dublin, College Green, Dublin 2

Sara Raymond
Geoscientist, GW3D Project, Groundwater and Geothermal Unit, Geological Survey Ireland
Geological Survey Ireland, Department of the Environment, Climate and Communications, Block 1, Booterstown Hall, Booterstown, Blackrock, County Dublin

Katie Tedd
Senior Hydrogeologist, Groundwater and Geothermal Unit, Geological Survey Ireland
Geological Survey Ireland, Department of the Environment, Climate and Communications, Block 1, Booterstown Hall, Booterstown, Blackrock, County Dublin

Programme

Saturday 22nd October

9.00 Grangegorman, County Dublin

Introduction to the field trip, and the Grangegorman locality.

Geothermal Energy in Ireland and the Grangegorman Geothermal Project

- **Deep borehole at Grangegorman**
- **Resultant Geological and Hydrogeological Interpretation**
- **Stratigraphy, and examination of core**
- **The future – district heating ?**

Sarah Blake

11.00 St. Gorman's Well, County Meath

Introduction to the field trip, and the Grangegorman locality.

Geothermal Energy in Ireland and the Grangegorman Geothermal Project

- **Geothermal Springs in Ireland**
- **The Leinster Warm Springs**
- **Geology and Hydrogeology of St. Gorman's Well at Hotwell House**
- **Hydrochemistry of the spring, and karstic aspects**

Sarah Blake

13.00-14.00 Lunch at Brogan's Bar, High Street, Trim

14.15   Boycetown Catchment, Trim to Kiltale area, County Meath

- **Sediment in waterbodies**
- **In-channel erosion risk**
- **Pressures, hydromorphology**
- **Sediment fingerprinting**

Patrick Morrissey

Sunday 23rd October

09.45 Kingscourt, County Cavan

- **The Kingscourt half-Graben**
- **Complex topography, geology and hydrogeology**
- **The Mullantra and Descart boreholes**
- **Delineating Source Protection Zones in an area of complex geology**

Peter Conroy

12.45-13.45 Lunch at Donegan's, Monasterboice, County Louth

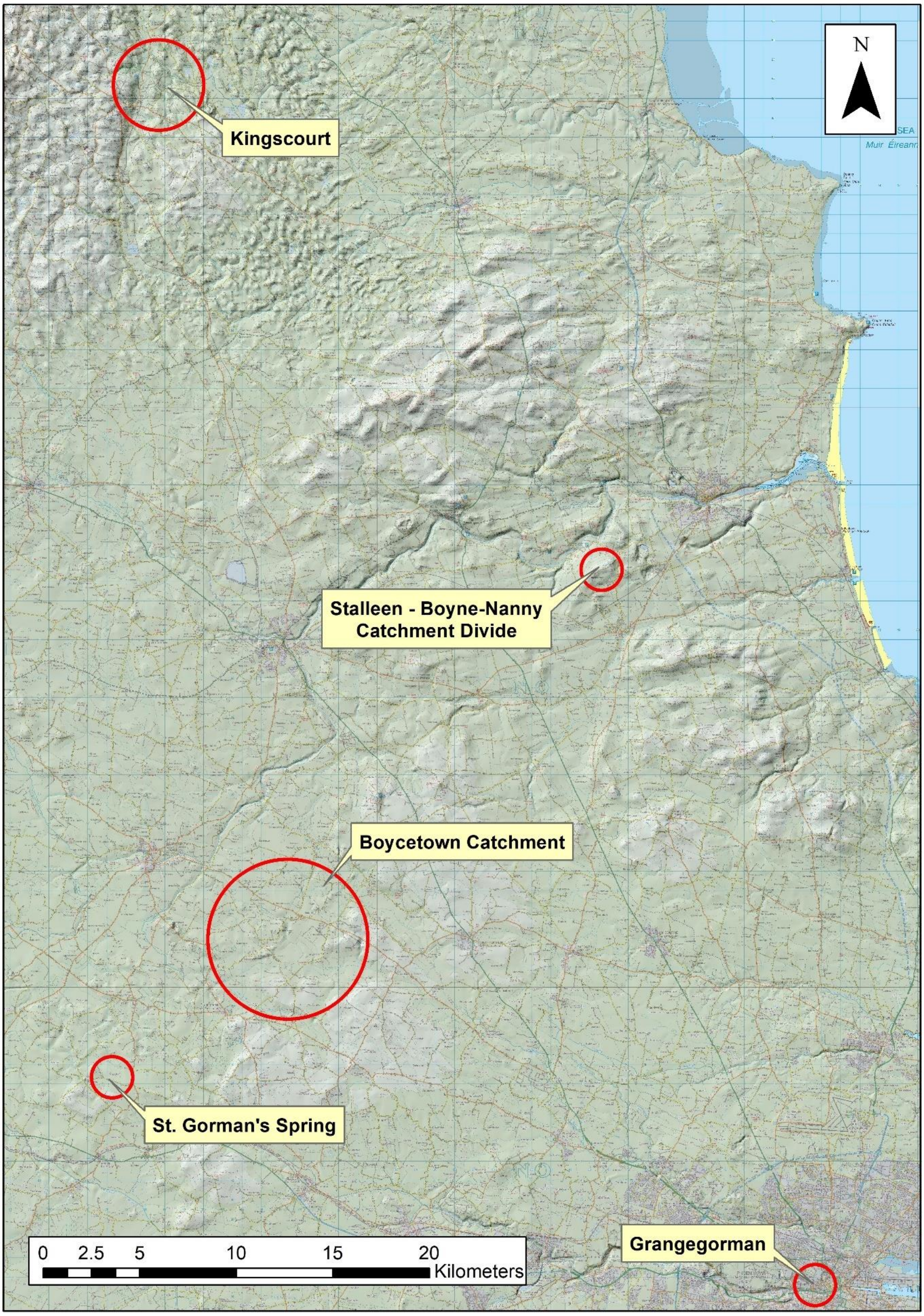
14.15 Stalleen Water Treatment Plant, Boyne-Nanny Catchment Divide, County Meath

- **GSI’s Groundwater 3D Project**
- **Catchment studies and water balance**
- **The setting of the Boyne and Nanny Catchments**
- **Inter-Catchment Groundwater Flow**

Katie Tedd, Natalie Duncan and Sara Raymond

16.30 Return at Beggar’s Bush

Location Map



Preface Map, showing field trip stops and other selected localities mentioned in this guide (O.S. Licence EN 0057922).

Preface

This year is my last year as IAH Field Trip Secretary, after six wondrous, educational, challenging, and fun-filled years.

I have enjoyed every minute of it. I wish Joe Greene the best as he prepares to take over the reins.

I want to thank all of the contributors for the various field trips, from 2017 through until now. As well as all the landowners who allowed us access to the lands.

And to all of the participants, just over 200 of them !

I hope to see ye on the next stop, down the road.

I, and all on the IAH Committee, hope you enjoy this trip to (probably) the best area in the country.

Robbie Meehan
IAH Field Trip Secretary, 19th October 2022

Acknowledgements

This field guide would not have been possible without significant efforts from many people, to whom the IAH are most appreciative.

All contributors produced excellent write-ups of sites, and thanks are due to all for giving us their time in preparation and delivery of the excursion.

We would like to thank Irish Water and Nick Wilkinson of Hotwell House, as well as all other landowners, for giving us permission to visit their lands, and it should be borne in mind that any future visits should only ensure when permission has been sought.

Thanks also to McCaffrey coaches, and to McCaffrey Coaches' bus driver, for getting us around safely, and to all of the IAH Committee for help and advice.

1. A brief introduction to the geology of East Central Ireland.
Robbie Meehan

Almost all of the bedrock geology of east central Ireland is of Palaeozoic age. The dominant rock types are Lower Palaeozoic (Ordovician and Silurian) formations and Upper Palaeozoic (Lower and Upper Carboniferous and Permo-Triassic) formations.

Lower Palaeozoic - Ordovician

Rocks of Ordovician age outcrop in two areas in east central Ireland, the largest area of which is to the north of Slane, extending as far as the Meath-Louth county boundary around Collon. These rocks consist of a series of tuffs, lavas and shales, which are overlain by basic lavas with intercalated sediments. These are overlain by conglomerates which are in turn overlain by fossiliferous sandstones followed by shales (Brenchley *et al*., 1967). Associated with these rocks are the Deerpark Andesites and Tuffs (quarried extensively by Cement Roadstone PLC at Carrickdexter) which are of uncertain age but may be Lower Devonian (Vaughan, 1991).

Ordovician rocks are also present as part of the Bellewstown Lower Palaeozoic Inlier to the east of the county. The rocks are found in the Bellewstown/Carnes/Raholland area and in the Hodgestown/Naul/Fourknocks area. The northern area consists of mudrocks, siltstones, volcanics and limestones and some diorite intrusions. The southern area consists of red and green mudrocks, greywackes and andesitic volcanics, the latter being especially common around the county boundary. Finally, some diorite intrusions crop out along the base of the northern face of the Bellewstown ridge.

Lower Palaeozoic - Silurian

Silurian rocks outcrop in three areas within the region.

The largest area of Silurian rocks in lies in the northwest of County Meath. It includes the southeast-northwest trending ridges of the Slieve na Calliagh, Ballinlough and Kells areas and extends northwards to the county boundary west of a line between Headfort, Moynalty, Altmush and Kingscourt. The outcropping rocks consist of shale, siltstone, sandstone and greywacke. The faults along the boundary are quite complex and the exact boundary is in doubt in places *e.g.* around Oristown. The rocks are much more resistant than the surrounding Lower Carboniferous rocks, hence the high escarpments of Slieve na Calliagh, Ballinlough, Screebog and Teevurcher.

An area of Silurian rocks surrounds those of Ordovician age (at Collon/Slane/Grangegeeth) in the northeast County Meath and extending northwards into mid-County Louth, and beyond. This is bounded on the northern side by the southern limit of the Permo-Carboniferous Outlier at Kingscourt, which runs from Oristown to Newtown, approximately. Outcrops in the area are quite rare but are supplemented by borehole data. The rocks consist of Silurian greywackes and rare black mudrocks. This area of Silurian rocks forms the Louth Uplands and surrounding ridges.

The final area consists of the post-Ordovician rocks of the Bellewstown Inlier, forming the northern edge of the Balbriggan Massif. The rocks take the form of a series of

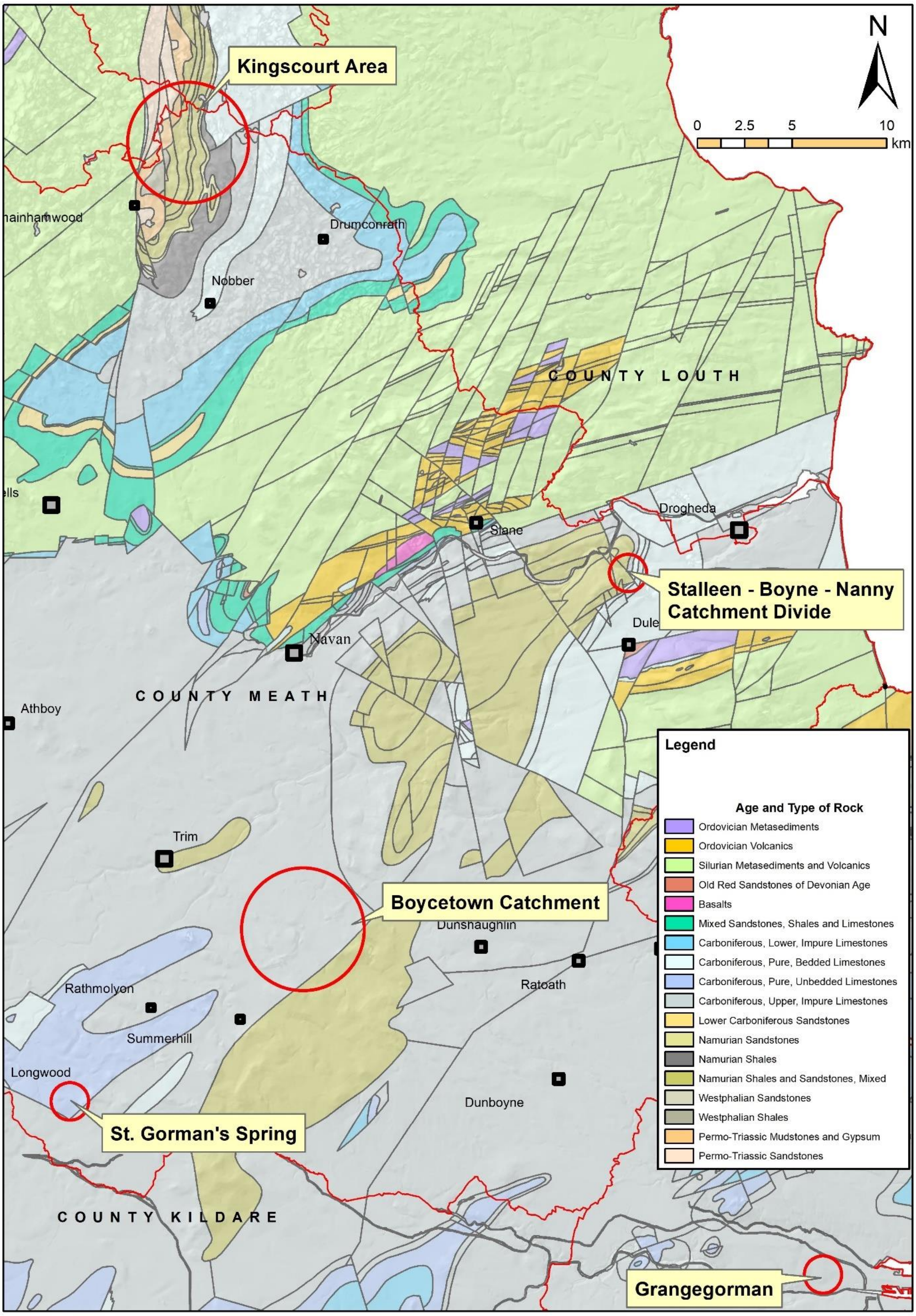


Figure 1. Bedrock Geology of the area travelled.

ridges trending east-west. The outcropping rocks are shales, mudrocks and sandstones for the most part. Some felsic to intermediate igneous intrusions are present, notably at Denhamstown. The Silurian rocks are intensely folded throughout the area.

Upper Palaeozoic - Lower Carboniferous

Rocks of Lower Carboniferous age are the most common in the region and consist mostly of limestones. They outcrop throughout the southern half of County Meath and extend into County Dublin, and also take up a sizeable proportion of the area east of the Kingscourt half-Graben. Basinal limestones of Holkerian to Brigantian age are the most common, consisting of dark, laminated argillaceous calcisiltites and calcareous shales ('Calp' limestone). Purer, shallow water limestones are present near Drogheda. Waulsortian limestone is also common, as is Courceyan argillaceous limestone. In the south of the county most of the limestone is overlain by Quaternary deposits up to 60m thick.

Upper Palaeozoic - Upper Carboniferous (Namurian)

Upper Carboniferous rocks outcrop in small areas of a few square kilometres each in various parts Counties Meath, Monaghan and north Dublin. They can be found pretty extensively at a local level in north Meath, east-central Meath and south Meath.

In north Meath and south Monaghan the Upper Carboniferous rocks are found in a north-south strip to the east of the Triassic rocks and west of the Lower Carboniferous limestones, within the Kingscourt outlier. They consist of mudstones, shales, siltstones and sandstones, with occasional thin coal seams. The shales are generally black but the sandstones are grey in places but mostly bright orange/red and highly weathered. Most of the sandstones are underlain by shale which is of considerable thickness (at least 60m).

In east central Meath, Upper Carboniferous shales and sandstones outcrop at four discrete localities: between Walterstown and Donore; south of Yellow Furze; south of Rathfeigh; and between Skryne and Tara. These outcrops trend southwest-northeast, as do the outcrops in south Meath. The shale is again black, but little is known of the sandstone. The Upper Carboniferous rocks in east central Meath are generally overlain by Quaternary deposits of varying thicknesses.

In south Meath, Upper Carboniferous rocks outcrop northeast of Trim and in a broad zone between Killeen Castle and the Dublin county boundary (around Oldtown Townland). This latter area incorporates the Moynalvey, Culmullen and Garadice region. Again the rocks outcrop as black shales and grey sandstones. In places, pronounced shale escarpments occur, for example at Warrenstown, Culmullen and Mullagh.

Palaeozoic to Mesozoic - Permo-Triassic

Most of the Kingscourt Outlier is composed of Carboniferous rocks but a narrow belt, covering only approximately 20 square kilometres of Counties Meath and Monaghan, consists of Permo-Triassic rocks. Natural outcrops are rare, but extensive drilling has supplied valuable information (Jackson, 1965). The rocks consist of reddish sandstones, which are underlain by gypsum deposits. This gypsum has been extensively quarried in recent years.

References

Brenchley, P.J., Harper, J.C., Romano, M. and Skevington, D. (1967). New Ordovician faunas from Grangegeeth, Co. Meath. Proceedings of the Royal Irish Academy, 65B: 297-304.

Jackson, J.S. (1965). The Upper Carboniferous (Namurian and Westphalian) of Kingscourt, Ireland. Scientific Proceedings of the Royal Dublin Society, 2: 131-152.

Vaughan, A.P.M. (1991). The Lower Palaeozoic geology of the Iapetus suture zone in eastern Ireland. Unpublished PhD Thesis, Trinity College, Dublin.

2. Grangegorman, County Dublin

Sarah Blake and Karina O'Donnell, Geological Survey Ireland

Introduction to Geothermal Energy

The need for renewable resources is more critical now than ever, and geothermal energy provides an efficient and effective method of obtaining energy required for the heating and cooling of homes, businesses, and public buildings, as well as various industrial and agricultural processes. Due to the increasing pressure to decarbonize our energy systems, geothermal energy is currently gaining interest and support throughout the EU. As geothermal energy is practically zero-carbon at source, tapping into Ireland's national geothermal energy resources would decrease our greenhouse gas emissions, while simultaneously lowering our dependence on imported oil and gas. Ireland's geothermal resources are under-utilised at present, and we have the lowest share of renewable heat (RES-H) in the EU (just 6 % of our heat is generated from renewable sources).

Geothermal energy is defined by the EU as "energy stored in the form of heat beneath the surface of solid Earth." This definition includes everything from heat stored in the soil and subsoil, to high temperature resources many kilometres beneath the Earth's surface. The temperature of the Earth is highest within the core, with temperatures generally decreasing towards the Earth's crust. The temperature (and the amount of available energy) increases with depth at an average rate of 25 to 30 °C per kilometre for most places in the world. Whilst Ireland does not have a 'traditional' geothermal setting (i.e., we are situated far from active volcanoes), geothermal energy can still be utilized and has a variety of applications, particularly for heating and cooling homes and businesses, district heating and the agri-food sector (Figure 2). Ireland's geological history has produced several deep sedimentary basins that present the most obvious targets for exploration for large amounts of deep geothermal heat.

A range of technologies can be used to extract useable amounts of geothermal energy, depending upon the geological setting and the nature of the heat demand. Geothermal systems can be divided into two separate categories: deep and shallow (the distinction between the two is arbitrary but useful from a legal and regulatory perspective). Shallow geothermal energy refers to the energy stored in the shallow subsurface of the Earth, usually within the first few 100's of metres. This energy is stored in the soils, subsoils and rocks and is influenced by both the geothermal gradient and heat derived from solar irradiation. Ireland's shallow geothermal energy resources are most often used for small-scale, domestic heating projects; however some notable large-scale uses of shallow geothermal energy exist, e.g., Ikea in

Ballymun, Co. Dublin. Ireland’s low-temperature, shallow resources have been well documented by Geological Survey Ireland in a series of geothermal suitability maps (Geological Survey Ireland, 2015). According to this classification, 94 % of Ireland’s land mass is either “suitable” or “highly suitable” for shallow geothermal installations (SEAI, 2022). The stable low temperature heat obtained from shallow geothermal systems is used alongside a heat pump to boost temperatures (termed Ground Source Heat Pumps, or GSHPs). The wide-scale implementation of GSHP systems as opposed to cheaper air source heat pumps (ASHPs) has recognised potential to have a significant decarbonising impact on how we heat our homes and businesses. In contrast to other ambient source heat pump systems, GSHPs can provide heating, cooling and thermal storage and offer higher seasonal efficiency due to the stable ground/groundwater temperatures all year round.

Although Ireland’s deep geothermal resources are poorly understood at present, progress is being made to identify the role deep geothermal energy could play in our transition to renewable energy. Geological Survey Ireland released a new suite of deep temperature maps in 2021 which highlights the potential for deep geothermal energy in southeastern, southwestern, and northern regions of the island (Figure 3).

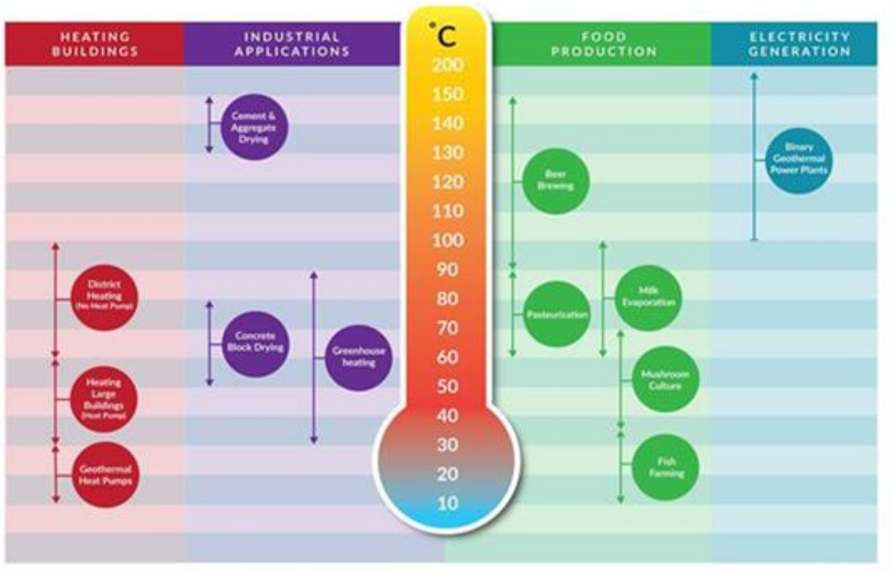


Figure 2. Applications of geothermal energy in Ireland.

The Grangegorman Geothermal Project

To further understand deep geothermal energy in Ireland, Geological Survey Ireland have partnered with Technological University Dublin (TUD) to explore the deep geothermal resource beneath the TUD Grangegorman campus in Dublin 7. This location was chosen for a deep geothermal pilot project due to its central location in the Dublin Basin, and existing district heating infrastructure. TUD’s Grangegorman campus is currently heated by gas boilers housed in the Energy Centre compound. A range of driving forces (planning, regulations, economic and social obligations) have made the decarbonisation of the campus heating system a top priority for TUD. The issues are compounded by the relatively small campus size in an urban, inner-city environment. The decision was made in 2021 to investigate the geothermal potential of the subsurface beneath the campus.

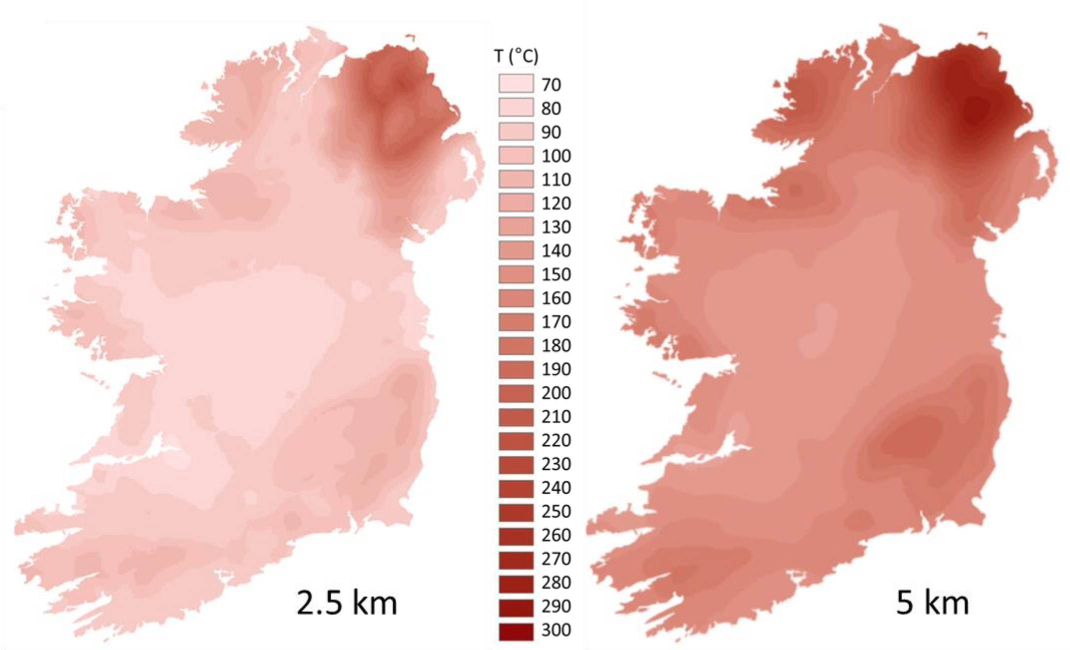


Figure 3: Modelled temperatures at depths of 2.5 and 5 km beneath the surface of Ireland (GSI, 2021). Maps produced using data from a geophysical model (Mather et al., 2019).

In late 2021 an exploratory corehole was drilled at Grangegorman by Geological Survey Ireland to a depth of 998 m, and a local average geothermal gradient of 28 ˚C/km was established (Figure 4). A continuous sequence of bedrock core samples were obtained from the project, as well as a suite of downhole geophysical data. The borehole was drilled close to the Grangegorman Energy Centre. The drilling process and final temperature measurements were filmed by RTÉ and featured on EcoEye in February 2022.

This borehole is the deepest cored hole in the central Dublin Basin and the deepest temperature measurement beneath Dublin City. The geothermal gradient at Grangegorman is very promising and highlights the potential of the geothermal resource beneath both TUD and Dublin City. A full well design and specification exercise was undertaken by Geological Survey Ireland and external specialists using the detailed geological information collected in 2021. This costing exercise will serve to a) establish the current cost of geothermal well drilling in Dublin and the approximate levelized cost of energy (LCOE) for geothermal district heating; and b) enable funding to be sought for a geothermal district heating project at TUD Grangegorman. A successful geothermal district heating pilot at Grangegorman will prove the technology in Ireland and pave the way for further projects to fulfil geothermal's potential in Ireland's energy transition.

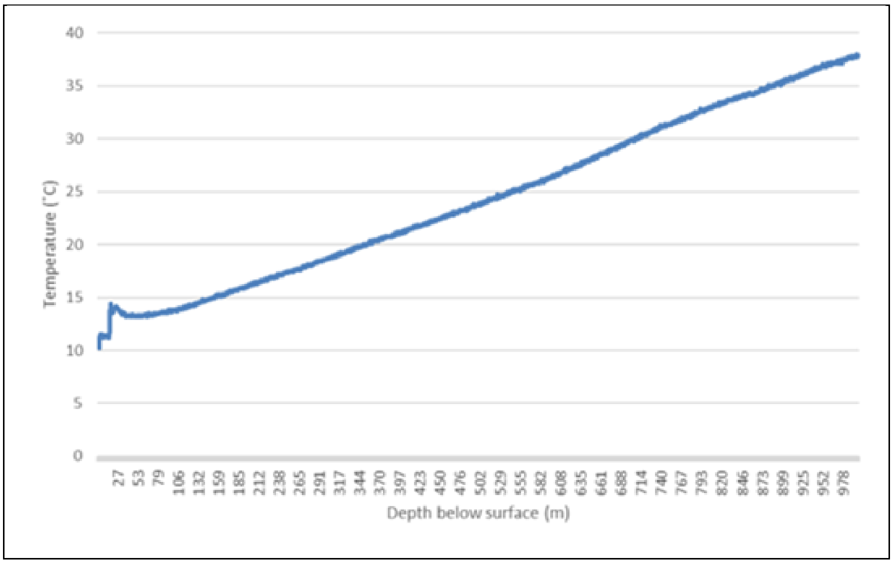


Figure 4. Fibre optic temperature profile obtained from Grangegorman geothermal borehole.

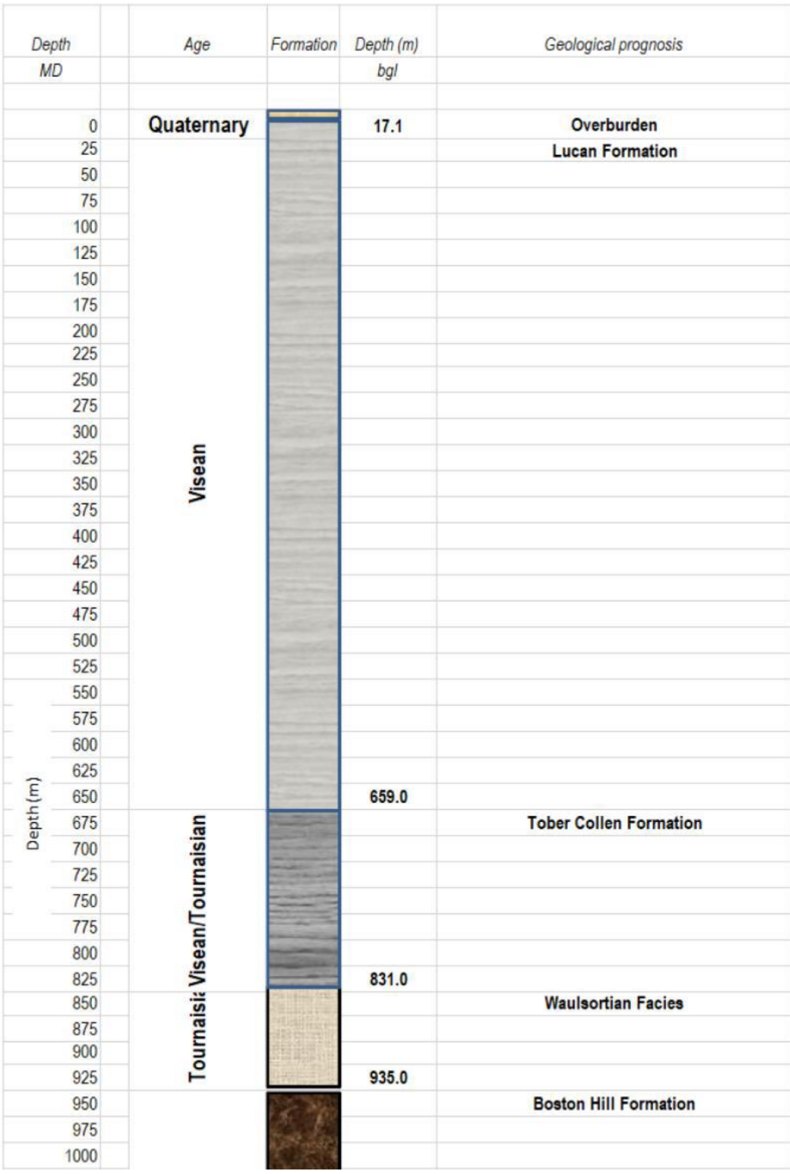


Figure 5. Simplified stratigraphy beneath Grangegorman.

Geology and Hydrogeology at Grangegorman

The bedrock beneath TUD Grangegorman campus was found to be typical of the Carboniferous limestone succession of this part of the Dublin Basin. The Lucan Fm. rockhead was encountered beneath 17 m of subsoil, and persisted until 659 m below ground level (mbgl). The Tober Colleen Fm. Was encountered to 900 mbgl followed by the Boston Hill Fm. with proximal Waulsortian reef facies until the end of hole. Groundwater was first struck at 10 mbgl. Some intensely fractured horizons were encountered at around 170, 370 and 500 mbgl. An interval of porous dolomite was located at 833 to 845 mbgl coinciding with an artesian water strike at this depth. A section of zebra dolomite was encountered between 935 and 947 mbgl. (The dolomite sections of core are available to view today.)

3. St. Gormans Spring, Enfield, County Meath

Sarah Blake and Karina O'Donnell, Geological Survey Ireland

St. Gorman's Spring (a.k.a. St. Gorman's Well)

Springs produced by the surfacing of geothermally heated groundwater are known as geothermal springs. In Ireland, thermal springs are considered as natural groundwater springs where the mean annual temperature appreciably exceeds the average groundwater temperatures (Aldwell and Burdon 1980; Goodman et al. 2004). Average groundwater temperatures across the island of Ireland typically range from 9.5 to 10.5 °C (Aldwell and Burdon 1980).

In Ireland, thermal springs occur in Carboniferous limestones, predominantly along the same trajectory as the Lower Palaeozoic Iapetus Suture Zone (Figure 6a). These limestones typically have poor primary porosity, with the majority of pathways created by secondary porosity and permeability. Secondary porosity is mainly created by both fracture and karst development, providing easier pathways for groundwater flow. Thermal springs in Ireland are often associated with deep-seated, high-angle faults, which facilitate the movement of warm waters towards the surface (Mooney et al., 2010). These springs appear to be associated with the dominant Caledonian NE–SW structural lineaments observed in Ireland's bedrock.

One of these thermal springs, St. Gorman's Well, is located close to Enfield, Co. Meath, and has historically been recorded as a "holy well" at this location. It is thought that the current name of the spring derives from an anglicisation of the Irish word *goradh*, which means heat. The well discharges naturally as an ephemeral pond and is usually dry during summer months. In the 1980s several boreholes were drilled in close proximity to the spring (Murphy and Brück 1989); with two significant boreholes located 20 m west of the natural spring pond. Both boreholes discharge artesian warm waters in the winter and exhibit some of the highest shallow groundwater temperatures in Ireland, with temperatures reaching up to 21.8 °C.

St. Gorman's Well is one of the warmest thermal springs, as well as being one of the most well studied and the least disturbed in the Leinster province, and possibly in the whole of Ireland. St. Gorman's Well springs from the limestones of the Carboniferous Dublin Basin (Figure 6b). The borehole nearest to the spring pond is a 48 m deep, open borehole in the limestone bedrock and is cased to a depth of 5.8 mbgl. Most of the monitoring of this spring system has taken place in this well. The temperature profile of St. Gorman's Well is quite complex, with temperatures varying throughout the year. The annual temperature range is from 10.5 to 21.8°C. The borehole has its maximum discharge in January, when the water level is artesian; this is when the water temperature is at its maximum (Blake et al., 2021). Historical discharge measurements indicate that the spring has a mean annual discharge of approximately 400 m^3/day. These variations add to the complexity of the spring as a potential geothermal resource, as the available thermal energy for exploitation varies considerably through time.

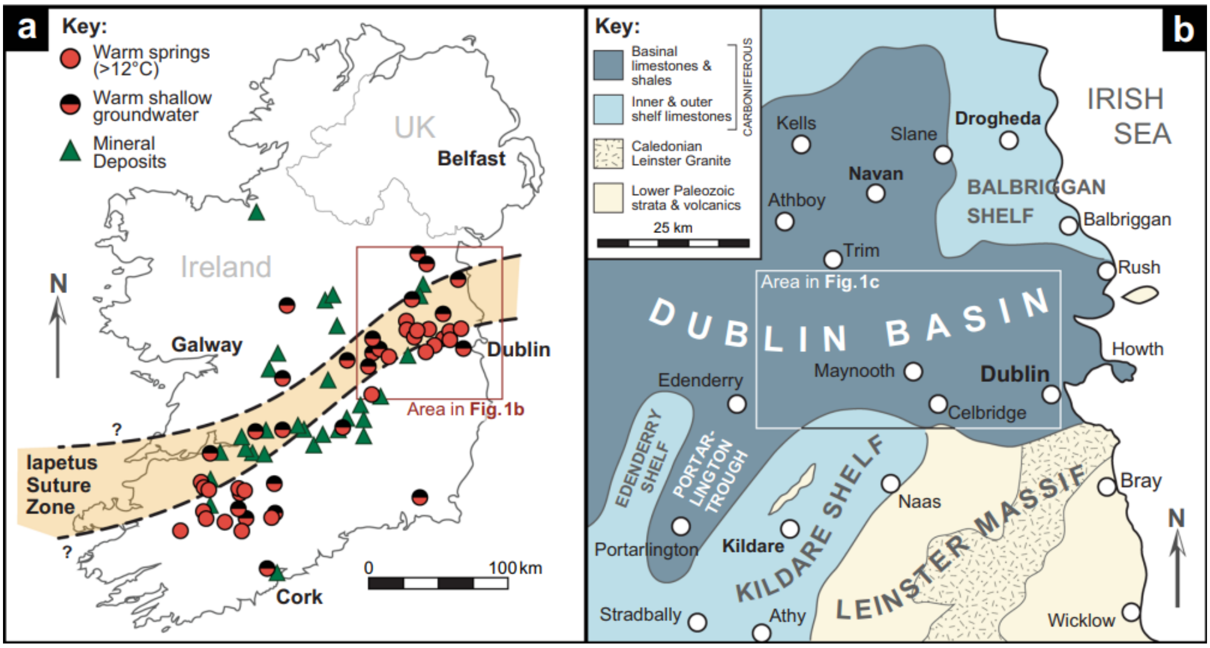


Figure 6a. Irish thermal spring and thermal shallow groundwater locations (after Goodman et al. 2004), with mineral deposits and the approximate trace of the Iapetus Suture Zone (after Wilkinson 2010).

Figure 6b. Paleogeographic map of the Dublin Basin during the Viséan Stage (modified from Sevastopulo and Wyse Jackson 2009).

Geology and Hydrogeology of St. Gorman's Spring

St. Gorman's Spring or Well is located in the "South Eastern zone" of the Boyne catchment, where groundwater flow is dominant over surface water flow. Here, it is estimated that between 41 and 72% of the effective rainfall is recharging. Low tritium levels from the borehole suggest long residence times. The seasonal behaviour of St. Gorman's Well suggests that the water is likely to be a mix of groundwaters from different sources and different recharge areas. It is a possibility that the thermal water is composed of a mixture of a deeper-circulating, older groundwater, and more recent, recharge water from a shallow groundwater system. However, hydrochemical data revealed nothing to suggest St. Gorman's Well was influenced by deep-basinal fluids (Blake et al. 2016).

St. Gorman's Well is situated in the Carboniferous Dublin Basin and discharges from the Waulsortian Limestone Fm. close to its faulted contact with the younger Lucan Fm. Existing data suggest that the spring is probably situated on a westward dipping faulted contact between the two formations, and significant fracturing of the Waulsortian limestones exists at depths of 38–55 m. Geological Survey Ireland's Tellus programme recently collected airborne electromagnetic data, which show prominent NE structural trend in the region programme (Geological Survey Ireland 2021). These deep-seated faults could provide fluid pathways (through karstification) and facilitate the flow of thermal spring waters from deeper sections up to the surface. These faults are likely very important in controlling regional groundwater flow (Henry 2014). Electromagnetic geophysical surveys were carried out in 2013 as part of the IRETHERM project and imaged electrically conductive features in the subsurface that are interpreted as water-bearing conduits along N-S Cenozoic strike-slip faults (Blake et al., 2021).

Using a downhole camera within one of the boreholes (the borehole beside the fence, furthest from the pond) a significant cave or conduit at a depth of 91 m was discovered. This corroborates existing studies and suggests that the high temperatures observed at St. Gorman's Well are the result of deep circulation patterns, controlled by the presence of permeable structures and karst conduits within the Waulsortian limestones. Geological Survey Ireland's downhole camera will be used today to look inside this underwater cave! It is evident that the development of karst along intersecting structures within the Waulsortian Limestone Formation. has been the main factor in the development of a thermal spring at St. Gorman's Well.

References

Aldwell CR, Burdon DJ (1980) Hydrogeothermal conditions in Ireland. Fossil Fuels Sec. 14.2, Abstracts 1043, XXVI International Geological Congress, Paris, 1980.

Blake S, Henry T, Murray J, Flood R, Muller MR, Jones AG, Rath V (2016) Compositional multivariate statistical analysis of thermal groundwater provenance: a hydrogeochemical case study from Ireland. Appl Geochem 75:171–188.

Blake, S., Henry, T., Moore, J., Murray, J., Campanyà, J., Muller, M., Jones, A., Rath, V. and Walsh, J., (2021) Characterising thermal water circulation in fractured bedrock using a multidisciplinary approach: a case study of St. Gorman's Well, Ireland. Hydrogeology Journal, 29(8) 2595–2611.

Geological Survey Ireland (2015). Ground Source Heat & Shallow Geothermal Homeowner Manual. https://www.gsi.ie/documents/GeothermalHomeownerManual.pdf. Accessed 07 October 2022.

Geological Survey Ireland (2021) Tellus. Geological Survey Ireland. www.tellus.ie. Accessed 07 October 2022.

Goodman R, Jones G, Kelly J, Slowey E, O'Neill N (2004) Geothermal energy resource map of Ireland final report. Sustainable Energy Ireland (SEI), Dublin.

Henry T (2014) An integrated approach to characterising the hydrogeology of the Tynagh Mine Catchment, County Galway, Ireland. PhD Thesis, National University of Ireland Galway, Galway, Ireland.

Mooney B, Allen A, Koniger P (2010) Investigation of source and conduit for warm geothermal waters, North Cork, Republic of Ireland. In: Proceedings World Geothermal Conference, Bali, Indonesia, April 2010, 13 pp. https://www.geothermal-energy.org/pdf/ IGAstandard/WGC/2010/1156.pdf. Accessed 07 October 2022.

Murphy FX, Brück P (1989) An investigation of Irish low enthalpy geothermal resources with the aid of exploratory boreholesurces with the aid of exploratory boreholes. Report 98/13, Conference: World Geothermal Congress, Melbourne, April 2015.

Sevastopulo GD, Wyse Jackson PN (2009) Carboniferous (Dinantian). In: Holland CH, Sanders IS (eds) The geology of Ireland, 2nd edn. Dunedin, Edinburgh, pp 241–288.
Somerville ID, Strogen P, Jones GL (1992) Mid-Dinantian Waulsortian buildups in the Dublin Basin, Ireland. Sediment Geol 79:91–116.
Wilkinson JJ (2010) A review of fluid inclusion constraints on mineralization in the Irish ore field and implications for the genesis of sediment-hosted Zn-Pb deposits. Econ Geol 105:417–442.

Sustainable Energy Authority of Ireland, 2022. National Heat Study District Heating and Cooling: Spatial Analysis of Infrastructure Costs and Potential in Ireland. http://www.seai.ie/publications/District-Heating-and-Cooling.pdf

4. Sediment studies in the Boycetown Catchment, Trim – Kiltale, County Meath

Patrick Morrissey[a], Robbie Meehan[b] and Timothy Meadows[c]

a: Trinity College Dublin (formerly EPA Catchments Unit), Dublin 2
b: Consultant Geologist, 86 Athlumney Castle, Navan, County Meath
c: APEM Ltd., Riverview, A17 Embankment Business Park, Heaton Mersey, Stockport, SK4 3GN, United Kingdom

Introduction to the issue of sediment in watercourses

The objective of the Water Framework Directive (WFD) is to achieve at least good status for all waters within Europe by 2027 at the latest. The implementation of the directive requires that the EPA perform a characterisation of WFD waterbodies identifying significant pressures and the associated impacts which pose a risk to achieved environmental objectives. Excessive levels of fine sediment have been identified as a key impact from various activities across multiple sectors including agriculture, forestry, peatlands and urban areas. Land drainage either undertaken privately or within OPW arterial schemes is often associated with sediment impacts. Drainage associated with peat extraction or other developments on peatland sites is also known to lead to significant levels of fine sediment or humic matter in downstream river and lake waterbodies. Excessive levels of fine sediment can cause various negative impacts in the receiving waterbody including invertebrate mortality (via smothering), and a reduction in dissolved oxygen (DO) and trophic structure alteration. Reduced DO and the altered trophic state impacts fish species resulting in: reduced food sources, increased stress levels, reduced growth rates and lower immune system response to viral and bacterial infections (amongst others). Heavy siltation also reduces available spawning habitat for fish, and suitable habitat for the freshwater pearl mussel, which would otherwise utilise clean gravels within the river substrate.

Sediment risk assessment tools

The issue of excessive sediment within our river waterbodies has arisen as an impact closely linked with hydromorphological pressures. Hydromorphological pressures relate to damage to habitat and natural river processes, through physical modifications (e.g. channelisation, land drainage, dams, culverts etc.). A healthy functioning river habitat will typically have both coarse and fine sediment present, however when physical alterations to the river habitat occur, excessive levels of fine sediment can be released into the river causing impacts. Following the initial works which release the fine sediment, on-going impacts can then also occur either through excessive erosion (resulting from the alterations) or changed river/land use dynamics typically through land drainage. Quantifying the extent and impacts of sediment cover related to hydromorphological pressures and the measures required for correction of same is therefore pertinent to achieve our WFD objectives. In this regard, the EPA Catchments Unit, supported by external contractors, have been developing national maps for in-channel erosion sediment erosion risk. Catchment based sediment erosion risk maps are also under development and will complement the in-channel risk maps when complete. It was initially decided that the methodology would first be developed and implemented in three pilot study catchments. Field validation would then follow in one catchment to verify and refine the conceptual model if required. The pilot WFD catchments were chosen to give a broad representation of hydromorpholoical conditions nationally. These were; the Blackwater (Munster) which is largely natural and unaltered, the Boyne which is heavily altered and drained and the Liffey & Dublin Bay which is largely urbanised – the pilot catchments are shown in Figure 7 following.

Figure 7: Sediment tool development pilot catchments throughout Ireland – the location of the Boycetown sub-catchment is also shown in blue.

A conceptual model was first developed to produce the in-channel sediment risk maps which was based on risk matrices. The scientific basis for the erosion and deposition aspect followed Parker et al. (2017) who developed the ST:REAM model in the UK. This methodology, which is largely based on steam power at the river reach scale, was modified to incorporate a catchment sediment delivery aspect derived from SCIMAP risk. SCIMAP (Sensitive Catchment Integrated Modelling and Analysis Platform) is a spatially based algorithm which identifies critical source areas (CSA) for fine sediment within the landscape and then calculates the accumulation and dilution of the 'risk' from these locations towards watercourses (Reaney et al., 2011). Other datasets which fed into the conceptual model risk matrices included expert knowledge of Irish soils and geology (Meehan, 2020) and the presence of OPW drainage schemes. Whilst this conceptual methodology utilised the most up to date and available GIS datasets and expert knowledge, it is still primarily a desk based conceptual approach. An example of the final output of one of the in-channel sediment risk parameters for the Boyne pilot catchment is given in Figure 8 below.

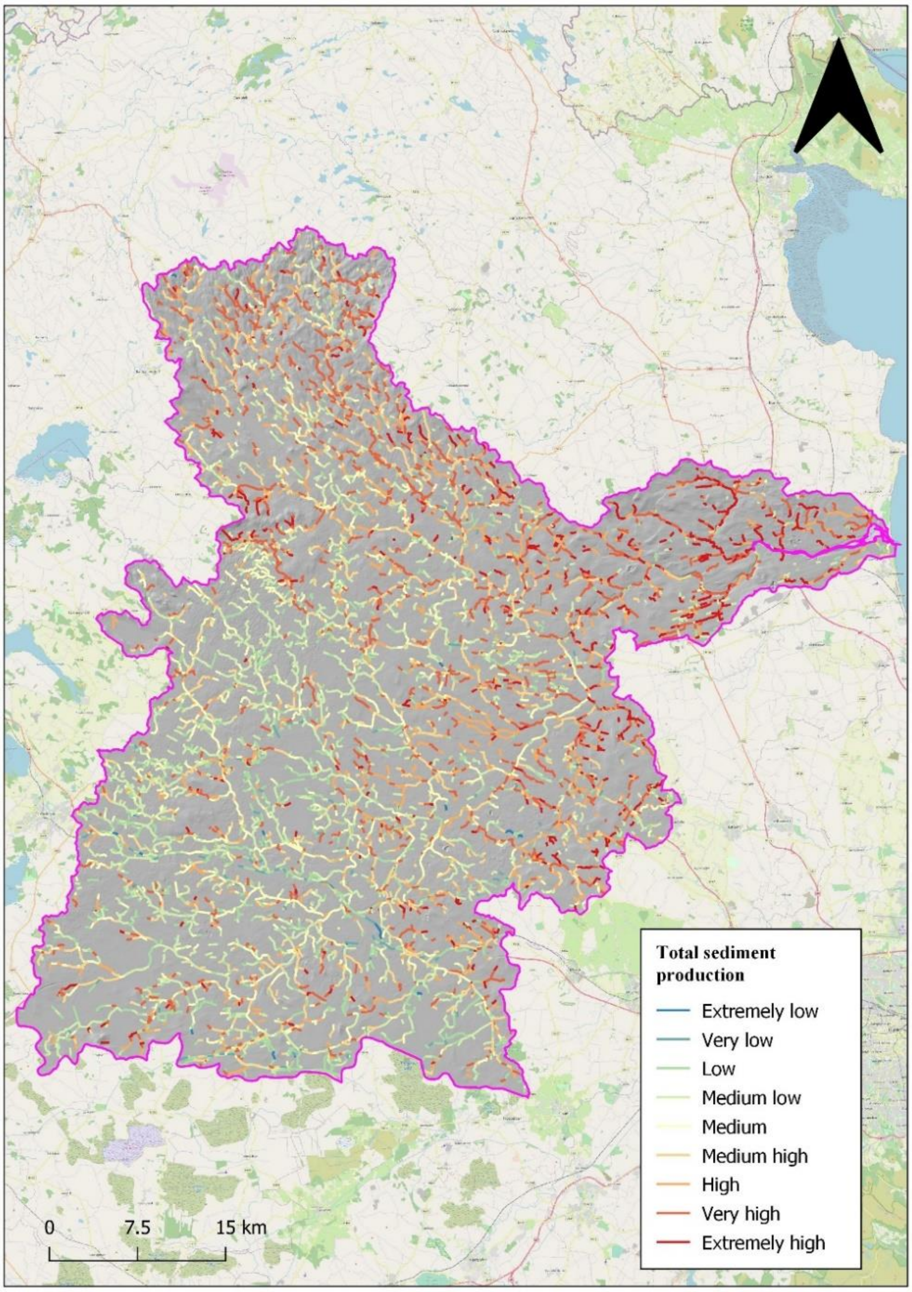


Figure 8: Output from the new in-channel sediment risk tool for the "Total sediment production" parameter within the Boyne pilot catchment.

The catchment-based element of the sediment risk maps (identifying CSA for sediment) were developed using specially derived land use mapping combining sediment production risk weightings and output through SCIMAP. The CSA are primary identified through topography (5m hydrologically corrected DEM), the land use risk weightings and rainfall intensity. Issues surrounding the accuracy of the land use maps delayed this aspect of the map production, however field validation was required and this could occur prior to the maps being completed.

Field validation in the Boycetown catchment

As part of their further characterisation work, Local Authority Waters Programme (LAWPRO) catchment scientists have commenced further characterisation field work in specific catchment areas around Ireland called Priority Areas for Action (PAAs). The Boycetown is a tributary of the River Boyne in Co Meath and was selected as a PAA during the 2nd cycle of the WFD – see Figure 7 for location. In the Boycetown PAA, there are two WFD river waterbodies named Boycetown_010 and Boycetown_020 which flow from generally north-west from Culmullin to the confluence with the River Boyne near Kiltale, southeast of Trim. Agriculture is main land-use in the Boycetown catchment, with a mixture of pasture and tillage, however small areas of forestry are also present. The geology within the catchment is a mixture of limestone and shales in the Boycetown_010 and impure limestone in the Boycetown_020. Soils are predominantly poorly drained in the Boycetown_010 and well drained in the Boycetown_020. The Boycetown is within the Office of Public Works (OPW) Boyne arterial drainage scheme, and the main channel is subject to regular maintenance.

The Environmental Protection Agency assign WFD status based on many quality elements which together demonstrate the overall health of the river (e.g. invertebrates, dissolved oxygen, nutrients etc) and also the physical condition of the river referred to as hydromorphology. The environmental objective for the Boycetown is Good which means Ireland must achieve Good Status for these two waterbodies by 2027[1]. Neither of the Boycetown waterbodies are achieving their WFD environmental objective with Boycetown_010 at Poor Status and Boycetown_020 at Moderate Status (see Table 1). LAWPRO have completed their field study within the Boycetown PAA and have determined that hydromorphological significant pressures are the primary cause of these failures with excessive fine sediment the main impact – refer to Table 1 below.

Table 1: Extract from the LAWPRO Boycetown Priority Area for Action: Desk Study Summary (LAWPRO, 2020)

Waterbody	Status (2013 – 2018)	Our findings
Boycetown_010	Poor	We have identified that the level of the sediment in the river is too high. The excessive sediment has caused a decline in water quality.
Boycetown_020	Moderate	We are unsure what is causing this unsatisfactory water quality in the river but maybe impacted by the Boycetown_010 upstream.

[1] A review of heavily modified waterbodies is underway by the EPA which may impact the environmental objectives for waterbodies such as the Boycetown_010 and Boycetown_020

In response to these sediment issues related to hydromorphology pressures in the Boycetown, LAWPRO embarked on a pilot study with the UK River Restoration centre using the Boycetown PAA as a study site. This was primarily aimed at developing a rehab framework at the reach scale in line with the River Habitat Survey (RHS) method. LAWPRO have highlighted that identifying the source of the sediment within the Boycetown River has proved extremely difficult and therefore making recommendations for restoration is severely limited.

Given that the Boycetown is a sub-catchment of the Boyne Catchment it was decided to focus initial field validation efforts for the sediment risk tools here and therefore make use of information collected by LAWPRO and maximise the outcomes for both studies. The objectives of the field validation were:

- Validate the sediment risk mapping by visiting targeted locations throughout the Boyne catchment completing visual and in-situ checks – this work was initially focused in the Boycetown PAA; and,
- Complete a small-scale sediment fingerprinting study in the Boycetown PAA sub-catchment to validate the catchment sediment risk maps and as a cross check of the in-channel sediment risk maps.

This field validation study would complement the work being undertaken by LAWPRO and would then tie the information together in terms of our understanding of hydromorphological pressures and sediment in drained catchments such as the Boyne.

Results - In-channel sediment risk

In order to validate the in-channel sediment risk maps, 20 sites were visited within the Boyne Catchment across a range of predicted erosion and deposition settings. An additional 3 locations were also assessed during the sediment fingerprinting study in the Boycetown sub--catchment giving a total of 23 locations included in the field validation assessment. An example of the process involved is given below for a location in the Boycetown catchment.

Spot check location 1 (SC1) was situated at the downstream end of Boycetown River near the catchment outlet to the River Boyne (see Figure 9). The bed material at this location was found to be coarse gravel and cobble with the bank material comprising silt and clay (soil). The rivers planform at this location was straight likely due to previous engineering modifications (realignment). Other visible modifications were also observed including small bed checks within the channel (cobbles/boulders). Observed sediment production at the location was mainly occurring from bank erosion caused by cattle poaching with some evidence of likely runoff from adjacent pasture. No discrete accumulations of sediment were observed in the bed of the river but it was noted that some storage is present in the vicinity upstream of the observed small bed checks.

Sediment production caused by fluvial action and cattle poaching is considered to be the dominant geomorphological process operating in this reach. It is assumed that a mixed sediment load is supplied from upstream given the catchment setting, and that there will be some exchange of bed material during sediment-transporting flows. Sediment storage on the bed may be enhanced by bed checks, which also probably reduce rates of bed erosion. These observations align well with categories calculated by the risk mapping tool for ‘Total Sediment Production’, ‘Deposition Risk’ and

‘Sediment Export’ however the predicted geomorphic context category of ‘Balanced Transport’ was found to be inaccurate at this location.

Figure 9: (a) View of the Boycetown River at spot check location SC1 facing upstream near its confluence with the River Boyne (b) Aerial view of spot check site SC1 with the River Boyne visible to the north and the river centreline shown in blue.

Results - Catchment sediment risk maps

A number of sites were visited across the Boyne catchment to visually access the accuracy of the CSA maps for sediment. An example of the outcome of the field validation at one of these sites located at Blundelstown, County Meath is included below.

The draft output for the catchment sediment production risk which was accessed during the field visit is shown in Figure 10 below. Only catchment sediment production risk categories at the higher end of the modelled spectrum were checked. At this location, this was assumed to reflect two shallow channels across the land surface in a set of arable fields, with the western most one curving around westwards as it runs downslope.

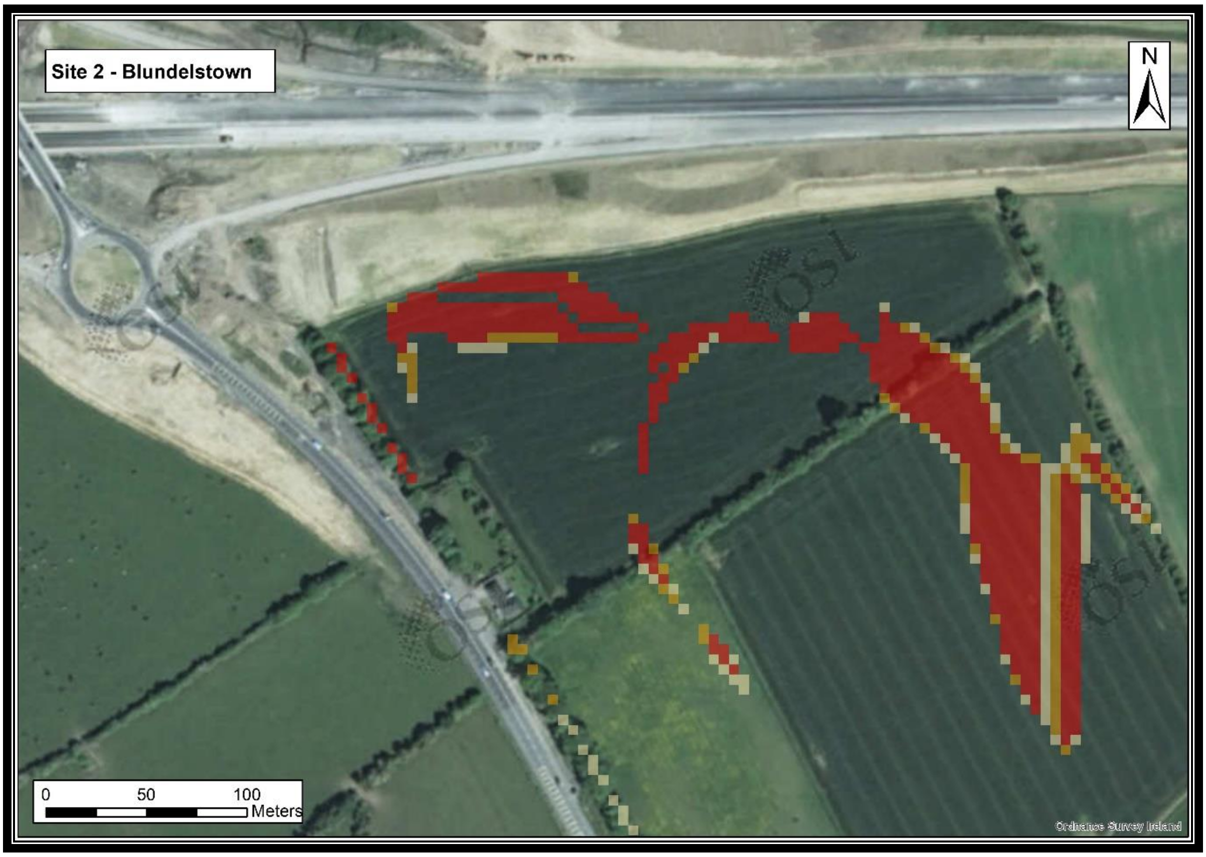


Figure 10: Field validation map for catchment sediment risk at Blundelstown, County Meath, showing modelled High (yellow), Very High (orange) and Extremely High (red) Erosion Risk classes.

On the ground, the field had only recently been sown, with fresh drills across the surface. The entirety of the soil surface was therefore exposed. It was seen that the shallow channels of the Digital Elevation Model (DEM) captured by the sediment risk maps were indeed very shallow, and almost imperceptible, even with no crop cover. This reinforced the assertion that the model seems quite effective at extracting subtle changes in land elevation and gradient in risky areas. From visual inspection, it was observed that the freshly ploughed soil was vulnerable to erosion during rainfall events and that sediment-laden water would flow across such bare, stripped ground very rapidly during intense rainfall events following the general line predicted by the risk maps. However, it was noted elsewhere across the catchment that whilst the erosion risk was evident at this particular site, when the land has vegetated over during the growing season almost no erosion risk will remain and thus the temporality of the maps should be captured going forward. The maps were therefore found to be quite accurate at identifying areas which are risky for sediment loss should the required conditions allow for erosion.

Results - Sediment fingerprinting

Sediment fingerprinting is a cutting-edge analytical technique to determine the proportional contribution of diffuse catchment sources to fine sediment stored and transported in rivers. In river basin sediment and contaminant mixing applications, the main parameters of interest are the proportions that each ‘source’ contributes to a downstream ‘mixture’ within a river network in which sources and mixtures are nested within the river basin and its sub-watershed structure. The method has been shown to provide a useful evidence base to support engagement of stakeholders and implementation of sediment management decisions (e.g. Walling and Collins, 2008; Blake et al., 2012). Sediment fingerprinting relies upon identification of statistically significant differences in soil properties between target catchment sediment sources which can occur due to a range of natural and anthropogenic processes generally linked to the geological substrate, cultivation practice and pollution.

Field sampling was undertaken within the Boycetown Catchment in November 2021. Channel bed sampling was undertaken at targeted strategic sites within the sub-catchment. Catchment based terrestrial sources were identified through field reconnaissance and land cover mapping techniques, with the aim of collecting samples to represent the major land cover types within each sub-catchment. Within the Boycetown these were: channel banks, pasture, arable, forestry and road runoff. Samples were collected, stored, prepared and analysed following standard sediment fingerprinting techniques with subsequent sediment source tracing modelling conducted by the Catchment and River Applied Research (CaRAR) group at the University of Plymouth. Modelling followed a channel source-receptor approach whereby upstream channel beds were sampled and modelled as discrete sources to a downstream receptor site. In addition, separate models were used to identify key land cover sources to these upstream channel bed sites. Results indicated that stored sediment in the downstream receptor site was most likely derived from material in the main channel of the sub-catchment, and that this material was likely to be derived from channel banks. These results must be treated with caution however as they are based on a single sampling campaign and it is therefore not possible to account for temporal variability in sediment source contributions across the year.

Figure 11: A view of a location where sediment bed sampling was undertaken in the townland of Culmullin, which is the upper portion of the Boycetown Catchment

References

Blake, W.H., Ficken, K.J., Taylor, P., Russell, M.A. and Walling, D.E. (2012). Tracing crop specific sediment sources in agricultural catchments. Geomorphology, 139, 322–2.

LAWPRO (2020). Boycetown Priority Area for Action: Desk Study Summary. Available online from https://catchments.ie/wp-content/files/areaforactionreports/AFA0027%20Boycetown%20AFA%20Report.pdf

Meehan, R. T. (2020). Conceptual models of substrate sequences in Irish catchments, Unpublished report prepared for the Irish Environmental Protection Agency, Johnstown Castle, Wexford, Y35 W821

Parker, C., Thorne, C. R., and Clifford, N. J. (2015). Development of ST:REAM: a reach-based stream power balance approach for predicting alluvial river channel adjustment, Earth Surface Processes and Landforms, 40, 403-413, https://doi.org/10.1002/esp.3641

Reaney, S., Milledge, D., Lane, S., Heathwaite, A., Shore, M., Melland, A., and Jordan, P. (2011).: Understanding nutrient connectivity at the landscape scale: The use of the SCIMAP approach in the UK and Ireland, AGU Fall Meeting Abstracts, 1157

Walling, D.E. and Collins, A.L. (2008). The catchment sediment budget as a management tool. Environmental Science and Policy, 11, 136-143

5. Mullantra and Descart Source Protection Zones.
Peter Conroy

Introduction and background

Robbie emailed me back in June to see if I would talk to other people about a groundwater supply in a small bit of An Cabhán. I was dressed as a pirate at the time, so my natural response should have been “Aaaaar(gh)!”. Ar an droch uair I accidentally said “Aye!” which Robbie took as acquiescence on my part, and the rest as they say is history.

And history is in fact the appropriate setting for this extraordinary tale of derring do … the story of two not so young anymore young men but who were relatively young at the time in summer 2010, galivanting about Cavan looking under every drumlin for a good cup of coffee and accidentally ending up in the King’s court with that most precious of commodities … cocai … I mean uisce.

Cutting to the chase (won’t happen again), all of this happened a long time ago and some of it is made up … I mean assumed … no, I mean professionally judged … tumbleweed …
… the beginning

Stardate 20100708, Captain’s log: Having recently been relieved of my command aboard the EUSS Starship Entertobin, I find myself in some inhabited corner of Cavan piloting a much smaller enterprise while trying to do exactly the same work as I did before, as a consultant to the Intergalactic Federation of Geological Surveys, abbreviated GSI after the French.

I reach into my satchel … searching … reassured as I thumb through the collection of hydrogeological essentials therein … a paper map, a hand lens, an orange (and a second orange for lunch), string covered in chalk dust, a geological hammer in a glass case printed with the words “for use in emergencies”, toilet paper in a glass case printed with the words “for use in emergencies” … until I find it … The BOOK OF NERDO (1981 Edition): Knower of all knowledge you will ever need to know about groundwater resources in the Northeast Development Region.

Exhaling, I relax as I absorb the gentle whisper of advice scrawled in red ink and highlighted in fluorescent yellow on the front cover, more of a shout really:

“Don’t Panic … no one will do anything with your report anyway”.

I jump straight to the dog-eared page 128 … Mullantra … Triassic Sandstone Aquifer … a useful water supply for the area. Could it really be true? Useful <u>and</u> in Cavan? Tri-a-sic joke more like. No, I must have faith … all is well.

Coming to my senses I consult the GSI Protocol and realise a series of testing challenges lie between me and my goal. Easy Peasy Lemon Squeezey Topography and Surface Water Features From A Map. Easy Geology From A Book. Tricky Structural Geology But In The End Also From A Book. Exhausting Site Walkovers And Talking To Other People From Planet Steakholders. Groundwater Levels. Aquifer Properties. The Dreaded Recharge. And of course, Spellcheck … already it haunts me … me and my gal … Damn it man, it’s a hydrogeological survey, not a 1930’s Musical … my goal and I!

I have no choice but to take each one in turn … it’s nearly half past two and I haven’t had lunch, I’m starving and there’s people holding steak everywhere distracting me with questions, stories, anecdotes, did I find oil … my eyes dart left and right … I break into a cold sweat and start whistling the theme tune from Lawrence of Arabia, his army crossing the parched desert on camelback … daaa daaa, daaa da da da daaa daaa, da da da da dummm … by the overflowing Well of Peter O’Toole’s Enthusiasm … may we all still be awake on the other side … FAAAWW … THERRRR … Zzzzzzz …. tumbleweed … cut

So … **<u>Mullantra</u>**, Co. Cavan – aka – Sragh or Mulla an t-sratha …

- given as “summit of the holm” in Loganim.ie;
- mullach given as top or summit on teanglann.ie;
- sratha (plural of srath) given as river valley or low-lying land along river on teanglann.ie;
- holm given as (Physical Geography) an island in a river, lake, or estuary, or low flat land near a river on thefreedictionary.com.

The groundwater supply source of interest here is BW01, on the eastern boundary of Mullantra.

Figure 12 shows the topographic map with a few additional layers of data overlain.

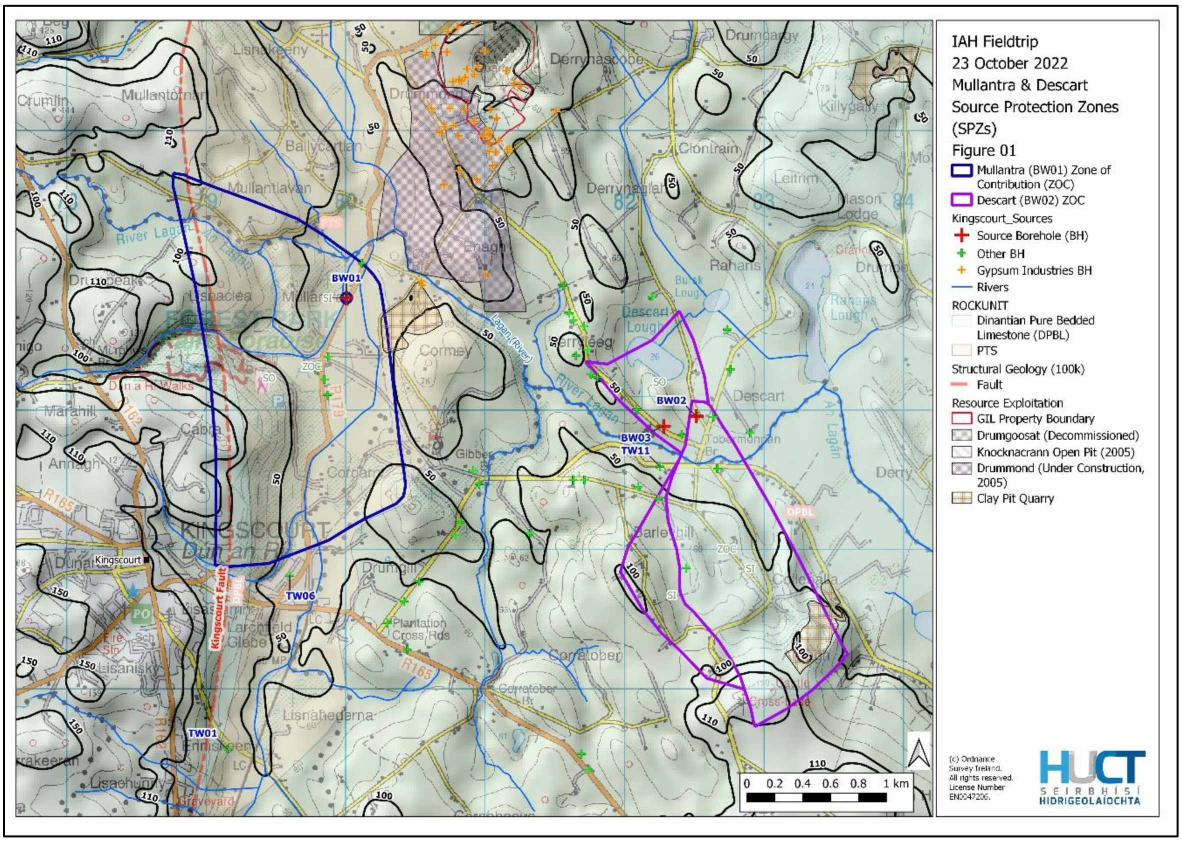


Figure 12: Topography and Surface Water Features of the Mullantra area.

- High ground above 110 mOD to the west of the Kingscourt Fault (… more on this to follow).
- Ground drops to below 50 mOD west of the fault, with drumlins rising to 70 m to 80 mOD. Regional gradient is to the east. Ground level at BW01 is 34.63 mOD.
- Surface water features drain eastwards off the high ground.
    - Main watercourse is the River Lagan predominantly trending WNW to ESE across the northern half of the map. It takes a meander around the "Summit of the Holm" between the fault and BW01, veering south first and then north, with the northwards leg passing by the western boundary of the BW01 site.
    - The Cormey Stream comes off the high ground in the south of Figure 01, then flows north along the low ground parallel to the fault, passing to the west of BW01, to join the Lagan a bit NNW of BW01.
    - Drainage density is high, with lots of rushes suggesting poorly drained soil.
- Development Features:
    - Old Lagan Bricks Clay Pit to east of BW01, on eastern side of Cormey Stream.
    - Gypsum Industries Opencast & Underground Mine to NE, north of River Lagan.
- Landuse is mainly agricultural. Some residential use and a golf course all with private wells.

Geology mainly from the Memoir (Sheet 13), Gardiner & McArdle (1992) & Minerex (2010).

Table 1: Main Relevant Bedrock Descriptions (See also Figure 13 Geology)

Generalised Rock Unit Classification	***Geological Description***	***Max thickness (m) (Geraghty & McConnell ,1999)***
Permo-Triassic Sandstones (PTS)	Siltstone unit 80 to 100 m thick overlain by up to 300 m of thickly bedded, cross-laminated sandstones.	400
Permo-Triassic Mudstones & Gypsum (PTMG)	Mudstone with Gypsum and Anhydrite units	120
Namurian Undifferentiated (NU)	Interbedded Sandstones and Shales.	Approx. 420
Namurian Sandstone (NSA)	(Carrickleck Sst Mb) Buff coloured sandstone	~ 60 (in Carrickleck Fmn)
Namurian Shales (NSH)	Ardagh black shale, contains minor limestone beds.	150
Dinantian Pure Bedded Limestones (DPBL)	Micrite, crinoidal grainstone/ packstone with localised chert. Some thinly bedded argillaceous limestone. Extensively dolomitised in parts.	> 850
Silurian Metasediments and Volcanics (SMV)	Dark, quartz, greywacke conglomerate	unknown

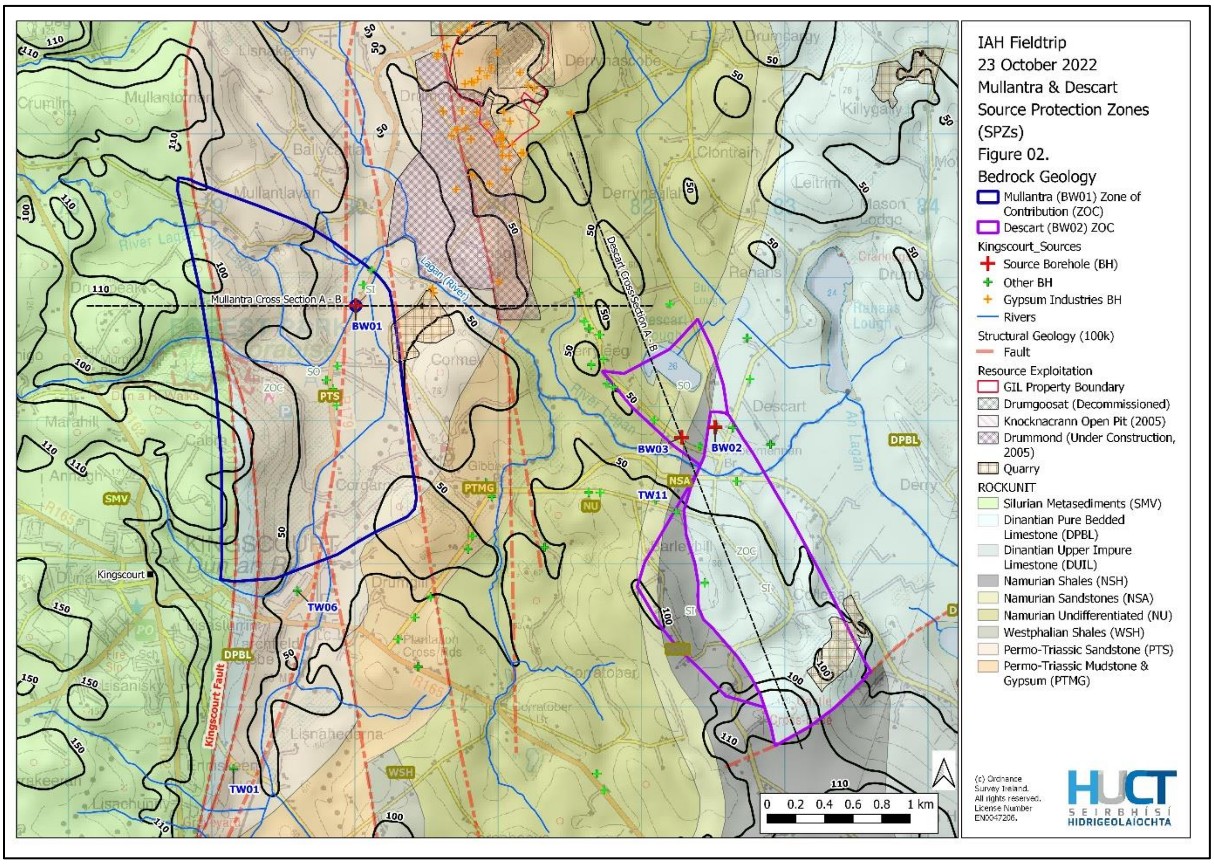


Figure 13: Bedrock Geology of the Mullantra area.

- Borehole BW01 Geology (*total depth 120 m)*:
    - 38 m of till overburden
    - underlain by 4 m of hard grey-green sandstone (38 to 42 mbgl)
    - underlain by 78 m of soft red mudstone which gradually becomes red sandstone.
- 1979 trial well 13 m from BW01 (*NERDO BH C35/3c, now destroyed, Total depth 104 m*):
    - 48 m overburden
    - Underlain by 7 m Triassic Marl (48 to 55 mbgl)
    - Underlain by 49 m fine grained red sandstone (55 m to 104 mbgl)
        - thin marl bed at approx. 87 m to 90 mbgl

Structural Geology (Figures 13 and 14):

- Permo-Triassic Sandstone (PTS) bounded to the west by the N-S trending Kingscourt Fault. Max downthrow to the east of approx. 2100 m (McConnell *et al*, 2001).
- Juxtaposes PTS and Silurian Metasediments (SMV), surface scarp expression up to 60 m high (Gardiner and McArdle, 1992).
- The bedrock strata dip westwards towards the fault at approximately 10 degrees, producing a half-graben structure (Gardiner and McArdle, 1992).
- Further faults to the east of and parallel to the Kingscourt fault, have throws of up to 150 m in the opposite direction.
    - BW01 fault passes 70 m west of borehole BW01
    - Clay pit fault passes 275 m east of the borehole at the clay pit
- The pattern of faulting results in a wedge shaped block of sandstone (NERDO, 1981).
- Gypsum Ltd. borehole 03A (at Cormey Bridge) – faulting likely to juxtapose PTS and PTMG at depth to the east of borehole BW01.
    - Likely that these faults will have a low permeability “gouge” of fine grained, ground-up, marl bedrock fragments at gypsum horizons on the upthrow side of the fault (NERDO, 1981).
    - The “clay pit” fault just west of borehole 03A would be an example of this condition.
    - The clay pit at Cormey Bridge probably resides in an outcrop of the PTS’s basal siltstone unit, which overlies the gypsum formation on the eastern side of the fault.
- Southern part of the study area – PTS bedrock is dominated by siltstone/mudstone.
- E-W Geological Cross Section through BW01 (Figure 03).

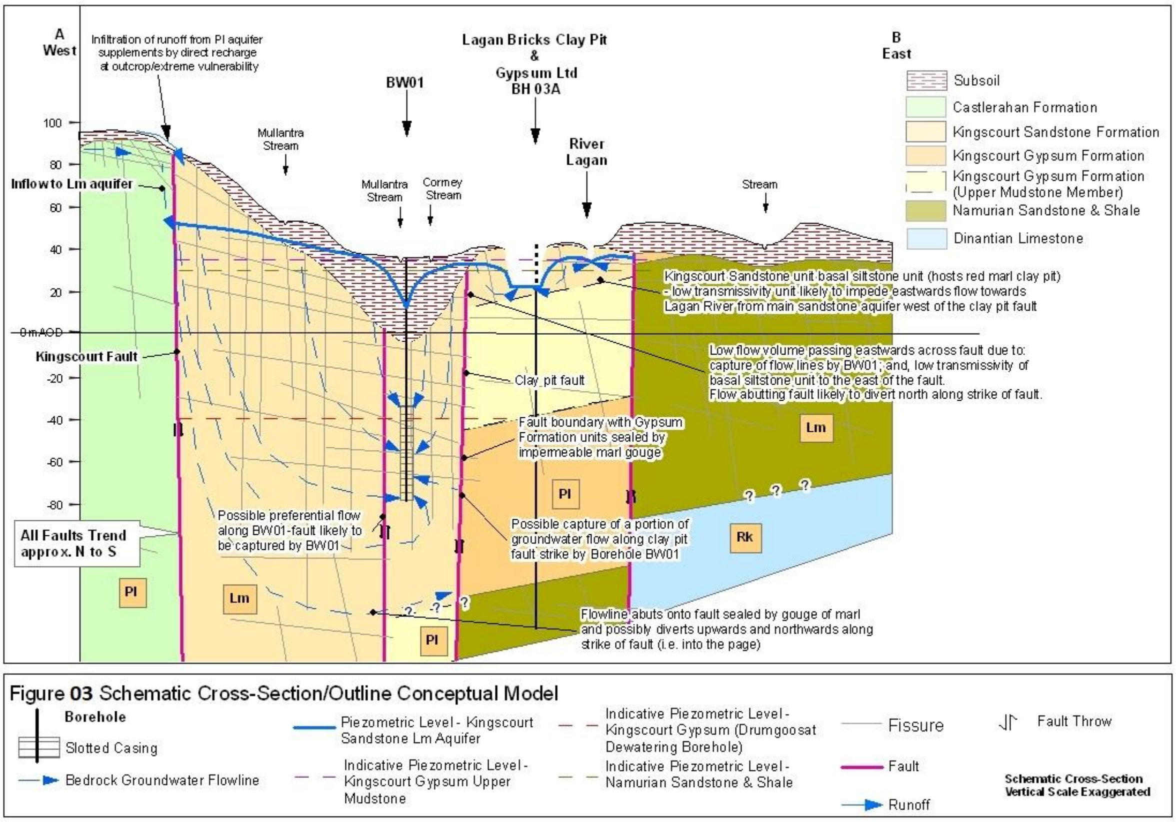


Figure 14: Cross Sectional, Structural Bedrock Geology of the Mullantra area.

Soil & Subsoil Geology (Figure 15)

- Soils surrounding the source are predominantly deep alluvial mineral soils derived from non-calcareous parent material, and are generally deep and poorly drained.
- BW01 is located within an area of alluvium, among drumlins underlain by till derived from Lower Palaeozoic shales and sandstones (TLPSsS) (Meehan, 2008). Glaciofluvial gravels, derived from shale and sandstone, flank the River Lagan 400 m to the north-northeast.
- Due to their predominantly shale parent material and hence relatively high clay and silt content, the alluvium and the till are of moderate to low permeability (Meehan, 2008).
- Borehole logs that intersected alluvial deposits &/or till to the east and south of borehole BW01, and from Gypsum Industries boreholes, show a predominantly clay subsoil.
- Where alluvial deposits are logged (boreholes BW01 and C35/3c) they are recorded to be underlain by significant thicknesses of till (boulder clay).
- The overall permeability of the subsoil column below the mapped areas of alluvium is therefore likely to be ‘low permeability’.
- DTB a generally exceeds 10 m and can be as much as 48 m.

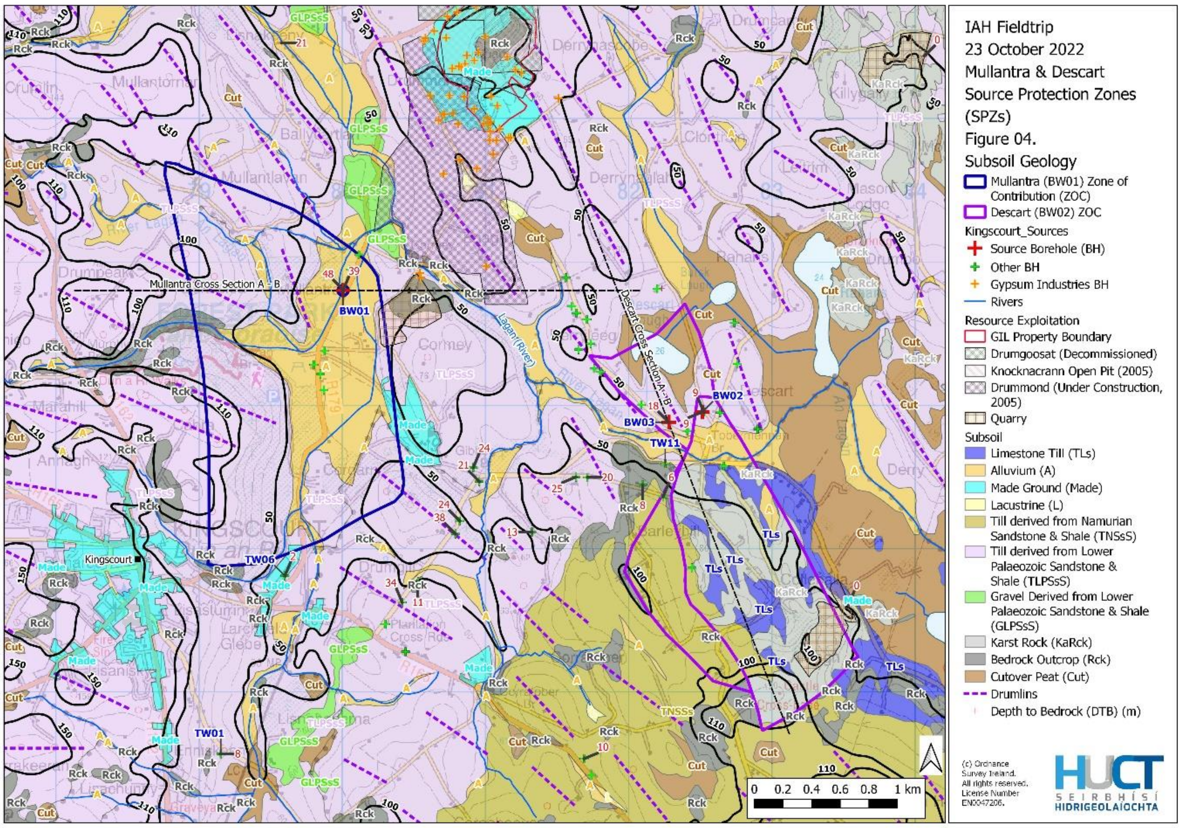


Figure 15: Subsoils Geology of the Mullantra area.

Groundwater Vulnerability (See SPA Figure 26)

- Borehole BW01 is surrounded by a large area of low vulnerability.
- At the Kingscourt Fault scarp, bedrock outcrops are mapped as extreme vulnerability grading outwards into high, moderate and low vulnerability moving away from the outcrop sites.
- Other areas of extreme vulnerability occur at the Lagan Bricks clay pit; Drummond mine; along the Lagan River; to the southeast of the source at Barley Hill; and, along the north bank of the River Lagan in the townland of Mullantlavan upstream of borehole BW01.
- Generally high and moderate vulnerability areas, depending on the DTB, to north of River Lagan, and to the southeast of the source in the Drumgill – Corgarry area.

Mullantra Source Borehole Details: BW01

The BW01 well details (below) are derived from various KT Cullen & Co Ltd. And WYG hydrogeological investigation reports and accompanying borehole logs prepared between 1996 and 2003. The borehole was commissioned in 2009 and Cavan County Council advises that it began supplying water to the scheme in January 2010.

Recent SCADA info from Cavan CoCo indicates that current abstraction is approximately 300 m^3/day at a discharge rate of 20 m^3hr (i.e. approximately 15 hours per day) (see screenshots).

	BW01 (a.k.a. TW5, PW5)
Grid ref. (GPS)	X: 280006 Y: 297801
GSI Well Database Reference No.	2629SEW503
Townland	Mullantra
Source type	Borehole
Drilled	1995 (Commissioned in January 2010)
Owner	Cavan County Council
Elevation (Ground Level)	34.63 mAOD
Depth (m)	120
Depth of casing	300 mm steel casing at 0 m to 70 mbgl 200 mm steel casing at 0 m to 70 mbgl and 113 m to 120 mbgl, as part of casing/well screen string. 200 mm galvanised well screen, 0.4 mm slot aperture, at 71 m to 113 mbgl, as part of casing/well screen string.
Grout Seal	Cement grout seal installed between the 200 mm and 300 mm diameter steel casings from 0 m to 70 mbgl
Diameter	200 mm
Depth to rock	38 m
Water Strikes (mbgl)	28 m, 40 m, multiple increases from 74 m to 115 m.
Static water level	0.35 mbRef(1) (24/02/2003; 34.28 mAOD), (WYG, 2003)
Pumping water level	Min PWL varied between 21.91 mbRef and 23.34 mbRef between 03 & 10/09/2010(2) (12.72 mAOD to 11.29 mAOD respectively)
Consumption (Co. Co. records)	375 m^3/d
Pumping test summary: (i) abstraction rate m^3/d	635 m^3/d & 735 m^3/d
(ii) specific capacity	14.8 m^3/d/m @ 635 m^3/day (1995, 10 day test after drilling) 18.3 m^3/d/m @ 735 m^3/day (2003, 6 week test)
(iii) transmissivity	21 m^2/d (based on 1995 data)
(iv) storativity (3)	0.00017 (1.7E-04) (based on 1995 data)

Note 1:Level at start of WYG pumping test on 24/02/2003. Ref point not recorded. Assume = top of 200 mm steel casing.

Note 2:Ref = top of 200 mm diameter Steel Casing = 34.63 mAOD (i.e. same as Ground Level).

Note 3: Storativity (S) of a saturated confined aquifer of thickness D is the volume of water (m^3) released from storage per unit surface area (m^2) of aquifer per unit decline in hydraulic head (m). It is the specific storage x the aquifer thickness (i.e. $S = S_s \times D$). As Storativity involves a volume of water per volume of aquifer, it is a dimensionless quantity. Its values in confined aquifers range from 5E-05 to 5E-03.

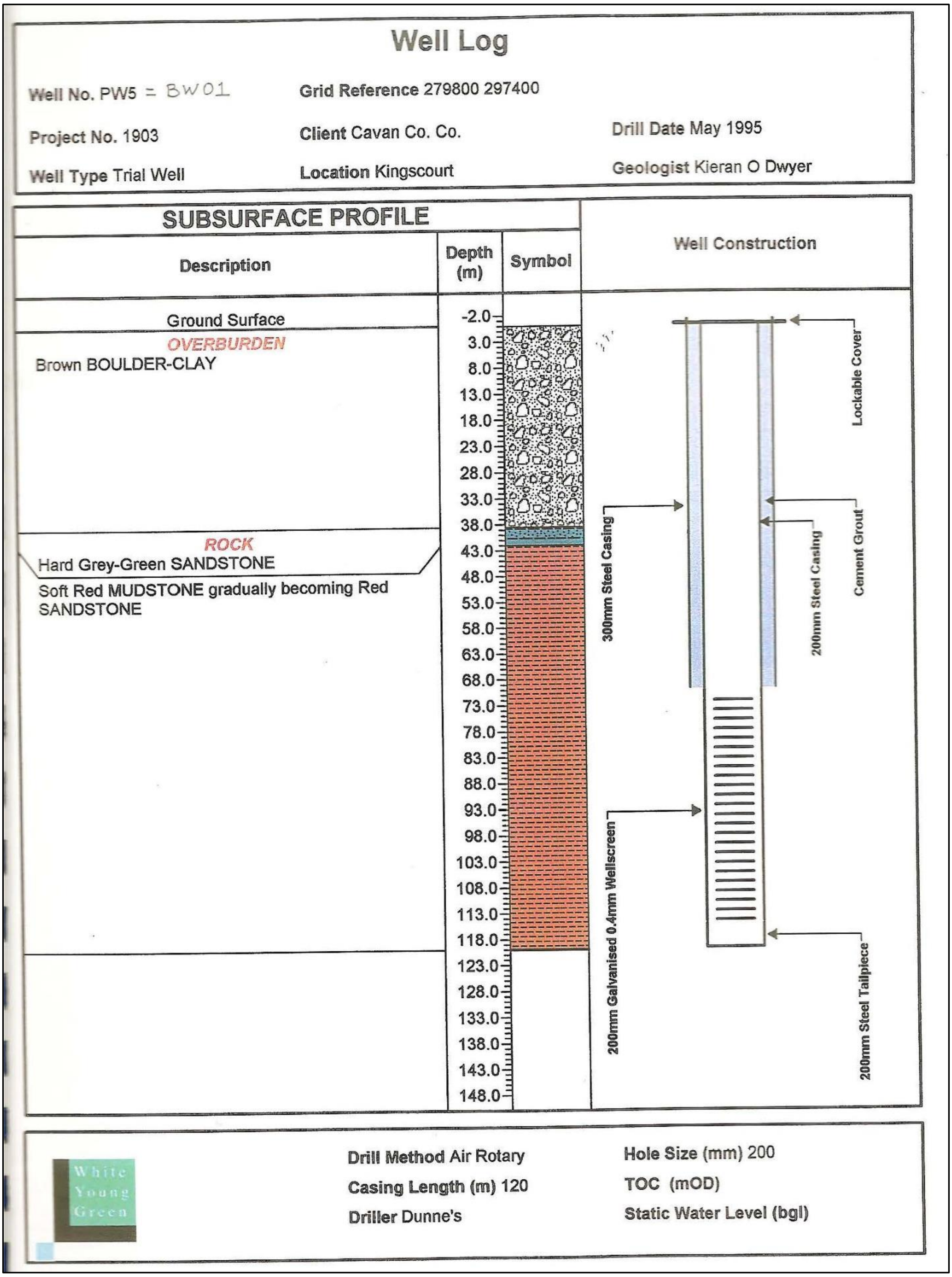


Figure 16: Log of Borehole BW01 at Mullantra.

<u>BW01 Drilling Experience</u>

The BW01 drilling conditions were particularly difficult and necessitated using drilling mud as the flushing medium. The sandstone was composed of fine particles and no chippings were returned. The well drilled like a very hard clay (KTC, 1996).

Borehole BW01 Groundwater Level Data (Figures 17 and 18:

- Hydrographs of water level data for borehole BW01:

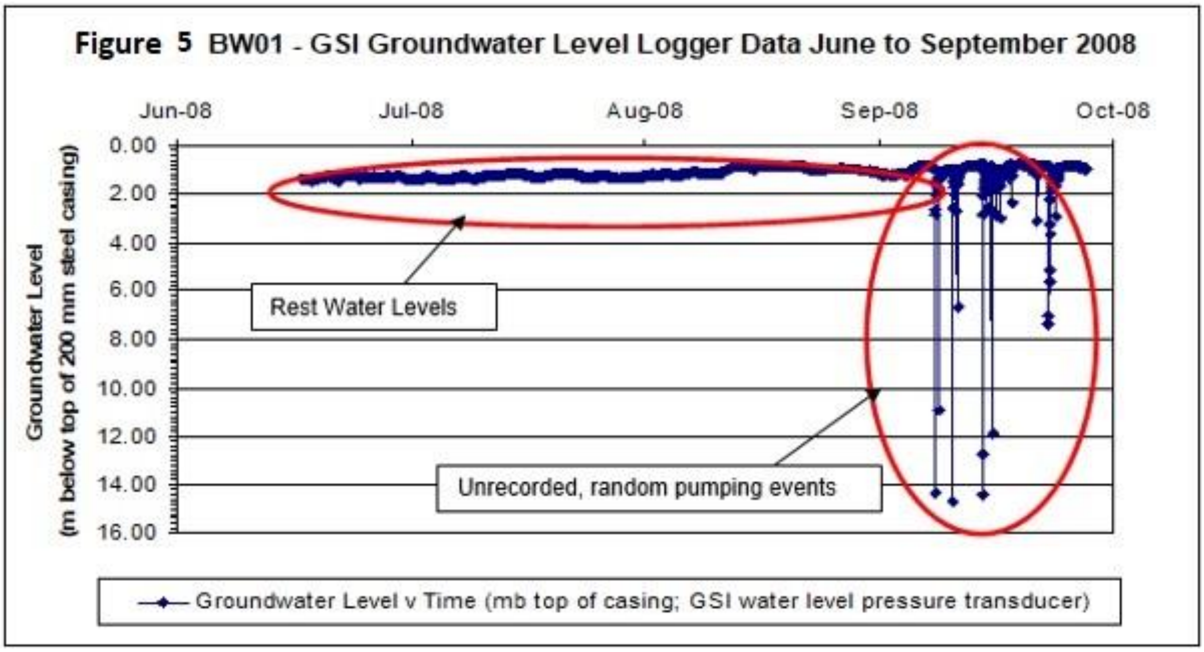


Figure 17: Water level data from BW01, 2008.

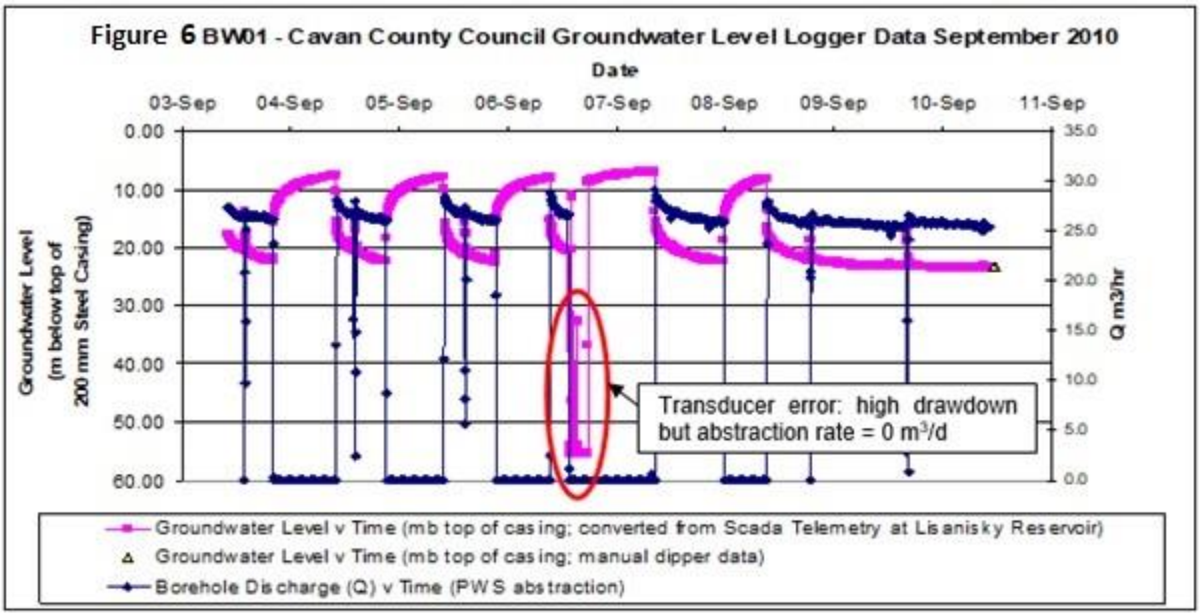
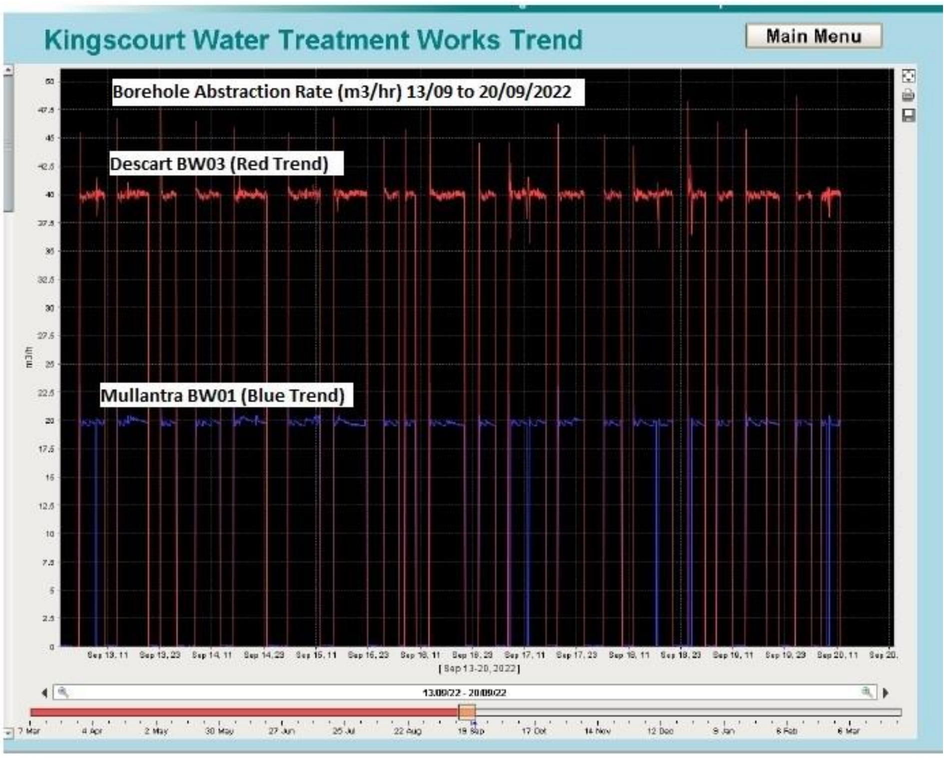


Figure 18: Water level data from BW01, 2010.

- Under the current pumping regime, the borehole does not recover to the aquifer rest water level between pumping periods (Figure 18).
  - Pumping test data for the borehole from March and April 2003 suggest that recovery to close to the rest water level can take up to 4 days following prolonged abstraction.
- Current minimum pumping water levels in the borehole vary between 21.91 mbRef and 23.34 mbRef (Figure 18).
- Pumping test data for a higher pumping rate between 864 and 980 m^3/day resulted in a water level of 48.6 mbRef (WYG, 2003).

- Recent Scada Abstraction & Groundwater Level Data shown in the screenshots below (provided by G. Boyd, Cavan CoCo.)



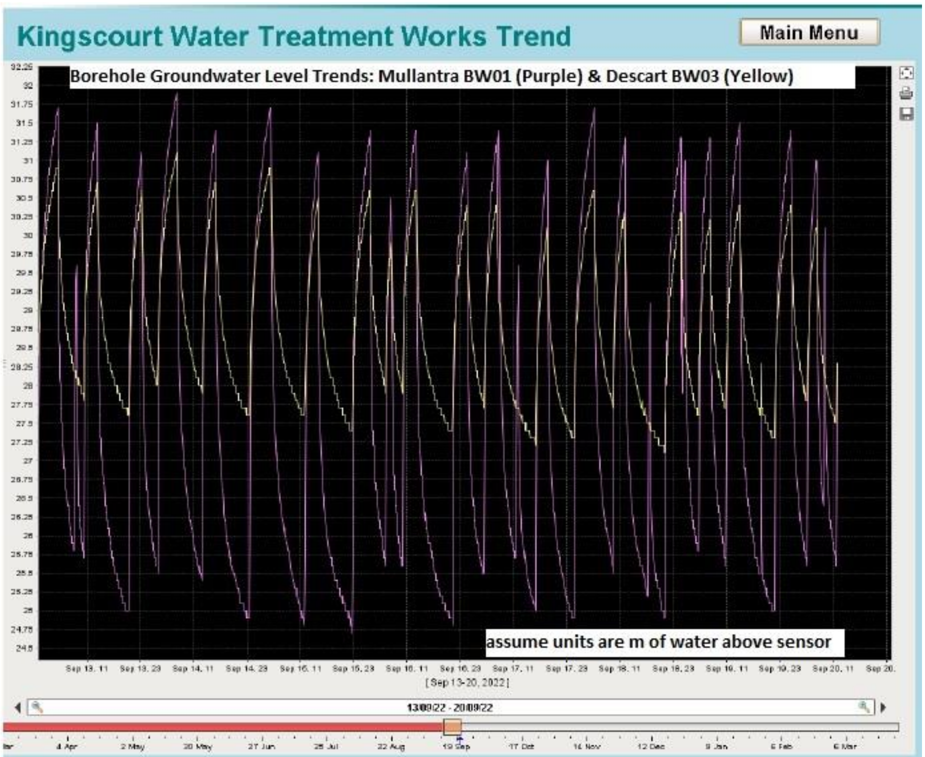


Figure 19: Scada Abstraction and Groundwater Level Data, September 2022.

BW01 pumping water level remains above the top of the well screen (70 mbgl) and above the top of the bedrock aquifer (39 mbgl).

Rest water level data at boreholes BW01, and the nearby PTS boreholes C35/3c, BH05 and TW01, show that the bedrock aquifer piezometric level is generally above the base of the overlying low permeability overburden material.
Hence the PTS aquifer is considered to be confined by the low permeability overburden.

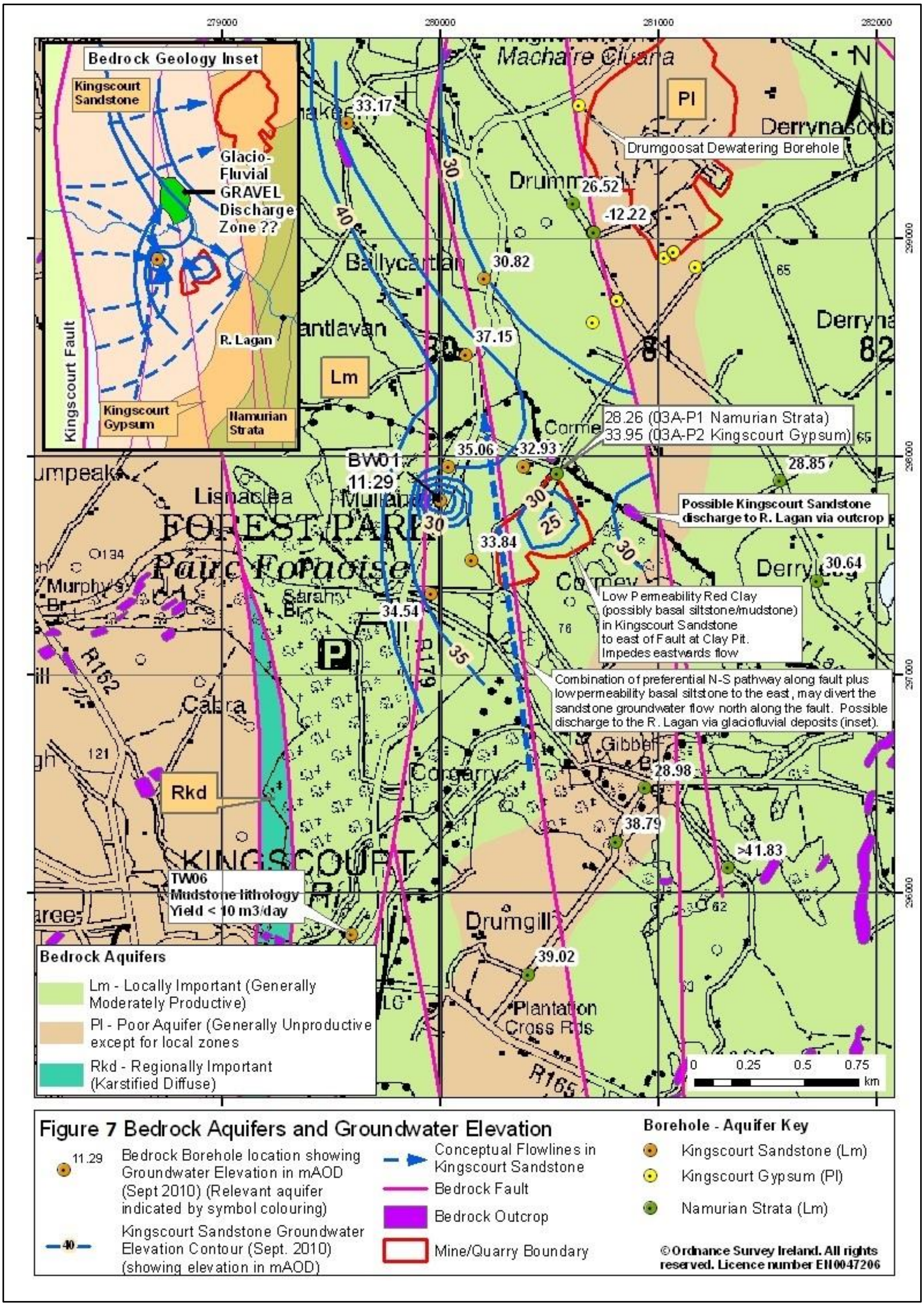


Figure 20: Mullantra Groundwater Levels, Flow Directions, Gradients and Aquifers.

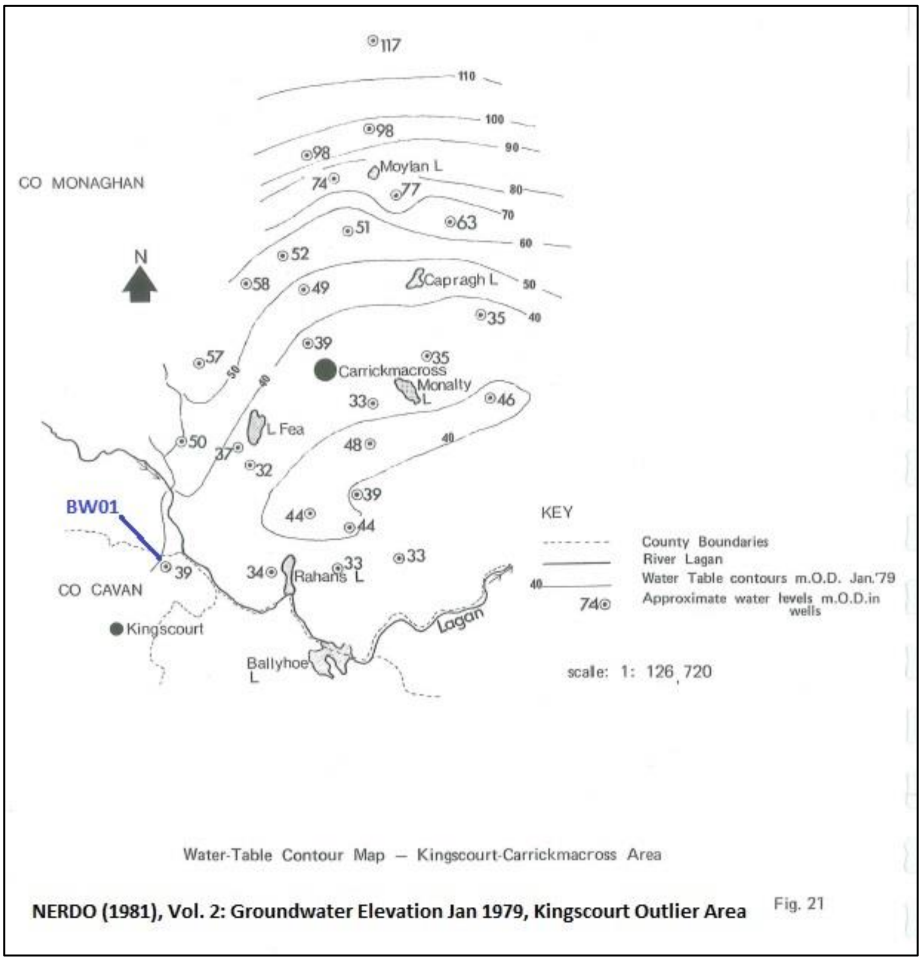


Figure 21: NERDO GW levels, January 1979, Kingscourt Outlier.

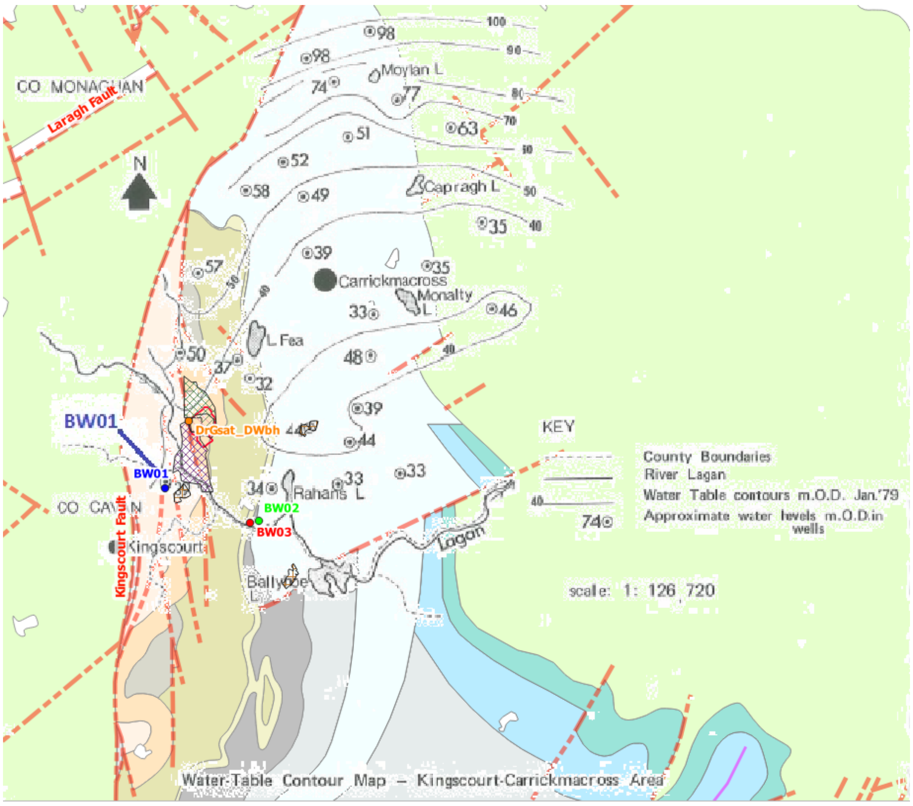


Figure 22: NERDO (1981) (Vol. 2) Groundwater Elevation Contour Map for January 1979 showing underlying Rock Unit Map (drawn at 1:100,000 scale).

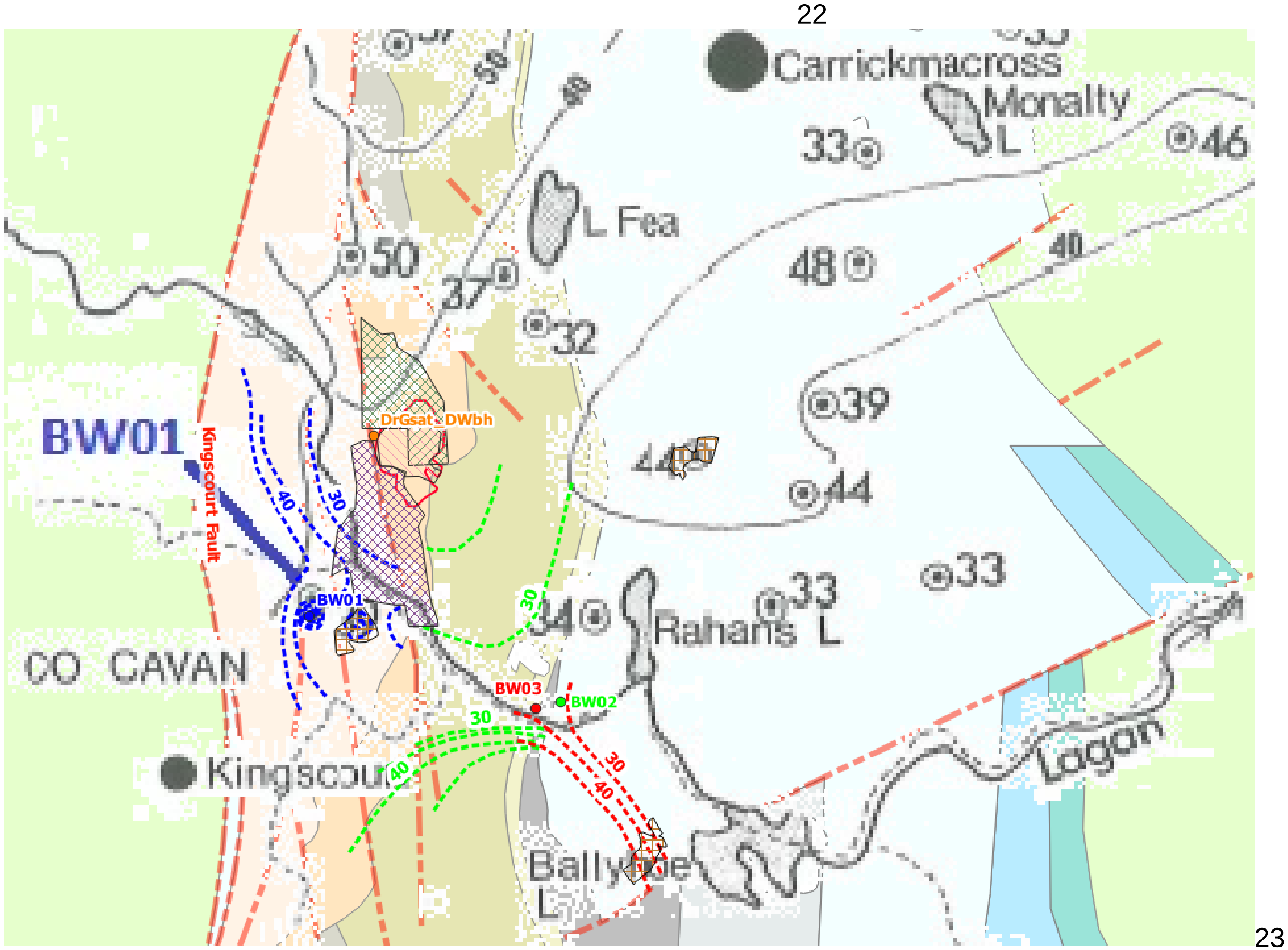


Figure 23: Mullantra and Descart Groundwater Elevation Contours of September 2010 overlain on NERDO (1981) Groundwater Elevation Contour Map for January 1979, showing underlying Rock Unit Map (drawn at 1:50,000 scale) – comparison of groundwater elevation contours from 2010 with those from 1979 gives an idea of drawdown of regional groundwater levels in the area by dewatering for the gypsum mining activities.

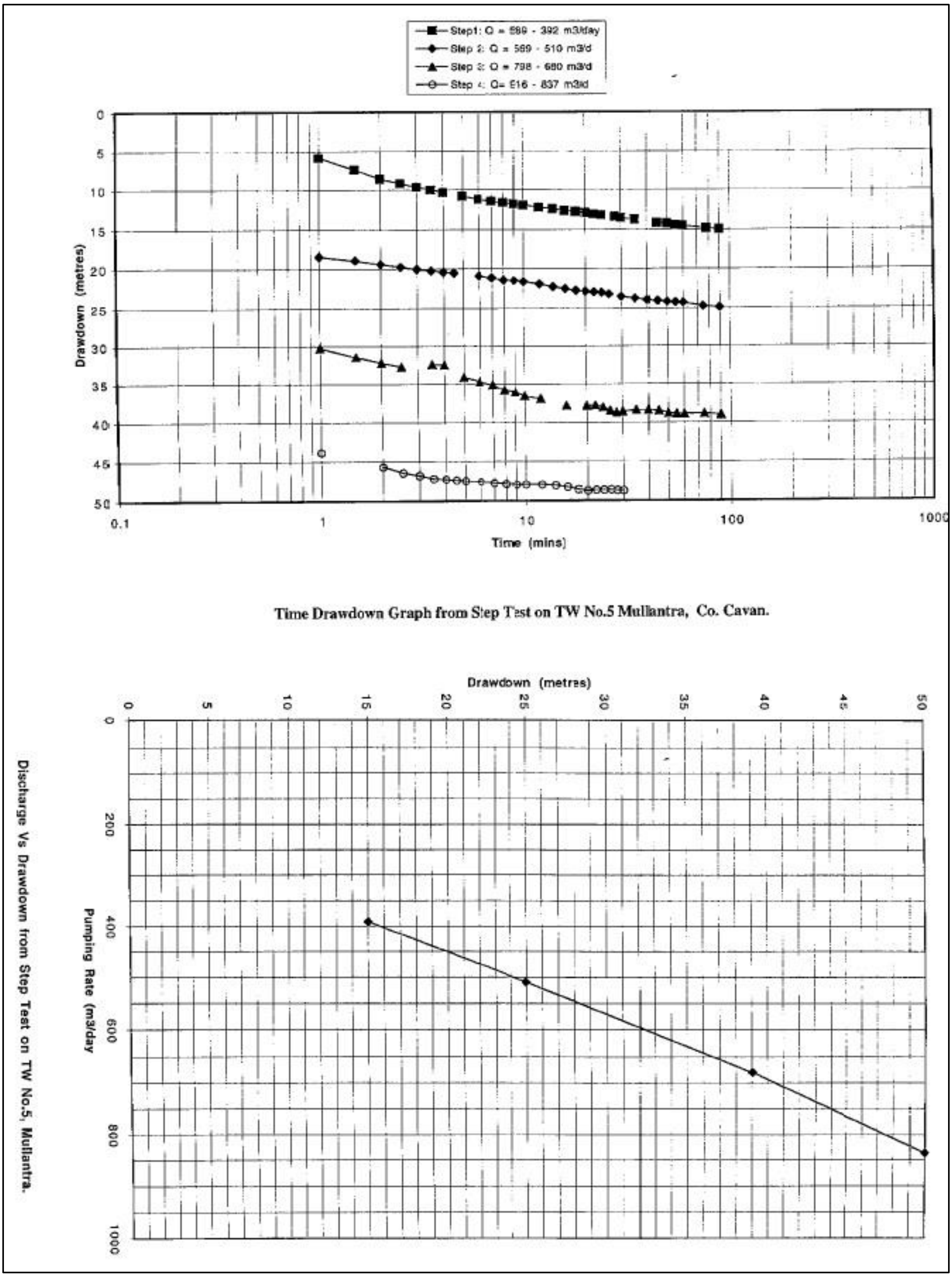
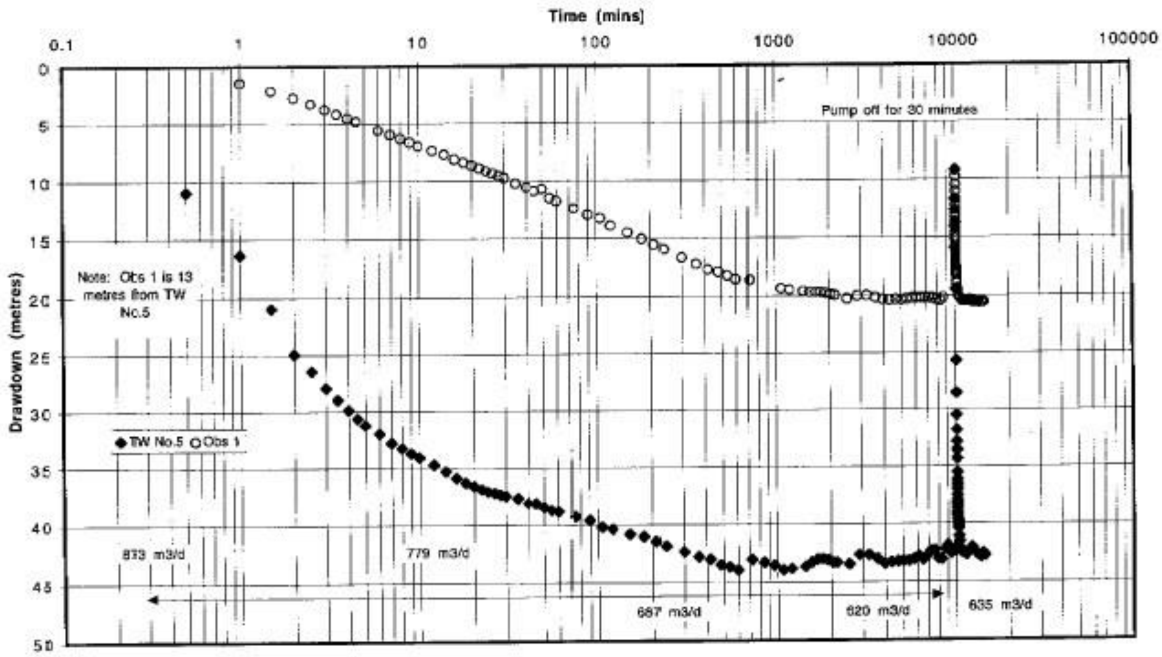
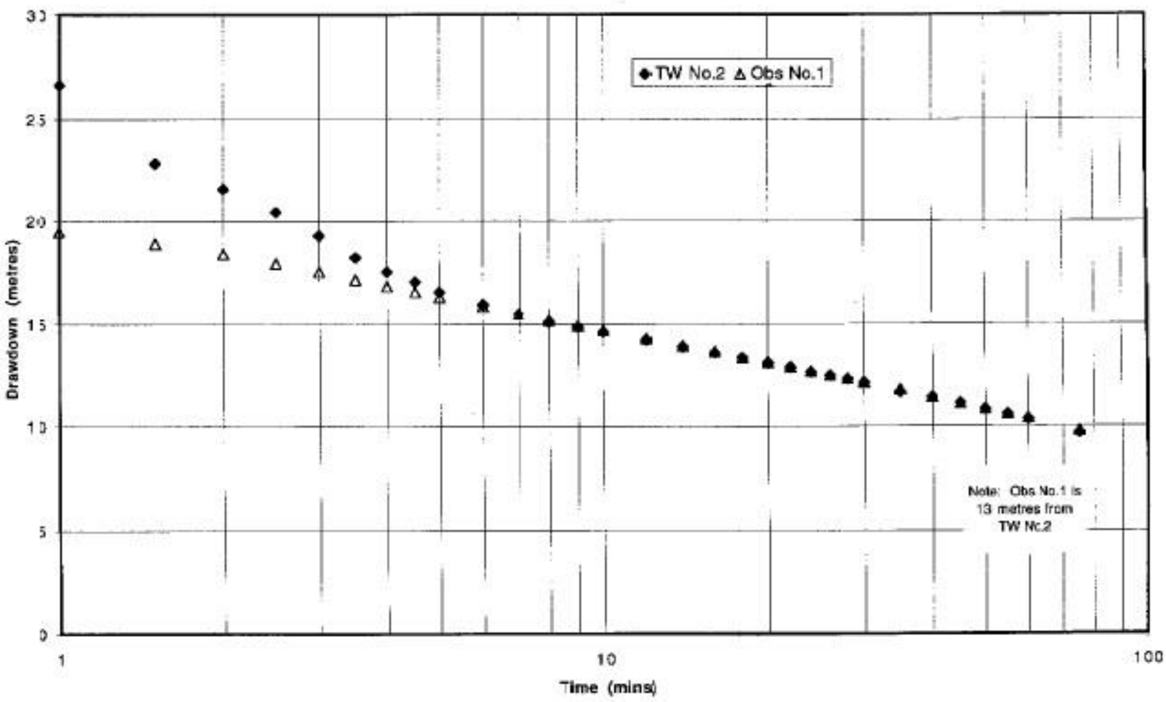


Figure 24: BW01 (a.k.a TW5) Time-Drawdown Graphs (KTC, 1995), Step Test Graph



Time Drawdown Data from 10 Day Test on TW No.5 (Mullantra), Kingscourt.



Recovery Data after 10 Day Test on TW No.5 (Mullantra), Kingscourt.

Figure 25: BW01 (a.k.a TW5) Time-Drawdown Graphs (KTC, 1995), 10 day Constant Rate Test Graph.

Mullantra BW01 Hydrogeological Conceptual Model (see cross-section in Figure 14)

Borehole BW01 abstracts water from the PTS rock unit *Lm* aquifer. The majority of the sandstone aquifer footprint is confined by the overlying, low and moderate permeability subsoil deposits. It is mainly recharged at areas of bedrock outcrop and extreme vulnerability along the Kingscourt fault scarp to the west of the borehole. These areas have a limited areal extent which in turn limits direct rainfall recharge. The direct recharge will be supplemented by runoff from the *Pl* aquifer to the west of the Kingscourt fault. There may also be a small component of leakage into the sandstone aquifer from the adjacent Silurian *Pl* aquifer, from the area immediately west of the fault. Recharge to the east of the scarp in the confined reaches of the aquifer is likely to be minimal due to the low permeability subsoils and the impedance resulting from the upwards pressure of the confined aquifer (drawdown may induce some limited additional recharge).

Interpreted groundwater elevation contours suggest groundwater flow is generally eastwards from the fault scarp towards borehole BW01 with a lateral gradient of 0.038. Borehole BW01 will capture groundwater flowing eastwards from the fault scarp. It may also capture a component of any preferential northwards flow in possible preferential flowpaths along the BW01 and clay pit faults.

The sandstone aquifer appears to be isolated from the gypsum aquifer by the low permeability basal layer of the sandstone and upper strata of the gypsum. Where the two aquifers are juxtaposed by faulting the gypsum appears to be sealed off by a low permeability “gouge” of marl.

Apart from PWS abstraction (south of the river) and mine/quarry dewatering (north of the river), the River Lagan is likely to be the main discharge boundary for flow in the sandstone aquifer; however the aquifer seems to be sealed off from much of the relevant river reach by thick low (to the south) and moderate (to the north) permeability subsoil. The sandstone aquifer groundwater elevation contours suggest that the natural discharge zone for the aquifer would be at the bedrock outcrop in the river bed at, and east of Cormey Bridge. These outcrops are situated in the area where low transmissivity basal siltstones of the sandstone aquifer form bedrock. The low transmissivity of the bedrock will limit the flow through this part of the bedrock aquifer and consequently the magnitude of the discharge to the river via this pathway. Groundwater flow volumes and aquifer transmissivity are also low in the south of the study area around borehole TW06.

It is assumed here that the BW01 and clay pit faults are transmissive along strike and that a large component of the eastwards flow reaching the faults gets diverted northwards along the strike. The northwards flow is then assumed to discharge to the river *via* a window through the thick till subsoils. The window is provided by the mapped glaciofluvial gravel deposits adjacent to the north bank of the River Lagan and which overlie the fault zones (BW01 fault passes slightly west of the gravels). Abstraction at borehole BW01 may capture a component of flow in the fault zones where they pass close to the borehole.

Speculation: If this pathway does exist, then groundwater abstraction (e.g. BW01) could potentially drawdown the groundwater pressure in the fault and induce leakage from the River Lagan/ gravels deposits into the preferential pathway along the fault to the borehole.

North of the river, the contours suggest that much of the flow in the sandstone is diverted north towards the gypsum mine by the mine dewatering.

The water has a calcium bicarbonate signature with a significant magnesium component. There is no evidence of elevated sulphate concentrations at the borehole. This suggests there is no inflow from where the Kingscourt gypsum formation underlies the site or is laterally adjacent to the east. The ammonia concentrations are detectable but low. Nitrate concentrations are below the detection limits, which indicates reducing conditions in the aquifer. To date the groundwater has been unpolluted but has naturally elevated manganese levels.

Mullantra BW01 ZOC Boundaries (Figure 26)

The eastern boundary is the downgradient boundary of the ZOC. This is delineated along the western side of the clay pit fault to account for the possibility that the borehole might intercept northwards preferential flow along the strike of the fault. The surface separation between the borehole and the fault is 270 m. This is a large downgradient distance, which is three times the calculated Uniform Flow Equation (UFE) X_L Distance[2]. Nonetheless, the fault zone is considered to dip towards the borehole and as such may come in close proximity to the borehole at depth. The large downgradient distance of the ZOC takes account of this and conservatively includes the potential recharge area for the fault zone.

The northern boundary is a flow line delineated perpendicular to the interpreted groundwater elevation contours. Groundwater flow in the *Lm* aquifer on the north side of the Lagan River, is towards the Drummond mine, which creates a groundwater divide and prevents the northern boundary of the ZOC from extending further north than delineated. The northern margin of the ZOC passes beneath the Lagan River. It is considered unlikely that borehole BW01 will draw water from the river due to the generally thick, low permeability subsoils separating the borehole from the river <u>upstream of</u> Cormey Bridge and the glaciofluvial deposits.

The western boundary of the ZOC is considered to be the mapped Kingscourt Fault. A 100 m buffer zone is added to the ZOC on the western side to allow for potential leakage of groundwater from the adjacent Pl aquifer into the ZOC.

The southern boundary is delineated at the likely southern extent of preferential northern flow along the BW01 and clay pit fault zones. At its eastern end the sandstone aquifer pinches out and inflow from the adjacent gypsum formation upper mudstone unit is likely to be negligible. The western end of the boundary borders the low transmissivity mudstones encountered at borehole TW06. Shallow and deep groundwater flow were negligible in this area, and any flow that occurs is likely to discharge to local surface water features via the thin, high to extreme vulnerability subsoils rather than migrate north to the borehole.

Recharge and Water Balance

Table 2 Diffuse Bedrock Recharge Calculation Summary

Parameter	Coefficient	Rate
Average rainfall (R)		1013 mm/yr

[2] UFE (Todd, 1980). $x_L = Q / (2\pi * T * i)$ where: Q is the pumping rate (design yield = 500 m^3/day);T is the *Lm* aquifer Transmissivity (taken from aquifer characteristics); and, i is gradient in the *Lm* aquifer.

Estimated P.E.		438 mm/yr
Estimated A.E. (95% of P.E.)		416 mm/yr
Effective rainfall		597 mm/yr
Potential recharge		597 mm/yr
Averaged runoff losses	(83%)	497 mm/yr
Bulk recharge coefficient	0.17	
Recharge		100 mm/yr

The water balance calculation requires that the diffuse recharge over the area contributing to the source, must equal the discharge at the source. At a diffuse recharge rate of 63 mm/yr, an average yield of 500 m^3/day (i.e. design yield, 33% greater than current abstraction rate of 375 m^3/day) would require a recharge area of 2.9 km^2. The area of the ZOC described above is 3.1 km^2, which is slightly in excess of the water balance requirement, but captures all likely flow-paths to the source.

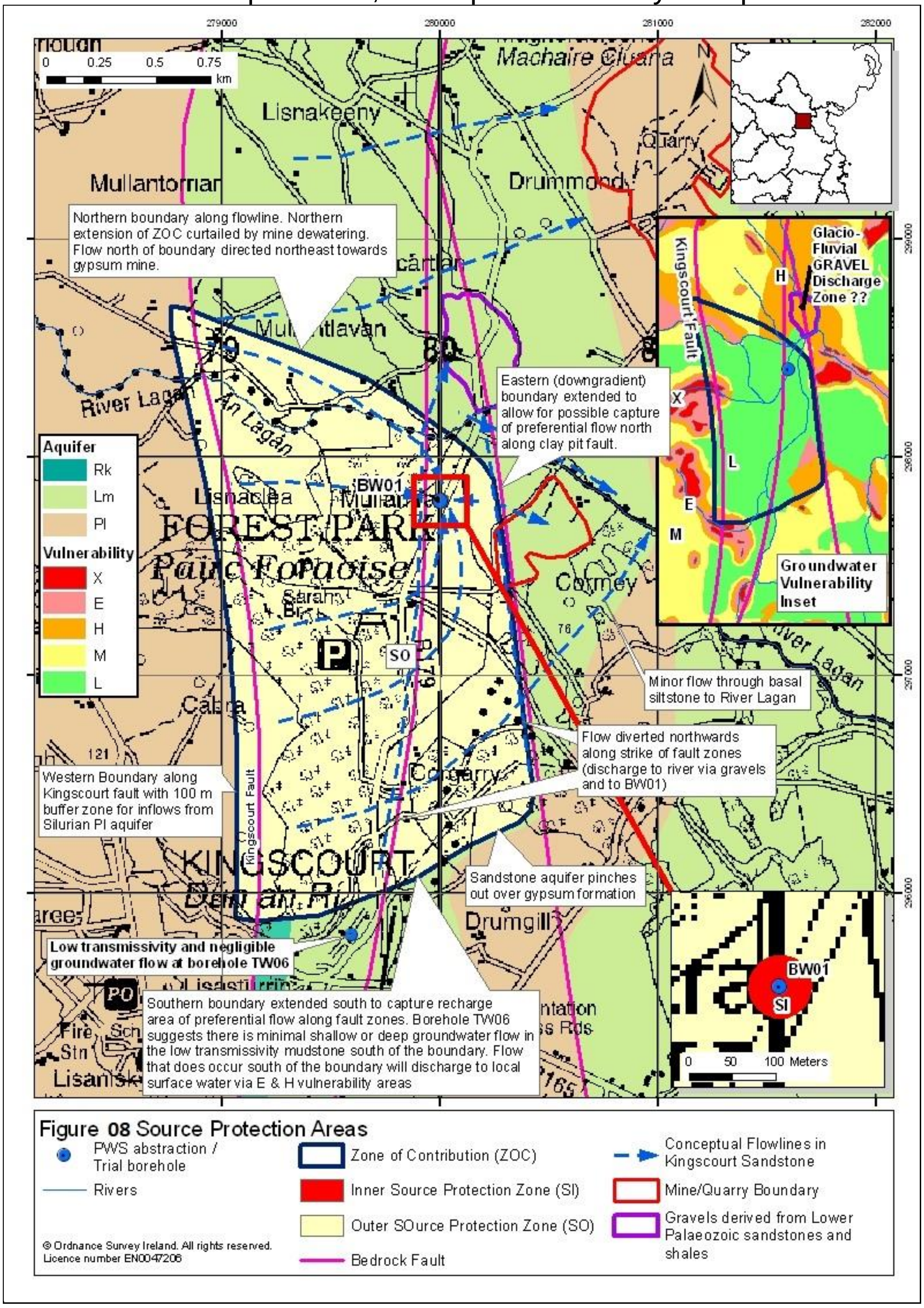


Figure 26: Source Protection Zones for Mullantra Borehole BW01.

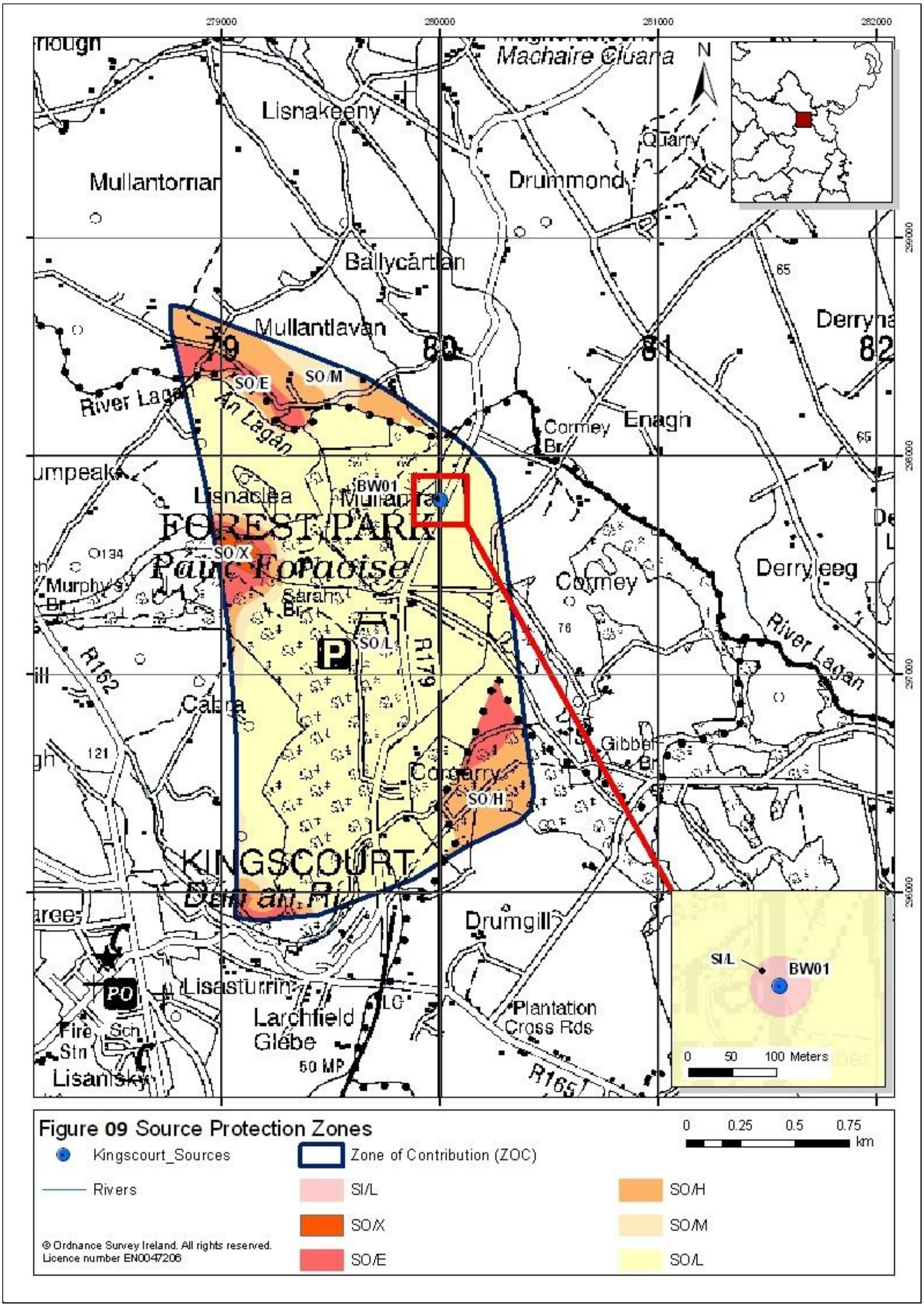


Figure 27: Inner and Outer Source Protection Zones for Mullantra Borehole BW01.

The Inner Protection Area (SI) is shown (Figure 27) is designed to protect the source from microbial and viral contamination and it is based on the 100-day time of travel (TOT) to the supply (DELG/EPA/GSI 1999). Using maximised aquifer parameter values (T = 48 m^2/d, i = 0.038, b = 51 m and n_e = 0.1) the velocity is calculated as

0.36, giving the 100-day TOT distance as 36 m. This maximum value is used in order to conservatively delineate the SI.

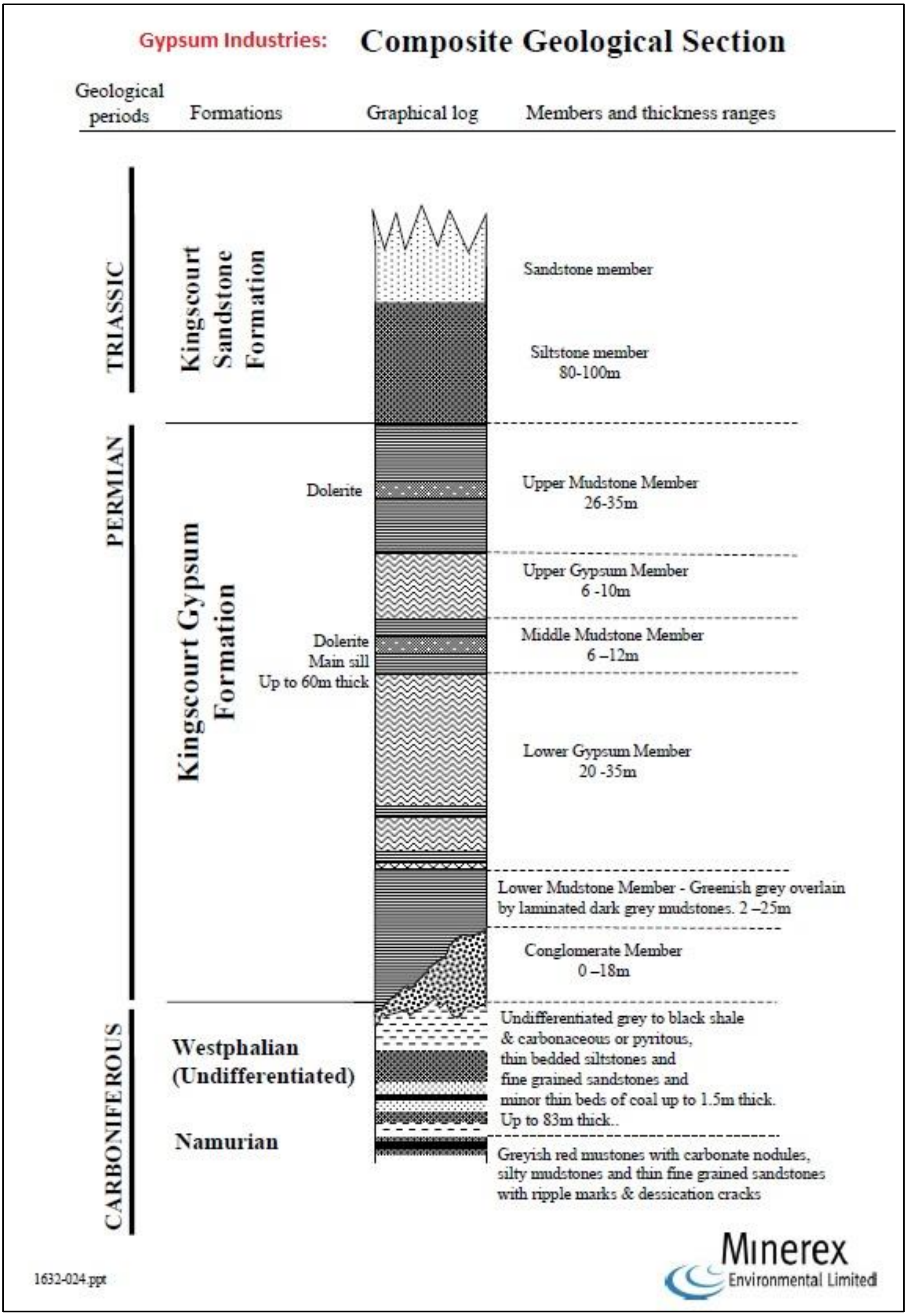


Figure 28: Composite geological section of the geology of the Kingcourt locality.

Figure 29: BW01 Photos

Namurian Sandstone and Dinantian Limestone Trial Well Drilling along Fieldtrip Route (KTC 1996 to WYG 2003)

Cavan County Council had ambitions to develop a regional scale public water supply in the Kingscourt area, within the Cavan county boundary. Trial well drilling at Mullantra (TW5, eventually became BW01) and elsewhere in the PTS (TW06, TW01) was not as successful as had been anticipated based on the NERDO (1981) report.

Namurian Sandstone Trial Wells

A trial well drilling campaign was undertaken targeting the Namurian Sandstone Lm aquifer in the east of the Kingscourt outlier (based on indications from a high yielding private well that it could support high yielding boreholes). Nearly all of the Namurian outcrop lies in Co. Meath, hence several of the trial wells (TW08, TW14, TW14A, and TW15) were drilled through the edge of the PTMG outcrop down into the Namurian bedrock in order to site the borehole as close to Co. Cavan as possible. Only TW14 and TW14A are in Co. Cavan.

The main trial wells targeting the Namurian Sandstone Lm aquifer in the area of the field trip were TW08, TW09, TW11, TW14, TW14A, TW15 and TW16. These wells had yields of 200 to 1,900 m^3/day based on 6-week pumping tests. The groundwater from the boreholes contained a component of sulphate rich groundwater, which increased with pumping duration and with proximity of the borehole location to the PTMG rock unit outcrop. The sulphate component was attributed to the capture of groundwater from the Kingscourt Gypsum Formation by the expanding cones of depression during the six week pumping tests. Calcium hardness was correspondingly high. TW14 and TW15, drilled through the PTMG rock unit into the underling Namurian Sandstones, developed concentrations of 509 mg/l SO_4 and 863 mg/l SO_4 respectively over the six week tests. In general, either total iron or total manganese, or both total iron and total manganese were present at elevated concentrations by the end of the six week tests, while nitrate was close to or below the detection limit.

Overall, the Namurian Sandstone aquifer was not considered suitable as a regional scale public water source due to the influence of gypsum dissolution on groundwater quality.

Namurian Sandstone/Dinantian Limestone Trial Wells

After the Namurian Sandstone Lm aquifer was abandoned as a potential regional water supply source, attention turned to DPBL rock unit regionally karstified (Rk) bedrock aquifer adjacent to the eastern boundary of the Kingscourt Outlier. Trial well TW10 (a.k.a. BW03) was nominally drilled through the thin Namurian Shale strata on the eastern edge of the outlier and into the underlying DPBL strata. Trial wells TW12 and TW13 (a.k.a. BW02) were nominally drilled directly into the DPBL. Boreholes BW02, TW12 and BW03 are located in County Monaghan.

These trial wells were high yielding and artesian, and had good water quality. It was recommended by WYG (2003) that BW02 and BW03 should be developed, together with the Mullantra borehole BW01, in order to provide a public water supply for the Kingscourt area.

2003 to the Present Day

The Mullantra borehole BW01 was commissioned as a public water supply in 2010, as discussed earlier. BW01 is currently referred to as Mullantra Borehole or PW5 by Cavan Co. Co.

Borehole BW03, in the townland of Descart was commissioned as public water supply sometime between August 2012 and July 2016. BW03 is currently referred to as Descart Borehole or PW10 by Cavan Co. Co.

SPZs were delineated for the Descart Borehole in 2010, and are discussed following.

Name	DTB (m)	TD	Logged Subsoil	Mapped Subsoil Category	Lithology	Water Strikes	2002 6-week Test Rate (m3/d) [& Ddn (m)]
TW08	11	107	Red Clay	TLPSsS	KC Gypsum Fmn: Weath. Shale 8-20m / Gypsum 20-75m) / Namurian: Shale 75 - 95m, SST 95 - 107m.	WS @ 80 & 84m. Main inflow (88-94)m from grey black shales.	410 [15.1]
TW09	8	82	Stoney CLAY	Rck	Namurian Sandstones & Shales: Shale 7-15m / White Limestone 15-24m / Shaley Limestone 24-68m / Sandstone 68-82m	25, 28, 45, 54, 69 and 79m. Main inflow from black shales, may have masked inflow from underlying SST. Sst collapsing below 82m.	208 [18.0]
BW03 (TW10)	18	91	Stoney Clay	TLPSsS	Namurian Sandstones: Limestone 18-28m / Shale 28-55m / White-brown Sandstone 55-82m / Dinantian Limestones: Cavern 82-88m / Brown Sandstone 88-91m	Inflows @ 57, 74 & cavern. Main Inflow 82 - 88m, from cavern. Inflow encountered in Sandstone. Cavern maybe in DPBL underlying the Namurian strata.	2003 6wk test: 1200 [3.5]
TW11	8	91	Gravelly CLAY	TLPSsS	Namurian Sandstones & shales: Siltstone & Sandstone 8-15m / Shale 15-65m / White Sandstone 65-91m	Main inflow in white Sst below 64.8m (540 to 1080m3/d)	1109 [21.8]
TW14	21	91	Gravelly Clay (0 to 12.2m) / over coarse Boulder Clay (12.2 to 21.3m)	TLPSsS	KC Gypsum Fmn: Gypsum 21-30m / Mudstone 30-38m / Namurian Sandstones & Shales: Sandstone, Shale & Cavities 38-62m) / Sandstone 62-91m	Main inflow in cavities in Sst (50 to 55mbgl, 1620m3/d). Lesser inflow at 40 to 45m (324m3/d)	1998 72hr test: 2462 [17.9]
TW14A	24	91	Red & Brown Clay (with at Gravel 3-12)	TLPSsS	Permo-Triassic: Sandstone 24-54m / Gypsum 54-60m / Namurian Sandstones & Shales: Interbedded grey black Limestone & Shale	Major Inflows between (66 & 68)m & at 90m	1907 [17.7]
TW15	38	122	Brown & Red CLAY with S&G to 30 m/ silty & clayey GRAVEL 30 to 38 m	TLPSsS	Permo-Triassic: Weath. Shale to 38-45m /Gypsum 45-82m/ Namurian Sandstone & Shale: Shale 82-92m / Sandstone 92-122m	Inflow 24-31.4m sealed off by casing. Inflow @ 45m. Main inflow in shale just below gypsum at 82m, & infow increasing below 82m.	1174 [13.4]
TW16	25	107	Red CLAY	TLPSsS	Namurian Sandstone & Shale: Siltstone 25-41m / Sandstone 41-64m / Siltstone 64-77m / Shale 77-107m	Main inflows at 45m & at 53m. No significant inflow below 53m.	573 [24.0]

		mg/l as CaCO3	ug/l	ug/l	mg/l as NO3	mg/l as NH4	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	
Name	**WQ at end 2002 6-week Test, Rate (m3/d) [& Ddn (m)]**	**Hardness**	**Fe**	**Mn**	**NO3**	**NH4**	**Ca**	**Mg**	**Na**	**K**	**HCO3**	**Cl**	**SO4**	**Ca**	**Mg**	**Na**	**K**	**HCO3**	**Cl**	**SO4**	**Ionic Balance %**
TW08	410 [15.1]	372	392	17	<1	0.11	116	22	20	4	285	15	158	5.8	1.8	0.9	0.1	4.7	0.4	3.3	1.1
TW09	208 [18.0]	245	**4370**	**204**	<1	0.09	58	25	3	19	224	20	60	2.9	2.1	0.1	0.5	3.7	0.6	1.2	0.7
BW03 (TW10)	2003 6wk test: 1200 [3.5]	195	20	**200**	<1	0.09	50	15	9	1	214.72	15	16	2.5	1.2	0.4	0.0	3.5	0.4	0.3	-1.5
TW11	1109 [21.8]	192	45	**278**	1.5	0.06	57	15	10	1	204	15	23	2.8	1.2	0.4	0.0	3.3	0.4	0.5	3.3
TW14	1999 72hr test: 2462 [17.9]	307	**400**	**180**	0.5	**18**	90	20	18	2.1	305	0	82	4.5	1.6	0.8	0.1	5.0	0.0	1.7	1.9
TW14A	1907 [17.7]	634	**1358**	**360**	<1	0.1	198	39	58	3	224	30	**509**	9.9	3.2	2.5	0.1	3.7	0.8	10.6	1.9
TW15	1174 [13.4]	1074	162	31	<1	0.09	394	31	24	5	225	17	**863**	19.7	2.6	1.0	0.1	3.7	0.5	18.0	2.7
TW16	573 [24.0]	190	**2290**	20	<1	0.05	46	20	22	2	149	27	68	2.3	1.6	1.0	0.1	2.4	0.8	1.4	3.4

Geology (Figure 13) and Geological Cross-Section (Figure 30)

The bedrock geology of the area comprises Kingscourt Sandstone strata overlying, in turn, Kingscourt Gypsum, Namurian Sandstone and Shales, and Dinantian Limestone (see Figure 13 and Table 1). The strata dip westwards at approximately 10 degrees in a half-graben structure towards the north to south trending Kingscourt Fault (Gardiner and McArdle, 1992). Further north to south trending faults occur to the west of the boreholes between the boreholes and the Kingscourt fault.

Two kilometres to the southeast in the vicinity of Ardagh on Barley Hill, the Milverton Group limestone abuts a northeast trending fault with Ardagh Shale, and Fingal Group shale and muddy limestone to the south. This fault forms a major structural boundary between the Milverton Group limestones of the Ardagh Platform to the north and the shales, calcarenites and limestones of the Moynalty Basin to the south.

The stratigraphic sequence in the vicinity of the test wells is recorded in the borehole logs for boreholes BW02 and TW12 (which are adjacent to each other), and BW03. At the site of BW02 and TW12 the logs record: shallow red sandstone; over thick white limestone with some interbedded shale; over white-brown sandstone at depth. At BW03 the log records bedrock of white limestone; over thick grey-black shale; over thick white-brown sandstone which contained a 7 m deep cavity at 82 to 89 mbgl.

It is considered here that the strata logged in these boreholes as “red sandstone”; and, “white-brown sandstone” are likely to have been dolomitised limestone bedrock. This is supported by:

- Hydrochemistry data, which show that the large inflows from these strata are saturated with respect to the mineral dolomite.
- A large karst cavern such as at BW03 is more likely to occur in dolomitised limestone than in sandstone. (Multiple cavities from 2 to 7 m in depth were encountered in borehole OW05).
- Interpretation as dolomitised limestone agrees with the bedrock map of the area which shows Milverton Group Limestone outcrop at BW02 and TW12. This limestone is known to be extensively dolomitised. At BW03, the map shows shale overlying Milverton Group limestone and a thick sandstone layer would not be expected with this configuration;
- Similar reinterpretations of the borehole logs also appear valid for boreholes OW05 and TW11 located on Barley Hill directly south of the trial boreholes.

Approximately 100 karst features are known to the north and northeast of the test wells, in the Co. Monaghan part of the Milverton Group outcrop. A swallow hole has been mapped on top of Barley Hill at KF01 (data from R. Meehan) (see Figure 20). A second swallow hole occurs to the south of KF01 according to the Monaghan GWPS main report (GSI, 2002). Karst features are in evidence at Mokeeran Quarry, which is a Co. Monaghan Geological Heritage Site and which we intend to visit as the final stop in this study area.

The caverns encountered in BW03 and OW05 may be part of a deep paleokarst conduit system in the limestone/dolomitised limestone. The upper surface of the Milverton Group limestone was eroded to varying depths before deposition of the overlying Namurian strata (Geraghty et al, 1999). As such, karstification may also occur at the boundary surface between the Milverton Group and the overlying Namurian strata. The extensive dolomitisation enhances the permeability of limestone by creating additional void space and can further increase the likelihood of karstification (GSI, 2004a). Due to the regional north-south trend in both the faults of the area, and the bedding strike, it is likely that karstification and dolomitisation will have developed preferentially with the same north south orientation.

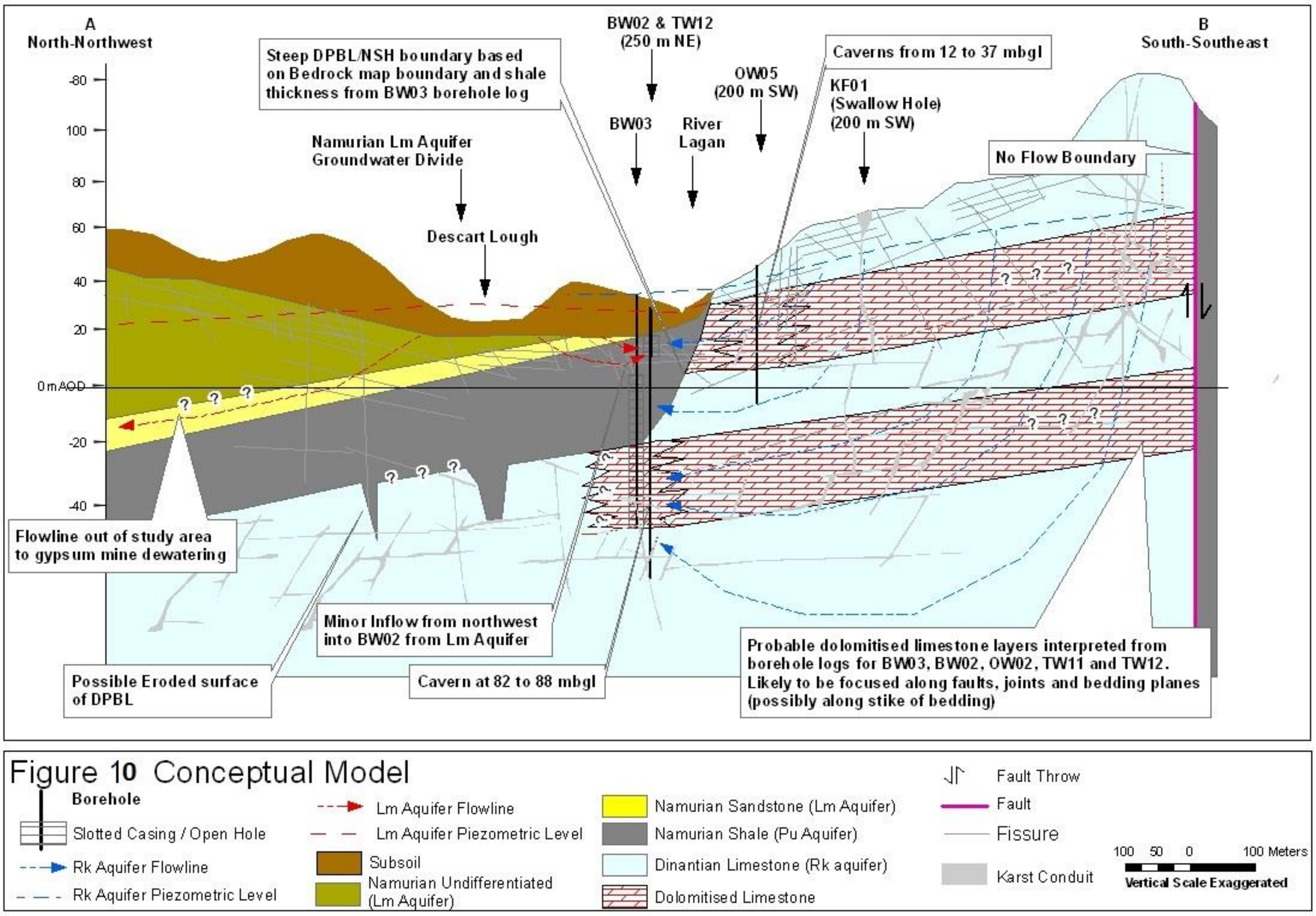


Figure 30: Geological Cross Section and Conceptual Model of Descart Source.

Subsoil (Figure 15) and Subsoil Permeability

Till subsoils cover the majority of the study area. Till derived from Lower Palaeozoic sandstones and shales is mapped across the majority of the area west, north and east of test wells. To the north and east of Descart on the limestone bedrock, this till is thought to form a thin skim over a thicker deposit of limestone-dominated till. Till derived from limestone is mapped at the surface on the flanks of Barley Hill itself and in pockets to the east of this. South and southwest of Barley Hill, the tills are mapped as being derived from Namurian shales and sandstones.

It is envisaged that, due to the predominance of shale in the Lower Palaeozoic and Namurian-derived tills, these materials are of low permeability. This is corroborated by borehole logs for the test wells and from other trial wells to the west, which show subsoil dominated by clay. The GSI classify the areas where the shale till is just a thin skim over limestone till, and the alluvial subsoil areas as moderate permeability.

Depth to Bedrock (DTB) and DTB Revisions

In the drumlin areas to the west and northwest of boreholes BW02 and BW03, DTB is generally greater than 10 m. In the inter-drumlin low area at borehole BW03, this drops to 8.8 m. Further east there are fewer data, however the available data suggest that the DTB in the inter-drumlin areas and away from mapped bedrock outcrop is between 5 and 10 m, with DTB possibly increasing to greater than 10 m at the drumlin summits.

The area mapped as rock close to the east of the test wells, and along the northern bank of the River Lagan, is considered here to have DTB of 3 to 10 m based on the available DTB data and landscape assessment. The DTB and vulnerability have been changed accordingly for the SPZs reports.

Descart Source Borehole Details: BW03

Borehole BW03 was drilled to a depth of 91 m where a cavern was intersected and resulted in an artesian overflow of 1,300 m^3/day. The well was plugged with an inflatable packer three months after drilling, which subsequently became stuck in the well and was still there in 2010. Presumably the packer was removed during commissioning of the borehole.

Recent SCADA info from Cavan CoCo indicates that current abstraction is approximately 600 m^3/day at a discharge rate of 40 m^3hr (i.e. approximately 15 hours per day) (see screenshots on Page 35).

	BW02	BW03
Grid ref. (GPS)	X: 282514 Y:296953	X: 282281 Y:296881
Other Names	TW13; Borewell no. 2	TW10; Borewell no. 3
Townland	Descart, Co. Monaghan	Descart, Co. Monaghan
Source type	Trial Borehole	Trial Borehole
Drilled	January 1998	February 1996
Owner	Cavan County Council	
Elevation (Ground Level)	~31 m OD	~ 34.5 m OD
Depth (m)	19.2	91
Depth of casing	200mm: 19.2 m (slots 10.2 to 19.2) 300mm: 9.14 m	29 m
Grout Seal	0 to 9.14 in casings annulus	none
Diameter	200 mm	150 mm
Depth to rock	8.8 m	17.5 m
Static water level	0.02 mbgl (Feb 1998)	Artesian
Pumping water level	11.39 mbgl for 1557 m^3/day (Feb 1998, unsteady) 11 to 12 mbgl for ~ 900 m^3/day (Feb – April 2003)	5.49 mbgl for 2072 m^3/day (Mar 1996) 3.5 mbgl for 1260 m^3/day (Feb – Apr 2003)
Consumption (Co. Co. records)	Not yet commissioned.	Not yet commissioned.
Pumping test summary: (i) abstraction rate m^3/d	1557 m^3/day (70hr, Feb 1998)) ~ 900 m^3/day (6 wk, Feb – April 2003)	2072 m^3/day (30 hr, Mar 1996) 1260 m^3/day (6 wk, Feb – April 2003)
(ii) specific capacity	137 m^3/d/m (Feb 98) 75 m^3/d/m (Apr 03)	377 m^3/d/m (unsteady) (Mar 96) 360 m^3/d/m (Apr 03)
(iii) transmissivity	47	114

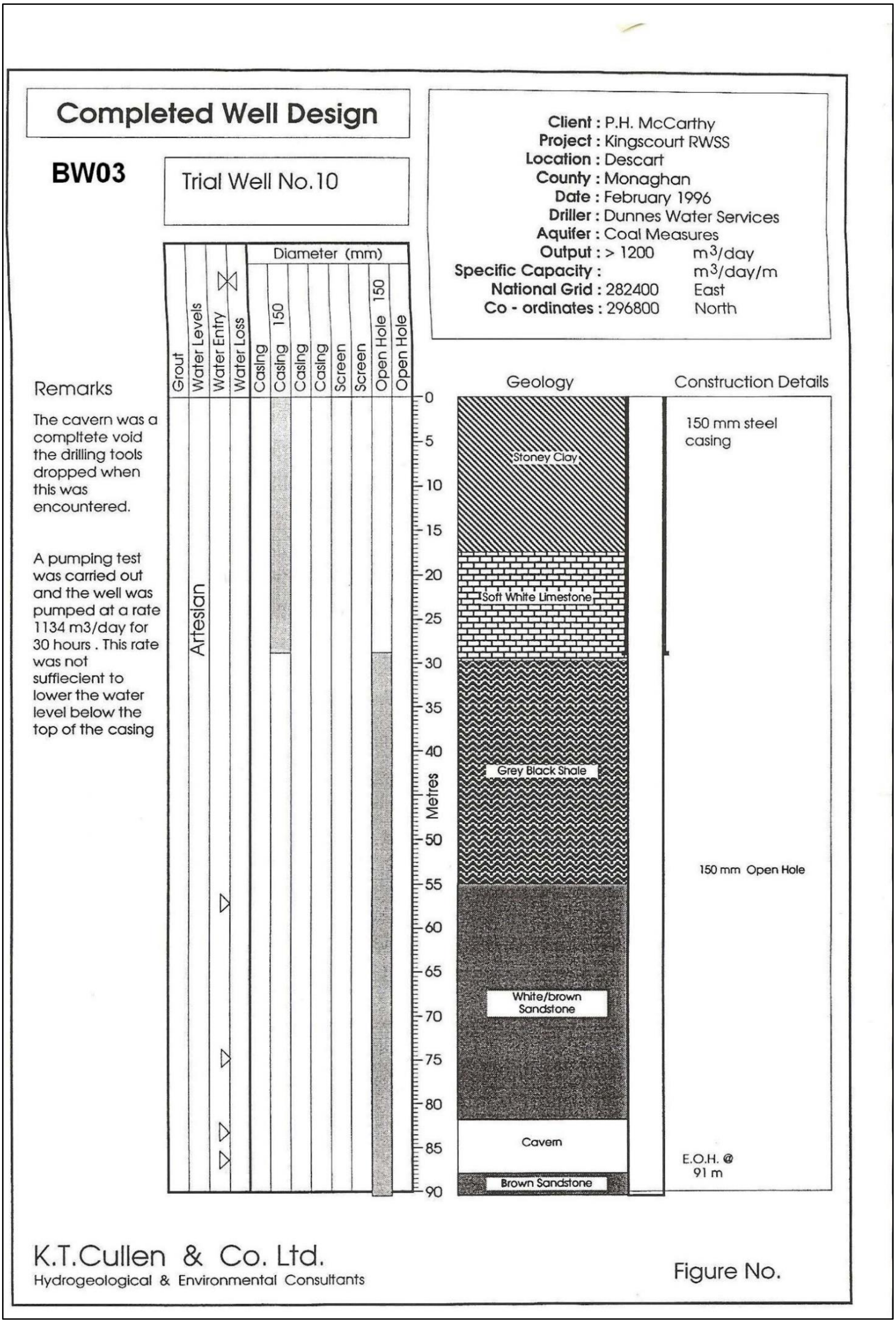


Figure 31: Descart BW03 Completed Well Design.

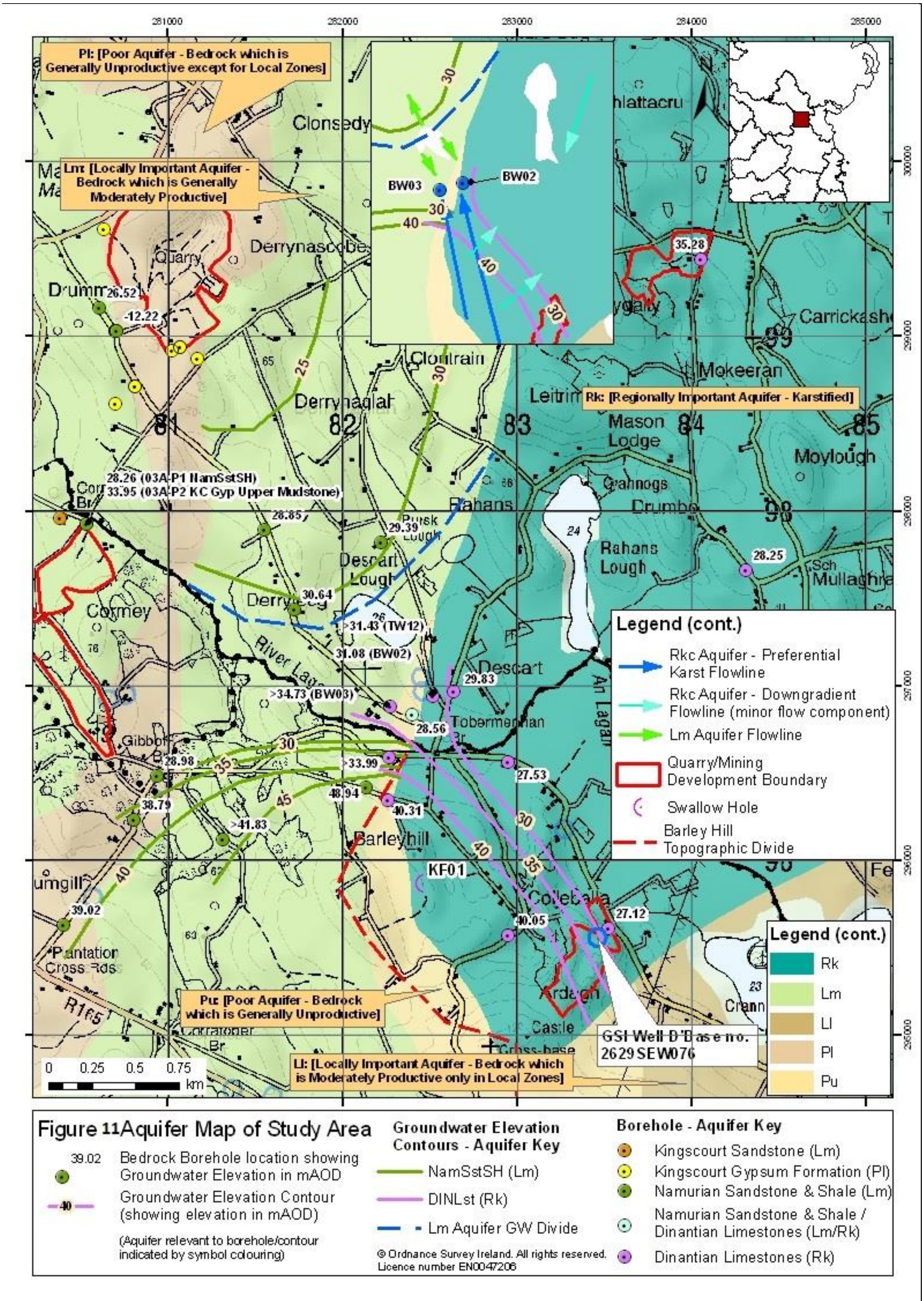


Figure 32: Descart BW03 Groundwater Levels, Flow Directions and Gradients.

Hydrogeological Conceptual Model

The test wells BW02 and BW03 abstract from the *Rk* limestone aquifer. Borehole BW02 is shallow and may also receive a minor input from the Namurian *Lm* aquifer immediately to the northwest. BW03 is deep and intersects a cavern which is considered to be in a dolomitised limestone layer of the *Rk* aquifer. Vertical hydraulic gradients at the boreholes, which result in artesian conditions in BH03 and TW12, suggest that upwards flow of confined groundwater is occurring in the vicinity of the boreholes. As such BW02 is also likely to be influenced by discharge from the deeper, confined, dolomitised limestone strata. Hydrochemistry at each of the boreholes indicates groundwater saturation with respect to dolomite. This reinforces that the boreholes intersect and abstract from dolomitised limestone strata. To date the groundwater has been unpolluted but with naturally elevated levels of manganese which are common in confined aquifers.

The *Rk* aquifer is mainly recharged at bedrock outcrop and karst features on Barley Hill, and where the overlying subsoils are thin. As well as direct recharge to the limestone outcrop, karst features are also likely to intercept runoff from the Namurian outcrop on the eastern flank of the crest of Barley Hill. Groundwater flow is mainly northwards from Barley hill along preferential karst flow paths with the River Lagan (and possibly nearby low-lying lakes) being the most likely natural discharge boundary. Flow to the south is prevented by a no flow boundary at the southern end of Barley hill, where the limestone abuts *Pu* and *Pl* aquifers. A minor component of groundwater flow is directed east off Barley Hill in the direction of steepest hydraulic gradient, but the magnitude of the flow is likely constrained by low transmissivity in that direction. Abstraction from the test wells is likely to induce northerly flow underneath the river to the boreholes. Groundwater flow from the north in the *Rk* aquifer currently appears to be directed toward the River Lagan.

The *Lm* aquifer to the northwest of the test wells is recharged by diffuse infiltration. The data suggest that the bulk of this recharge flows northwest toward the Drummond gypsum mine dewatering system. A southwest to northeast groundwater divide in the vicinity of Descart Lough separates the test wells from the dewatering system. Recharge to the southeast of the divide will flow towards the Lagan River in the weathered upper bedrock zone. There is only a small recharge area to the southeast of the divide such that groundwater flow volumes from this region are likely to be low in comparison with the *Rk* aquifer. A small component of the *Lm* aquifer flow may discharge into the weathered upper *Rk* aquifer and be intercepted by BW02. Direct recharge to the *Lm* aquifer at Barley Hill is expected to flow north and northwest to the River Lagan.

The conceptual model for the Descart study area is illustrated in the cross section in Figure 30. Groundwater elevation contours across the study area, the aquifer types, and interpreted groundwater flow directions are shown on Figure 32.

Descart BW03 ZOC Boundaries (Figure 33)

The ZOC has been delineated across both the *Rk* and *Lm* aquifers. A single ZOC has been delineated for both boreholes. The boundaries of the areas contributing to the test wells are considered to be as follows (Figure 33):

<u>In the *Rk* aquifer</u> the south-eastern boundary is the no-flow boundary between the *Rk* aquifer and the *Pu* and *Pl* aquifers to the south. `

The southern and northern extremes of the western boundary are defined by the geological boundary between the limestone and Namurian shale. To the west of this the limestone becomes confined and does not receive any recharge. For the middle section, the ZOC boundary extends west of the geological boundary to account for runoff from the eastern, upper slopes of Barley Hill, which is likely to flow onto the limestone surface and enhance the limestone recharge either diffusely or at karst features. As such the majority of the western boundary is defined by the topographic divide along the top of Barley Hill.

The north-eastern boundary is delineated with the same orientation as the geological faults and karst preferential flow paths. The positioning of the boundary has been determined by the water balance (Section 10.3), with the boundary given an easterly position sufficient to include the required recharge footprint within the ZOC.

The short northern boundary for the *Rk* aquifer curves around the north side of BW02 from the north-eastern boundary to intersect the limestone geological boundary. The separation distance from the borehole is conservatively based on the Uniform Flow Equation downgradient distance (x_L) (Todd, 1980). This is calculated to be 130 m based on the average parameters.

A small extension has been added to the ZOC in the <u>*Lm* aquifer to the northwest of borehole BW02</u>. This is to account for the possibility of some groundwater in the *Lm* aquifer discharging into the upper weathered *Rk* aquifer and then into the borehole. The north-western boundary of this extension is taken as the *Lm* aquifer groundwater divide.

The southwestern and north-eastern boundaries are conservatively delineated as flowlines (+/- 20^{O} to allow for possible flow direction variation) which discharge into the Rk aquifer ZOC area. It is considered that pumping from BW02 will have a negligible impact on the position of the groundwater divide, as the abstraction from borehole BW02 will predominantly derive from the Rk aquifer dolomitised limestone.

Descart BW03 Recharge and Water Balance

The vast majority of the water abstracted from boreholes BW02 and BW03 is expected to come from the *Rk* aquifer. As such, the recharge rate and water balance have been calculated for the *Rk* aquifer component of the abstraction alone. The calculation does not include the small input from the *Lm* aquifer northwest of BW02, or contributions from runoff via karst point recharge. Hence, the ZOC is likely to be conservative. The breakdown of the recharge calculation is shown in Table 3.

Table 3 BW03 Recharge Calculation for Rk aquifer component of the ZOC area

Parameter	Coefficient	Rate
Average rainfall (R)		1013 mm/yr
Estimated P.E.		438 mm/yr
Estimated A.E. (95% of P.E.)		416 mm/yr
Effective rainfall		597 mm/yr
Potential recharge		597 mm/yr
Averaged runoff losses	(19%)	116 mm/yr
Bulk recharge coefficient	0.81	
Recharge		481 mm/yr

The water balance calculation requires that the recharge over the area contributing to the source must equal the discharge at the source.

At a recharge of 481 mm/yr, the proposed demand of 1,408 m^3/day would require an *Rk* aquifer recharge area of 1.07 km^2. During the February 2003 multi-well pump test, boreholes BW02 and BW03 were pumped at a combined rate of 2,160 m^3/day. This is approximately 150% of the target yield. The ZOC has been delineated conservatively for this maximum tested value to allow for unexpected increases in demand and for expansion of the normal (100% demand) ZOC under prolonged drought conditions. This requires an *Rk* aquifer recharge area of 1.6 km^2. The area of the ZOC described above is 1.49 km^2 (equivalent to 1995 m^3/day), which is slightly below the target area, and is shown in Figures 33 and 34.

Point recharge of runoff from the *Lm* aquifer area (0.41 km^2) on the crest of Barley Hill has not been quantified, however it is likely to increase the total available recharge volume for the ZOC footprint to at least the 150% of proposed demand value of 2,160 m^3/day.

In the same way as for the *Rk* aquifer, the bulk recharge coefficient for the north-western ZOC extension onto the *Lm* aquifer is estimated as 0.06 (6%). The ZOC extension has an area of 0.35 km^2, which implies that the recharge to the ZOC from this additional area is only 35 m^3/d.

Descart BW03 Source Protection Zones

The Inner Protection Area (SI) is designed to protect the source from microbial and viral contamination and it is based on the 100-day time of travel (TOT) to the supply (DELG/EPA/GSI 1999). Based on the indicative aquifer parameters presented in section 8.5, the groundwater velocity is 4.2 m/d and 0.17 m/d in the *Rk* and *Lm* aquifers respectively. The 100-day TOT distance therefore, is 420 m in the *Rk* aquifer and 17 m in the *Lm* aquifer. The Outer Protection area (SO) is the remainder of the ZOC outside the SI.

Parts of the ZOC delineated in the *Rk* aquifer lie outside the relevant 100-day TOT limit, however flow paths in individual karst conduits can greatly exceed the calculated average for the bulk aquifer. As such, the entire *Rk* aquifer ZOC is conservatively classified as SI. The extension of the ZOC onto the *Lm* aquifer on eastern flank of the crest of Barley Hill is also classified as SI because runoff from this area is likely to rapidly enter the karst system.

Borehole BW03 is cased off from the *Lm* aquifer such that inflow to the borehole only comes from the *Rk* aquifer at depth. Furthermore the strongly artesian *Rk* aquifer suggests that any leakage along the casing will be upwards out of the *Rk* aquifer rather than downwards from the *Lm* aquifer. As such, no SI zone is delineated around BW03 in the *Lm* aquifer. Nonetheless, BW03 is located 80 m inside the ZOC boundary, which provides protection to the area surrounding the wellhead. Borehole BW02 is physically sited in the SI zone on the *Rk* aquifer at a minimum of 50 m from the *Lm* aquifer. As such, it is already buffered by an SI zone exceeding the 17 m requirement of the *Lm* aquifer. As a result, no additional SI area has been delineated on the *Lm* aquifer footprint northwest of the boreholes. The *Lm* aquifer in this area is classified as SO.

The Inner and Outer Protection Areas are illustrated in Figure 34.

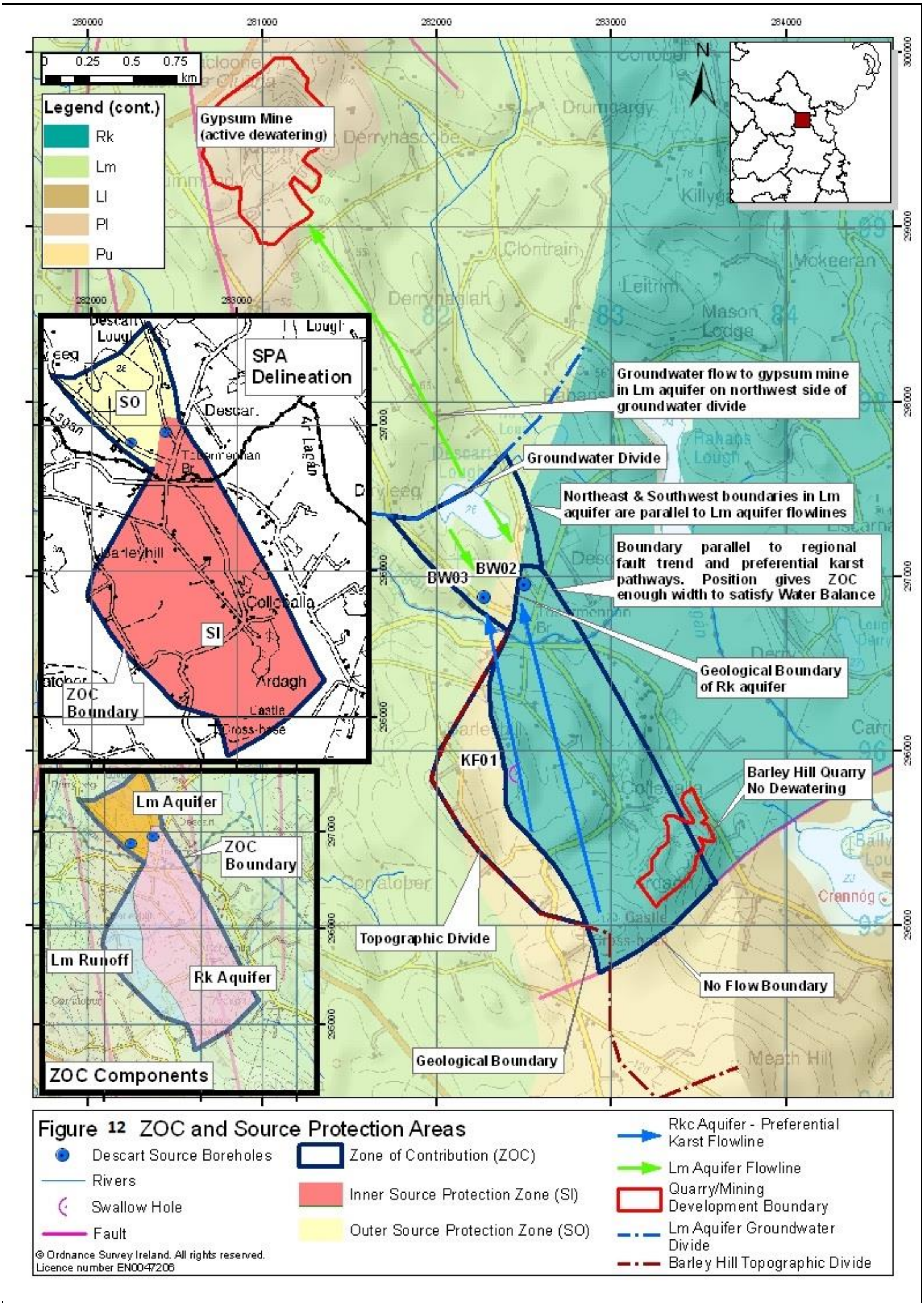


Figure 33: Descart BW02 and BW03 ZOCs and Source Protection Zones.

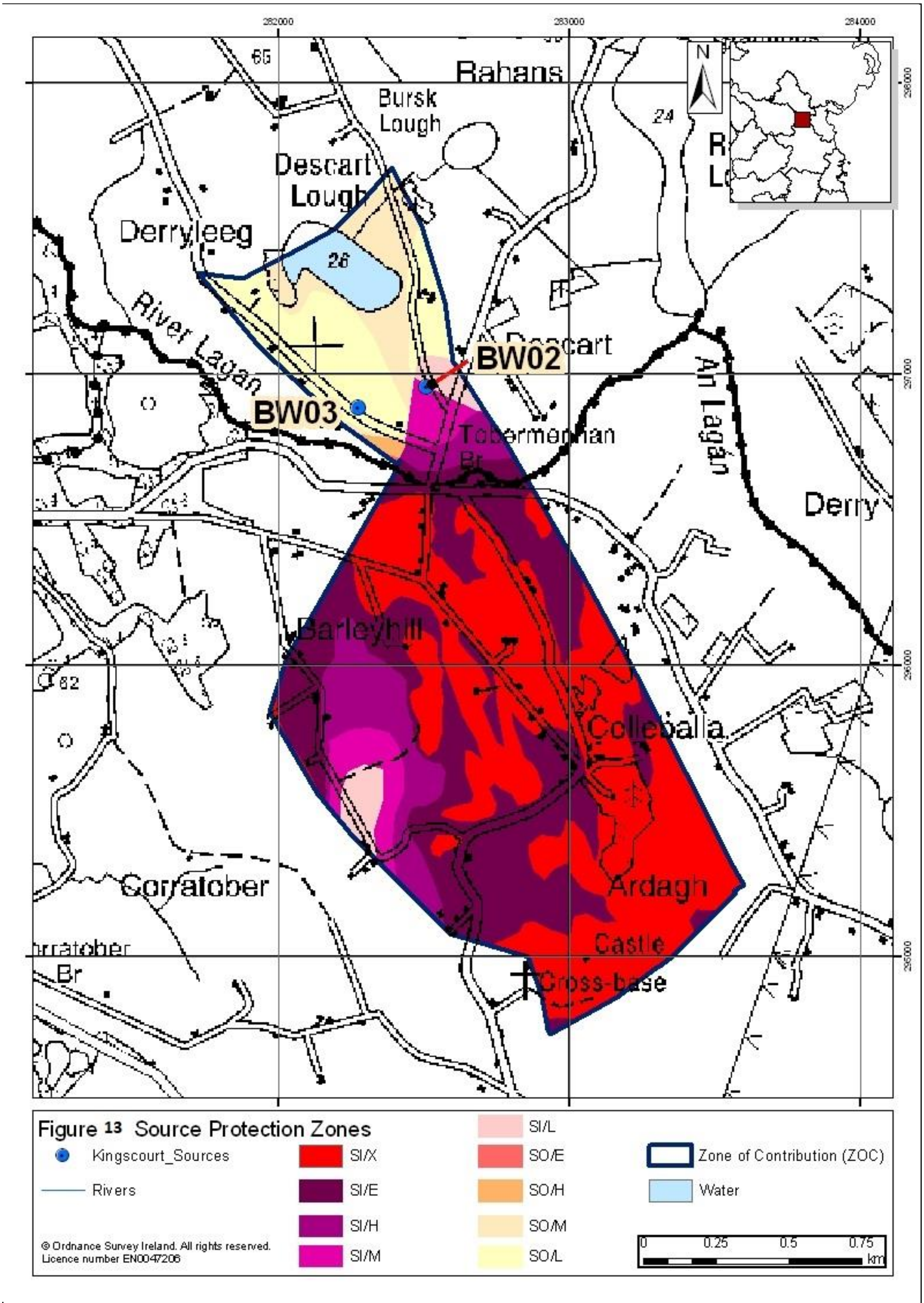


Figure 34: Descart BW02 and BW03 Source Protection Areas.

BW03 Photos

Figure 35: Drilling BW03 (Feb 1996, photo from Gary Boyd, Cavan Co. Co.)

References

DELG/EPA/GSI (1999). Groundwater Protection Schemes. Dept. of the Environment and Local Government; Environmental Protection Agency; Geological Survey of Ireland.

Fitzgerald, D. and Forrestal, F. (1996). Monthly and annual averages of rainfall for Ireland 1961 to 1990. Meteorological Service Climatological Note No. 10. Glasnevin Hill, Dublin 9.

Fitzsimons, V., Daly, D., Deakin, J. (2003). GSI Guidelines for Assessment and Mapping of Groundwater Vulnerability to Contamination. Geological Survey of Ireland.

Gardiner, P.R.R. and McArdle, P (1992) The Geological setting of Permian gypsum and anhydrite deposits in the Kingscourt district, Counties Cavan, Meath and Monaghan. In: Bowden, A.A., Earls, G. O'Connor, P.G. and Pyne, J.F. (1992) The Irish Minerals Industry 1980-1990. Irish Association for Economic Geology, 301-316.

Geraghty, M. and McConnell, B. (1999). Bedrock Geology 1:100,000 Scale Map, Sheet 13. Meath. Geological Survey of Ireland.

GSI (2004). Kingscourt Groundwater Body – Water Framework Directive Initial Characterisation Summary – 1st Draft. Geological Survey of Ireland.

IWWG (2005). Guidance on the Assessment of the Impact of Groundwater Abstractions. Guidance Document No.GW5. Intergovernmental Working Group on Groundwater.

KTC (1996). Report on Groundwater Investigations at Kingscourt, County Cavan. K.T. Cullen & Co. Ltd. Unpublished report.

McConnell, B., Philcox, M., and Geraghty, M. (2001). Geology of Meath. A Geological Description to accompany the Bedrock Geology 1:100,000 Scale Map Series, Sheet 13, Meath. Geological Survey of Ireland.

Meehan, R. (2008). Hydrogeological Assessment for Proposed Development At St. James Court, Cabra, Kingscourt, County Cavan. Unpublished report.

Minerex, (2010). Database of Groundwater Elevation Measurements for the Groundwater Monitoring Network of the Gypsum Limited Mine at Drummond, Carrickmacross, Co. Monaghan. Minerex Environmental Limited. Unpublished reports.

NERDO (1981). Groundwater Resources in the N.E. (R.D.O.) Region. An Foras Forbartha. Northeast Regional Development Organisation.

Noel Duffy, pers comm. (2010). Noel Duffy, Environmental Technician for Lagan Bricks, Kingscourt, Co. Cavan.

PH McCarthy. (2008). Cavan County Council, Kingscourt Water Supply, Contract 4, Groundwater Abstraction and Treatment, Volume 2, Specification. PH McCarthy Consulting Engineers. Unpublished report.

Teagasc (2006). National Soils & Subsoils Maps. Maps produced as part of EPA Soils and subsoils Mapping Project. Teagasc, Kinsealy, Dublin.

Todd, D.K. (1980). Groundwater Hydrology. 2nd Edition New York: John Wiley & Sons.

WYG. (2002). Report on Drilling and Multi-Well Pumping Test Programme at Kingscourt, Co. Cavan. Unpublished report, White Young Green – Ireland.

WYG. (2003). Report on a Multi-Well Pumping Test Programme at Kingscourt, County Cavan. Unpublished report, White Young Green – Ireland.

6. GSI Groundwater Resources Assessment Project, 'GW3D'
Katie Tedd, Natalie Duncan and Sara Raymond

GW3D Project background.

The Groundwater and Geothermal Unit of Geological Survey Ireland is reviewing groundwater resource potential in the east and southeast of Ireland, as part of its "Groundwater 3D" project. Groundwater resources within each catchment are assessed for potential for long term, sustainable and resilient water supplies.

A regional overview of each catchment incorporates analysis of all available, relevant national and site-specific data, including physical structure, climate data, surface water flows and quality, and groundwater levels and quality. The impact of both groundwater and surface water abstractions and discharges, and the potential impact of climate change on water resources in each catchment is examined. A steady state water balance calculation is completed for each catchment, that accounts for all significant natural and anthropogenic inputs and outputs of water to and from the surface water and groundwater systems and any interactions between them. A conceptual model for each catchment is developed which identifies zones of similar hydrogeological settings and likely groundwater resource potential. Promising zones are further investigated to assess potential considerations to future abstractions with particular reference to (i) local hydrogeological settings; (ii) ecologically sensitive areas; (iii) impact of existing abstractions and (iv) hydrochemistry. Localities which are found to have regional groundwater resource potential and no apparent considerations to future abstractions, are recommended for further, detailed, field-scale investigation for large-scale water supplies.

The methodology for GSI's GW3D project follows international best practice of using surface water boundaries as the unit of assessment for the impact of abstraction on the catchment's water resources. This methodology assumes that groundwater flow follows the catchment boundaries. The Nanny - Boyne catchment boundary is an example of where that assumption does not hold. In settings that vary from the assumptions the report methodology is adapted.

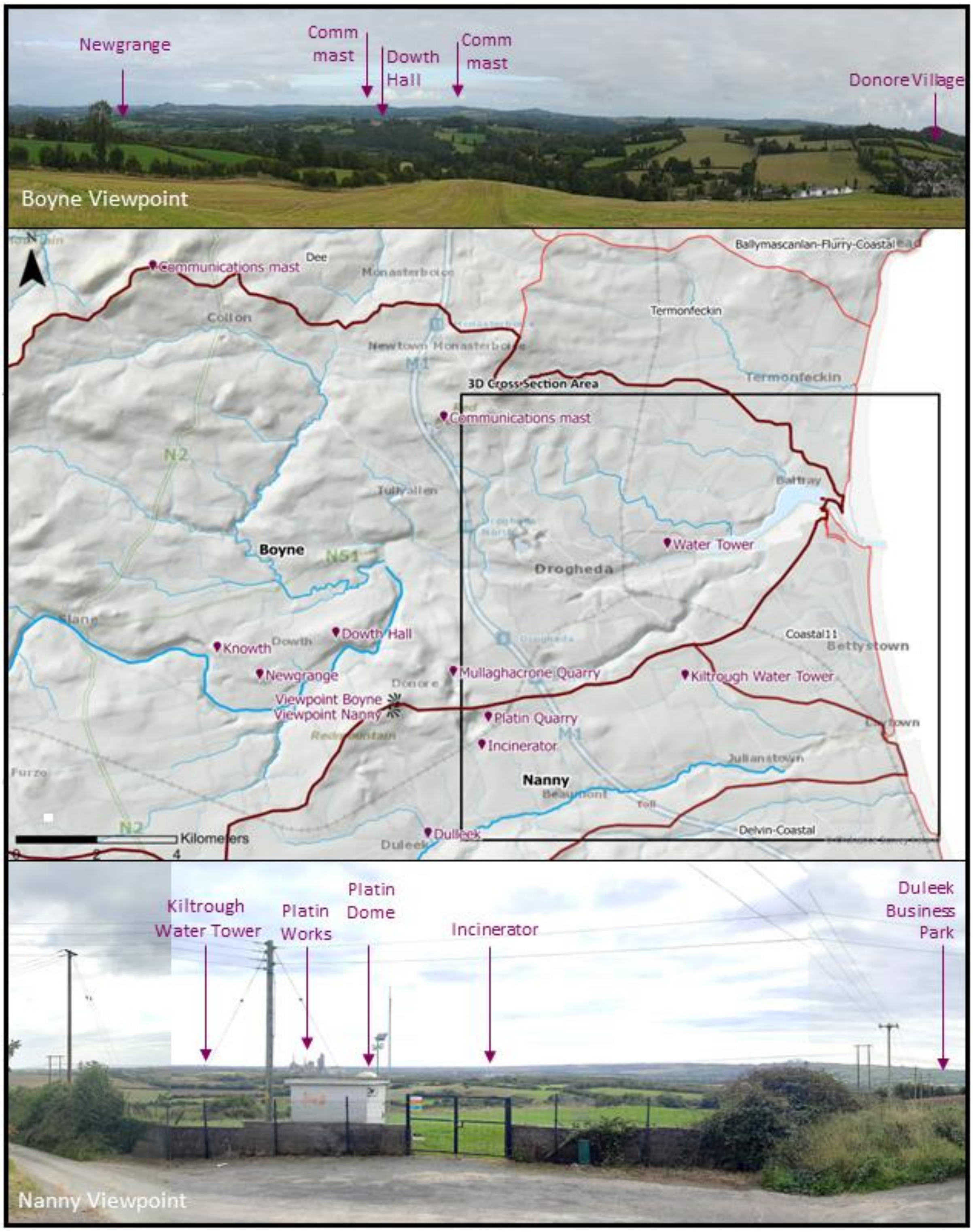


Figure 36:. Orientation photos and map for Stalleen fieldtrip stop.

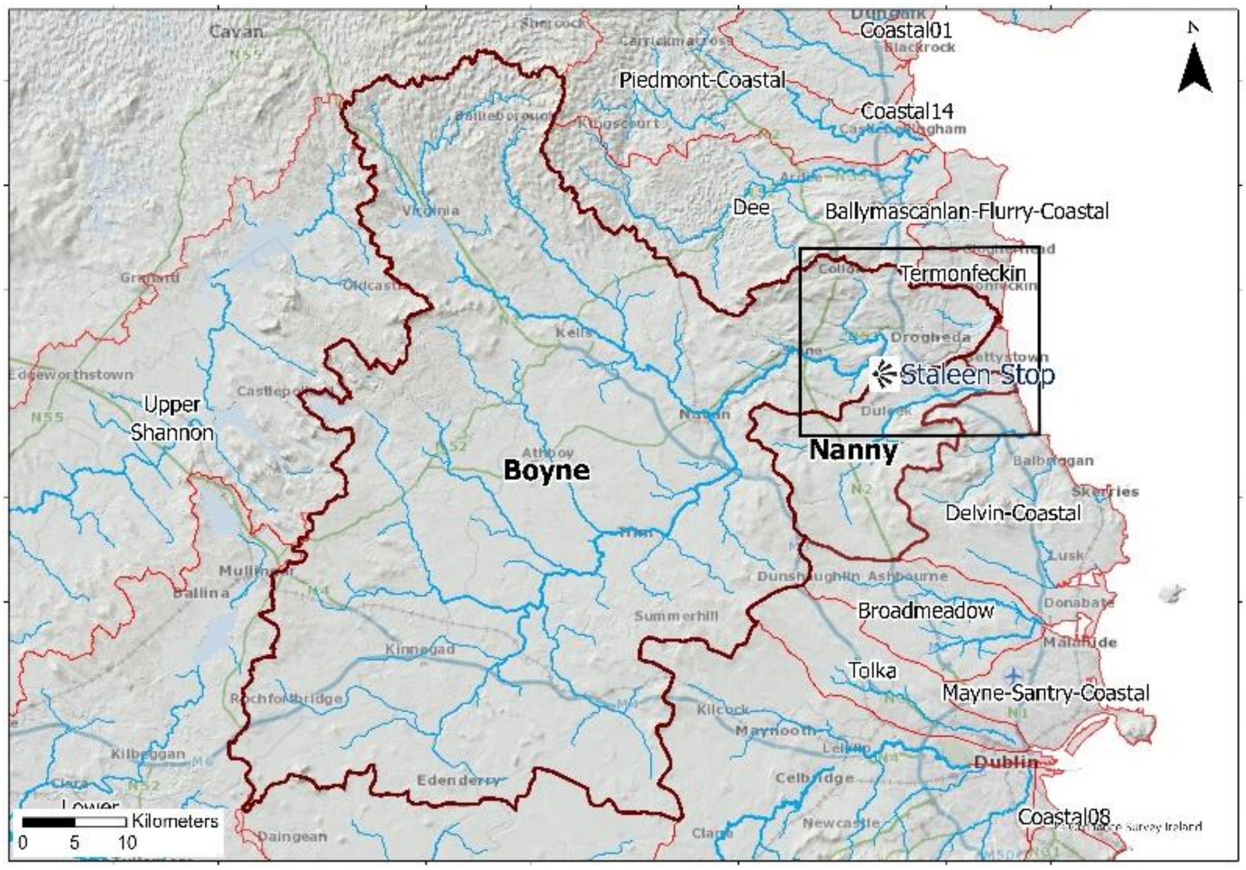


Figure 37: Boyne and Nanny Catchments overview.

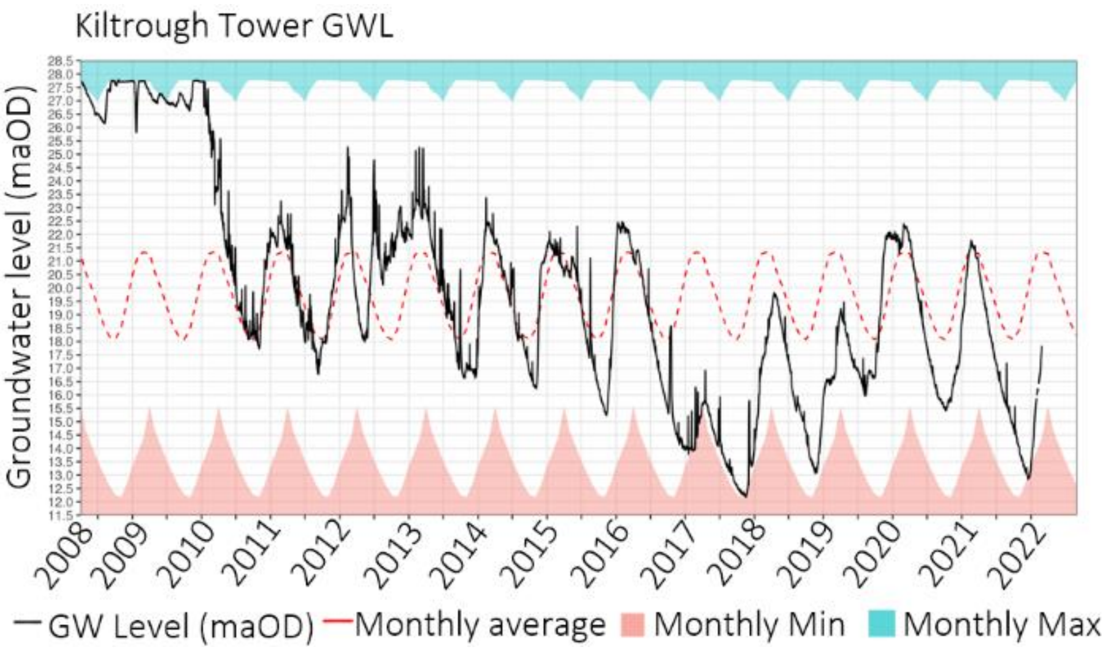


Figure 38: Groundwater levels at Kiltrough Water Tower.

Boyne and Nanny Catchments – an overview.

The Boyne Catchment covers 2,693 km^2. The division of effective rainfall between groundwater and surface water flow is estimated to be 28% and 72% respectively. Steady state water balance calculations estimate that 1.5% of the mean flow and 12% of the Q95 flow is consumptively abstracted (i.e. abstractions minus discharges) from the Boyne Catchment. GW3D has identified areas recommended for further field-scale investigation for the development of large-scale, sustainable, resilient groundwater supplies in the south and east of the catchment.

The Nanny Catchment has an area of 235 km^2. The division of effective rainfall between groundwater and surface water flow is estimated to be 19% and 81% respectively. Steady state water balance calculations indicate that the volume of discharges in the catchment exceeds abstractions in the catchment. Discharges in the catchment are dominated by the discharge from Platin. The anthropogenic flows (i.e. discharges–abstractions) make up approximately 13% of the Q95 flow and 0.6% of the mean flow. Groundwater levels have dropped significantly since 2008 and 2009; and have been lower than average for the past five years (Figure 38). GW3D has not identified any areas within the Nanny Catchment for further field-scale investigation for the development of large-scale, sustainable, and resilient groundwater supplies.

Hydrogeological Setting.

The geology of the Boyne and Nanny Catchments is illustrated in Figures 39, 40 and 41. Carboniferous Rock Units are faulted against Ordovician and Silurian Metasediments and Volcanics Rock Units at the Slane Fault (orientated ESE-WNW) in the Boyne Catchment, and the Nanny Fault (ESE-WNW) in the Nanny Catchment. The Silurian and Ordovician Rock Units within this area are categorised as Poor Bedrock Aquifer which is Generally Unproductive (Pl) or Poor Bedrock Aquifer which is Generally Unproductive except for Local Zones (Pu). Carboniferous Rock Units in this area are categorised as a Locally Important Aquifer which is Generally Moderately Productive (Lm), Regionally Important Karstified Aquifer dominated by diffuse flow (Rkd) and Poor Bedrock Aquifer which is Generally Unproductive except for Local Zones (Pu) (Namurian undifferentiated) (Fig 42).

The dominant subsoils in this area include Till derived from Namurian sandstones, Till derived from Lower Palaeozoic sandstones and shales, Irish Sea Till derived from Lower Palaeozoic sandstones and shales, Till derived from Limestones, Alluvium and Sand and Gravel deposits (Fig 40). Rock outcrops at higher elevations. Subsoil permeability is generally ‘Low’ with the exception of the Alluvium and Gravel deposits which are categorised as having ‘High’ permeability. Extreme and High Groundwater Vulnerability is associated with thin or absent subsoils along the Ridge at Staleen and the Alluvium and Gravel deposits along the River Boyne and River Nanny. According to the GSI Recharge Map, recharge in this area varies between <50 mm/a to 450-500mm/a. The relevant WFD Groundwater bodies in this area include, Drogheda, Donore, Trim, Realtage, and Bettystown. The 2013-2018 Water Framework Directive Quantitative Status for these groundwater bodies is ’Good’ with the exception of Bettystown, which has ‘Poor’ status

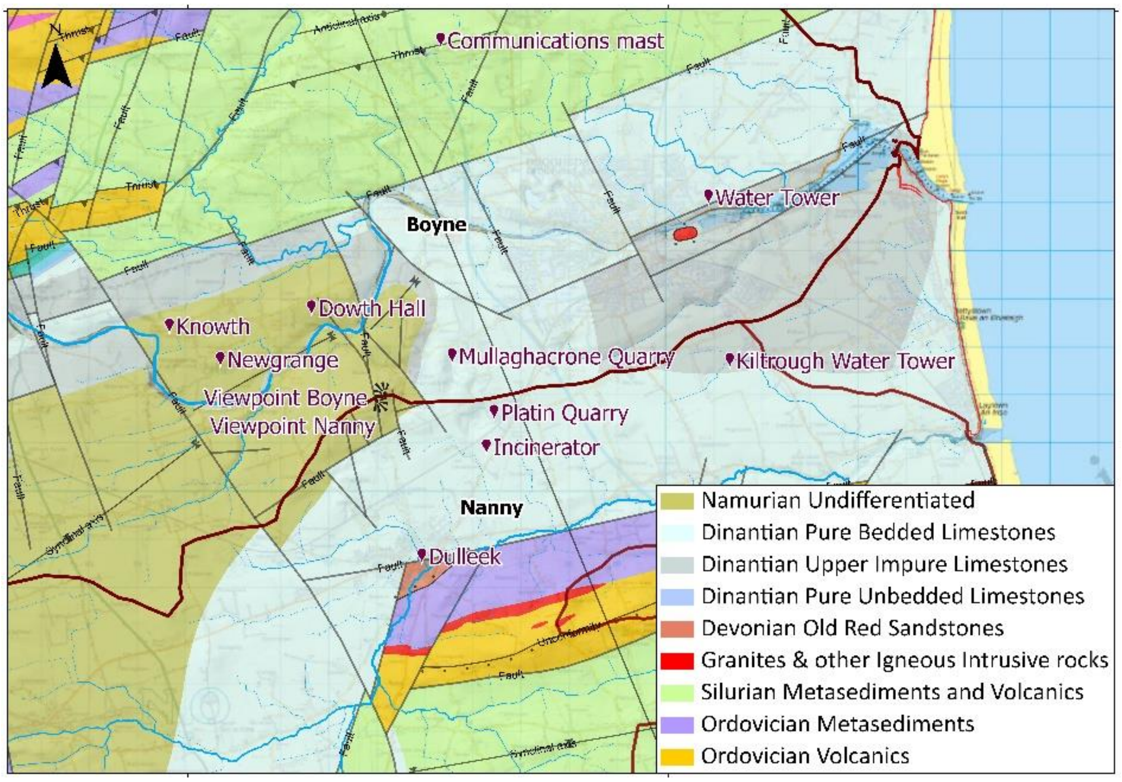


Figure 39: Bedrock geology of east Meath / south Louth (Boyne / Nanny Catchment Divide).

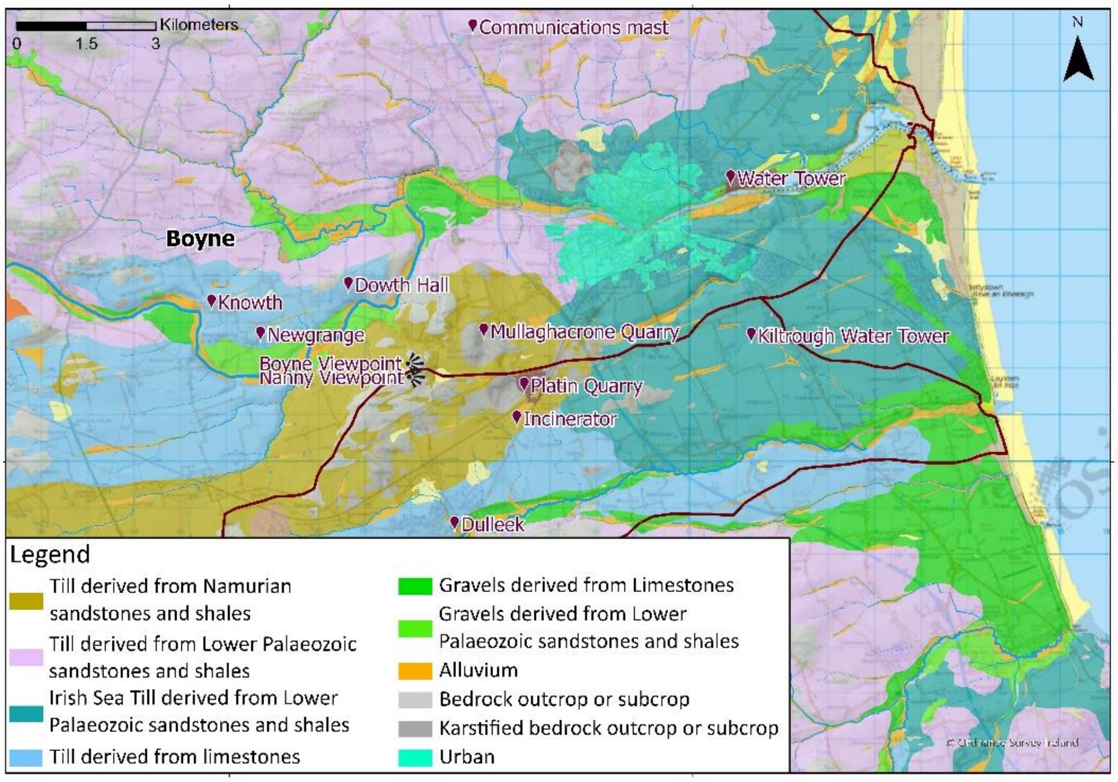


Figure 40: Subsoils geology of east Meath / south Louth (Boyne / Nanny Catchment Divide).

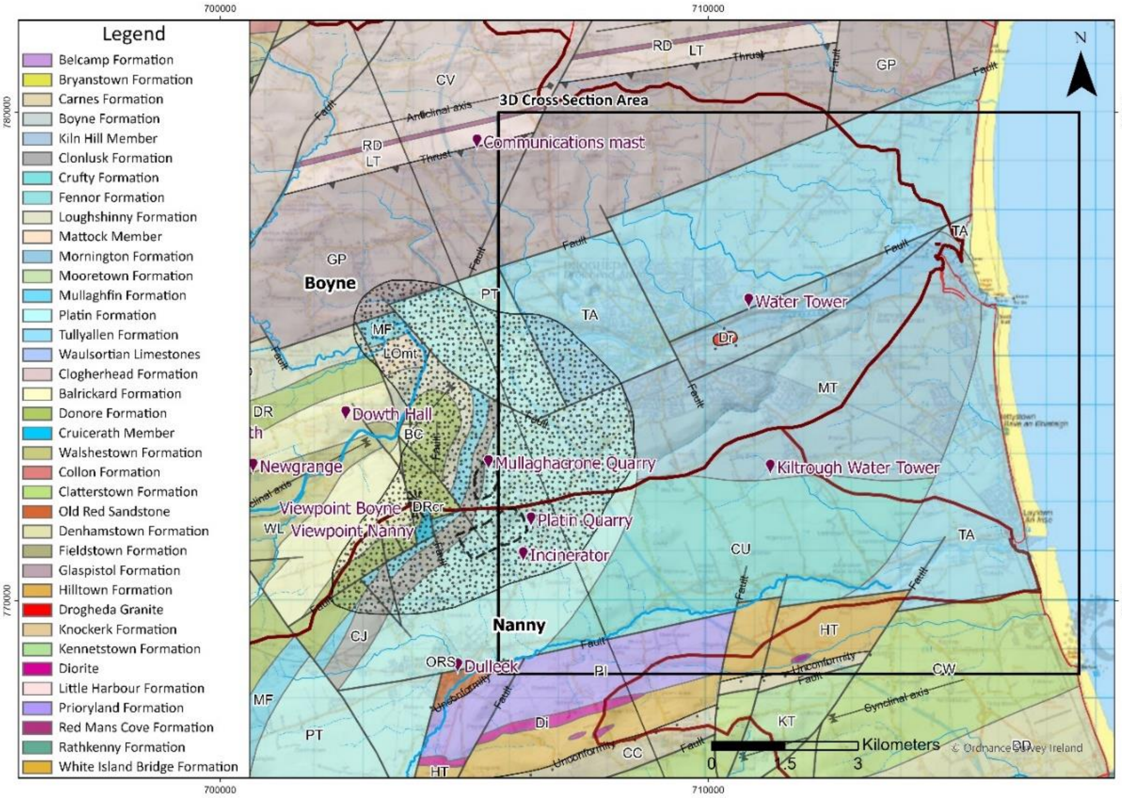


Figure 41: GSI Bedrock Geology of Ireland, at a scale of 1:100,000. The Platin Quarry Zone of Contribution (stippled area) is shown (delineated by AWN, 2019) and the 3D cross section area (Figure 42) is indicated by the black box

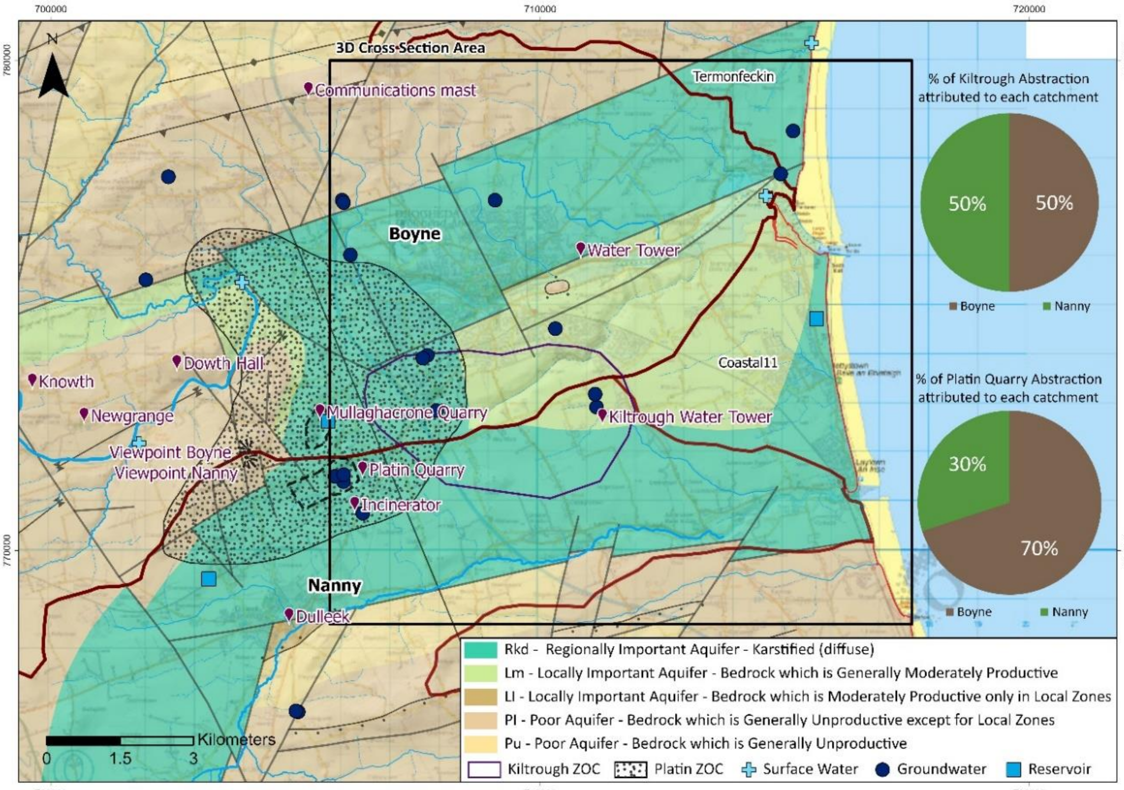


Figure 42: GSI Aquifer Map. Data sources: EPA abstraction database, Platin Quarry ZOC (AWN), Kiltrough ZOC (Tobin, 2008).

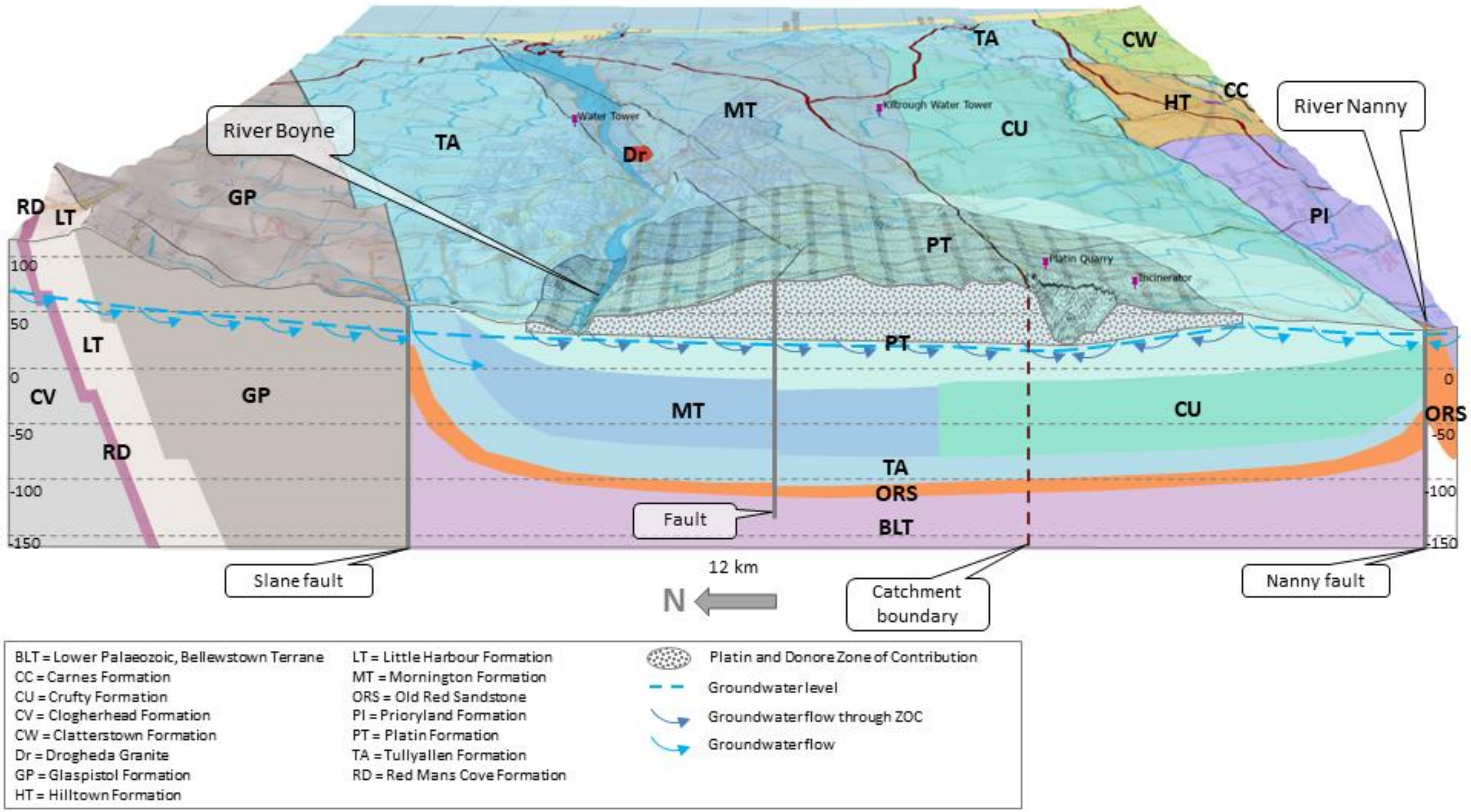


Figure 43. Hydrogeological Cross Section through the Platin Quarry Zone of Contribution (delineated by AWN, 2019) which bridges the Boyne and Nanny Catchments (see figure 6) illustrating groundwater flow from the Boyne Catchment to the Nanny Catchment .

Inter-Catchment Groundwater Flow

The GW3D groundwater resource assessment methodology assumes that groundwater flow follows catchment boundaries. The delineated Zones of Contribution (ZOC) to the Platin Quarry abstractions and the Kiltrough abstraction bridge the Nanny - Boyne Catchment divide indicate that this assumption is not met within these zones. The GW3D project has dealt with the variation from this assumption by interpreting available data and using water balance calculations to estimate the volume of groundwater crossing the catchment divide.

In this case the areal proportion of the ZOC delineated within each catchment, is used to estimate the volume of groundwater contributed from each catchment to support the Kiltrough/Bettystown boreholes and the Platin Quarry abstractions.

Summary

The methodology for GSI's GW3D project follows international best practice of using surface water boundaries as the unit of assessment for the impact of abstraction on the catchment's water resources. This methodology assumes that groundwater flow follows the catchment boundaries. The Nanny - Boyne catchment boundary is an example of where that assumption does not hold. In settings that vary from the assumptions, the report methodology is adapted.

For the Boyne and Nanny catchments the methodology is adapted to estimate inter-catchment groundwater flow, where appropriate, and adapted estimates are included in the catchment water balance calculations. The adaption of the methodology to account for inter-catchment groundwater flow ensures the groundwater resource assessment provides the best estimate of regional groundwater resource potential for all catchments.

References

AWN (2019) Conceptual site model for East Meath groundwater augmentation scheme, for Meath County Council.

EPA Abstractions Database (2020).

EPA Discharges Database (2020).

Geological Survey Ireland Maps (2022).

Hydrometric data (waterlevel.ie

Tobin Engineers (2008). Kiltrough Groundwater Source Protection Report, for Meath County Council.