Poorly Productive Aquifers

Monitoring Installations and Conceptual Understanding

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Acronyms

2-D	Two-Dimensional
CDM	CDM Ireland Ltd.
DC	Dripsey Catchment
DSA	Drill-String Assembly
EC	Electrical Conductivity
EPA	Environmental Protection Agency
ERBD	Eastern River Basin District
GC	Glencastle Catchment
GOC	Gortinlieve Catchment
GIS	Geographic Information System
GWG	National Groundwater Working Group
GWP	Groundwater Works Programme
HiRAT	High-Resolution Acoustic Televiewer
IGI	Institute of Geologists of Ireland
K	Hydraulic conductivity
km^2	Square Kilometres
m	Metres
m^3	Cubic Metres
m ags	Metres Above Ground Surface
m bgs	Metres Below Ground Surface
m TOC	Metres Below Top of Steel Casing
MC	Mattock Catchment
MCC	Meath County Council
mg/L	Milligrams per Litre
mm	Millimetres
µg/L	Microgram per Litre
NC	Newvillage Catchment
NO_3	Nitrate
NPWS	National Parks and Wildlife Service
NWRBD	Northwestern River Basin District
OCM	O'Callaghan Moran & Associates
OPW	Office of Public Works
pNHA	Proposed Natural Heritage Area
PPA	Poorly Productive Aquifers
RC	Ryewater Catchment
RHT	Rising Head Tests
SAC	Special Area of Conservation
SERBD	Southeastern River Basin District
SH	Supervising Hydrogeologist
TZ	Transition Zone
WRBD	Western River Basin District

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Lastly, the CDM/OCM team wishes to acknowledge the interest and assistance received from all of the various landowners, including Coillte and Carton Estate, for allowing monitoring networks to be constructed on their lands.

1. Introduction

Project Background

As part of implementation of the European Union (EU) Water Framework Directive (WFD), the Environmental Protection Agency (EPA) is implementing a national groundwater monitoring programme across Ireland. The present monitoring network, shown in **Figure 1**, was established in December 2006, and comprises more than 220 wells and springs. It includes routine monitoring of groundwater levels, spring flows, and groundwater quality.

The monitoring points are mostly located within “productive aquifers” (as defined by the Geological Survey of Ireland - GSI) which are regionally or locally important as sources of groundwater for public and private supply schemes. With the exception of wells that are located within higher-yielding fault zones, the monitoring network does not include wells or springs located within “poorly productive aquifers” (PPAs) i.e., aquifers which are generally considered as “unproductive” (low well yields). As defined by the GSI, PPAs include aquifer categories Pu, Pl, and Ll (DELG/EPA/GSI, 1999; GSI, 2006).

- Pu – bedrock aquifers which are generally unproductive;
- Pl – bedrock aquifers which are generally unproductive except for local zones;
- Ll – bedrock aquifers which are moderately productive only in local zones.

PPAs are of particular significance as they are mapped by the GSI to cover nearly two-thirds of the total land area of Ireland. Although they are generally not regarded as important sources of water for public water supply (although occasionally high-yielding wells can be drilled in fault-zones), they are nonetheless believed to be important in terms of delivering water (and associated pollutants) to rivers and lakes via shallow groundwater pathways (EPA, 2006). For this reason, the EPA is incorporating PPAs into its long-term monitoring programme, but with a focus and means of monitoring which is very different from regionally important aquifers, as described below.

To begin the process of WFD-monitoring of PPAs, the EPA funded the construction of new monitoring wells through the Groundwater Works Programme (GWP). Commissioned by Carlow County Council, the programme was carried out between November 2007 and December 2009. Although monitoring is being led by the EPA, ownership of new monitoring wells has been assumed by Local Authorities in respective counties as Local Authorities are the recognised competent authorities for long-term WFD implementation.

EPA’s monitoring of PPAs is a long-term commitment, and data will be periodically reviewed to feed into the WFD-required process of river basin management planning and implementation of Programmes of Measures (EPA, 2006).

Objectives and Approach

The key objectives of the GWP were two-fold:

- To improve the hydrogeological characterisation and understanding of PPAs;
- To leave behind a high-quality monitoring network that is representative of PPAs.

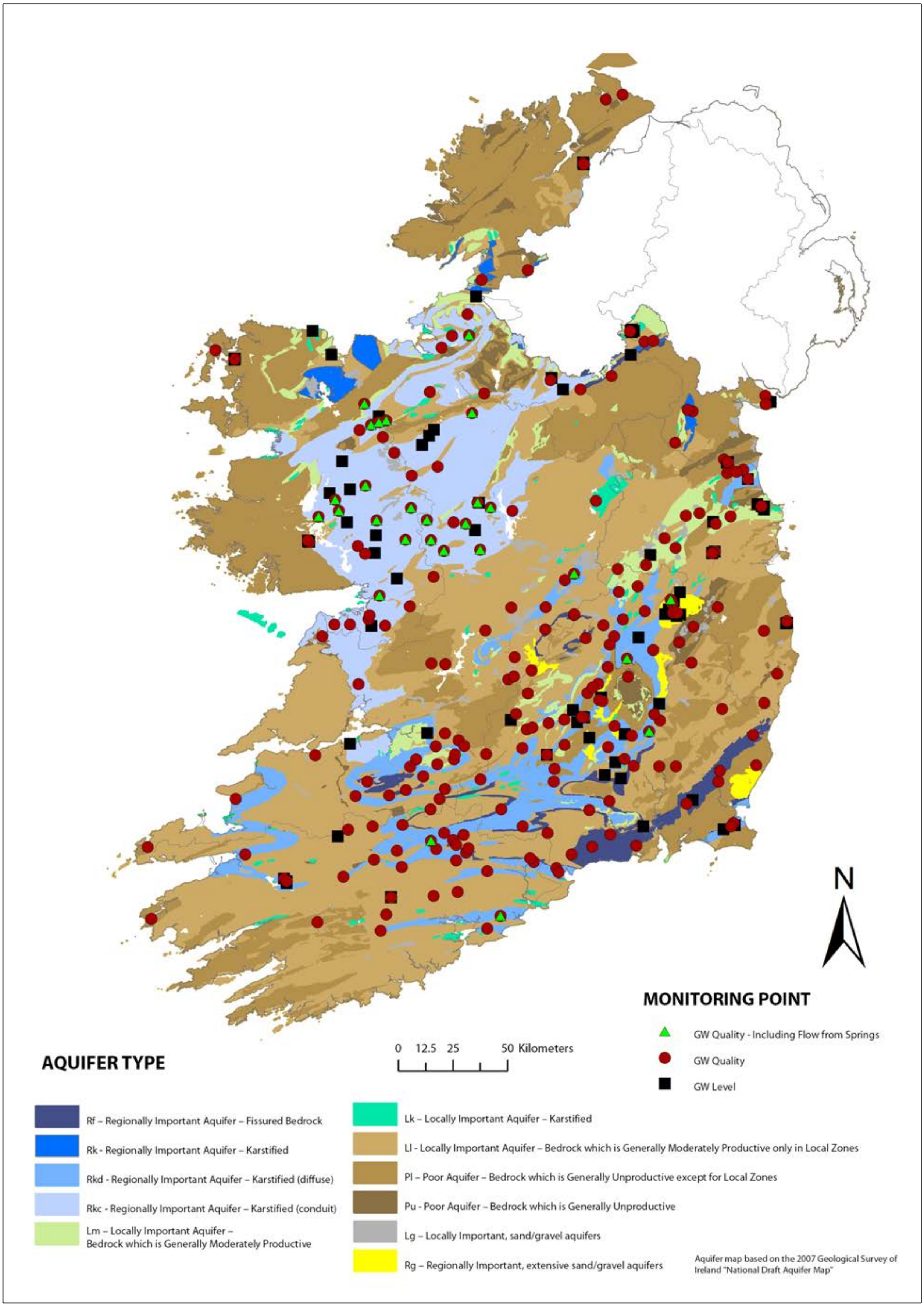


Figure 1: *EPA's Groundwater Monitoring Network and Mapped Distribution of Poorly Productive Aquifers*

To achieve this objective, an investigation-focused approach was needed to quantify, to the extent possible, the primary controls on groundwater flow. Groundwater in PPAs flows through fractures and fissures. What distinguishes PPAs from regionally important aquifers is that they tend to transmit, and therefore yield, small quantities of water compared to regionally important aquifers. PPAs are characterised by low transmissive and storage properties. As such, groundwater occurrences are unpredictable and flow patterns are determined by heterogeneities associated with the geometry of related fractures and fissures.

Because of these properties, PPAs are in theory not capable of accepting all of the recharge that may be available from rainfall, resulting in rejected recharge (Aldwell et al, 1983) and enhanced discharges to local streams via shallow groundwater pathways and overland flow. As a result, PPAs tend to be characterised by small, localised groundwater flow systems. Whereas groundwater flow paths in regionally important aquifers are known to occur on a scale of several hundred metres to a few kilometres, groundwater flow in PPAs tends to be localised at a subcatchment scale, with flow occurring over a few tens to hundreds of metres between recharge and discharge areas.

Selected PPA Catchments

Catchments in which monitoring wells have been constructed to date are summarised in **Table 1** and shown in **Figure 2**.

Catchments were selected based on a set of selection criteria:

- Land access (landowner agreements);
- Access for drilling equipment and materials;
- Single rock type (geology) present within catchment;
- Single (dominant) environmental pressure within a catchment;
- Hydrometric gauging station present on associated stream/river.

A large number of candidate catchments were initially screened for suitability, with follow up site visits. Many candidate catchments were dropped on the basis of land ownership and access issues.

2. Technical Approach

The inherent heterogeneity of PPAs adds complexity to their monitoring, and it is difficult to define or judge what truly constitutes a “representative” monitoring network. Different monitoring approaches were discussed extensively in the national groundwater working group (GWG) that was established in 2001 following the start of WFD implementation in Ireland. One of the principles that were quickly agreed to was that single monitoring wells in single catchments do not provide an adequate or representative description of groundwater conditions in PPAs, and that the site-specific nature of PPAs warrants a “statistical” approach, whereby several wells are needed to adequately describe groundwater movement and water quality within a given catchment. The technical approach adopted by the GWG therefore centres on two main themes:

- Establishing a high-quality monitoring network of clustered wells in different catchments representing different PPA settings across Ireland;
- Encouraging the participation of academic institutions to carry out relevant catchment studies for purposes of research.

Table 1: *Summary of Selected PPA Catchments*

Catchment	Geology and Land Use	Reason for Selection
Glencastle, Mayo	Precambrian Gneiss; Low-intensity cattle and sheep grazing	Representative catchment of Co. Mayo; Single land use over catchment; Hydrometric gauging station available.
Newvillage, Galway	Granite; 100% managed forestry	Granites cover large areas in the east and west of Ireland; Single rock type over catchment; Single land use (pressure) over catchment; Single landowner.
Dripsey, Cork	Devonian Old Red Sandstone; Grassland – grazing (cattle farm)	Catchment already intensively studied under the STRIVE project (Tunney et al, 2007), but not from a groundwater perspective; Hydrometric gauging station available; Single rock-type over catchment; Single land use over catchment; Nutrient-impacted streams; Single landowner.
Mattock, Meath	Ordovician meta-sediments (greywacke); Grassland – grazing (cattle farm)	Representative catchment of Louth/east Meath; Single rock-type over catchment; Single land use over catchment; Nutrient-impacted (Poor Status) streams; Good access for installing much-needed hydrometric gauging station; Single landowner.
Ryewater, Meath	Dinantian impure limestone (“Calp”); Low-intensity grassland and natural forests	Calp setting – representative of east-central Ireland; Adjacent to a wetland cSAC; Nutrient-impacted (Poor Status) salmonid river; Hydrometric gauging station available; River subject to numerous past environmental studies; Single landowner.
Gortinleive, Donegal	Dalradian metasediments (schist, psammite); Grassland (sheep, cattle) and tillage	Cross-border region; Shared use of catchment with the Geological Survey of Northern Ireland; Good access for installing hydrometric gauging station.

To establish a representative monitoring network in a PPA catchment, adequate site-specific hydrogeological information must be developed. The underlying principle towards establishing a monitoring network in PPAs is therefore adequate hydrogeological site characterisation, involving geological mapping, drilling, geological and geophysical logging, and hydraulic testing.

Given the importance assigned to the investigative work and the means of well construction, all drilling, testing and completion activities have been supervised on a full-time basis by a qualified hydrogeologist. As well, the drilling equipment used was carefully selected during a tendering process in which technical approach, proposed equipment and the experience level of drilling firms were assigned high priority.

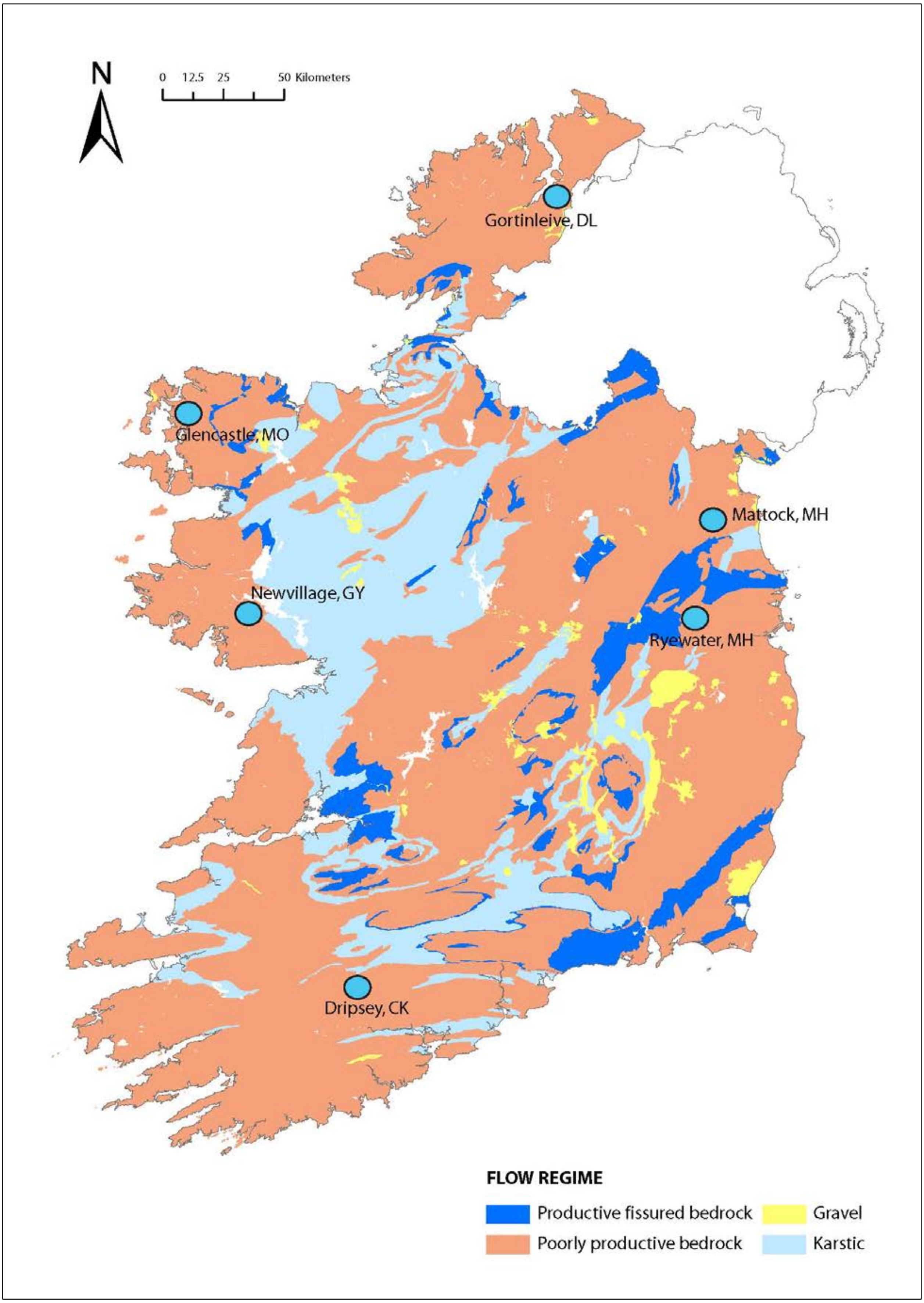


Figure 2: *PPA Catchments Included in the Groundwater Works Programme*

Drilling in each of the 6 catchments took place in the winter and spring months. The intent was to construct wells during wet conditions when groundwater tables are higher and the chances of installing 'dry' wells are reduced.

On average, drilling, testing and well construction works were completed within a 4 week period in each of the 6 catchments. Landowner discussions and agreements have required much longer time, and in one extreme case, the lead-in time to begin drilling required more than 4 months of discussion and negotiations. Each agreement that has been reached is quite different in scope and nature, reflecting constraints and circumstances that are typically imposed by individual landowners.

All drilling works were preceded by a non-intrusive surface geophysical survey along and perpendicular to the selected transect on which wells are constructed. The purpose of the surveying was to assist in the development of the conceptual model of each catchment and describe the hydrogeology of each site in context of drilling results.

To the extent possible, drilling works began at the site nearest the stream or river in each catchment. Drilling then proceeded up the same catchment. This sequencing was not always possible due to unforeseen circumstances that would usually involve landowners' schedules or opinions.

Groundwater Pathways

The conceptual model for PPAs considered four groundwater pathways, as shown in **Figure 3**:

- Subsoils;
- A "transition zone" between subsoils and underlying bedrock;
- Shallow bedrock;
- Deeper bedrock.

Subsoils are represented by lithologies such as glacial till or alluvial sediments along stream courses. The "transition zone" (TZ) is the boundary between subsoils and weathered bedrock. Its physical appearance is often "rubbly", represented by broken pieces of rock and a dense network of shallow fractures which may be infilled to varying degrees by subsoil and/or weathered bedrock.

The TZ can transmit relatively large quantities of groundwater quickly (driven by physical TZ gradients). In the lower portions of a catchment, the TZ (if present) can be saturated all year around. However, at higher positions within a catchment, the TZ can dry up temporarily during periods of no rainfall. Shallow bedrock occurs immediately beneath the TZ. It may or may not be weathered, and the fractures and joints in the rock may or may not be clogged with residual clays. Like the TZ, shallow bedrock may be temporarily (seasonally) dry.

Deep bedrock is conceptually a deeper section in which fractures and fissures transmit groundwater and support baseflow of streams all year around. Conceptually, there are fewer (or less frequent) fractures and fissures with increasing depth, but this is not always the case.

In context of groundwater monitoring, the decision about what constitutes shallow and deep bedrock is somewhat subjective, and is ultimately interpreted and defined by the hydrogeologist in the field based on investigation results.

It is important to note that all pathways may not be present or apparent at any given location within a PPA catchment.

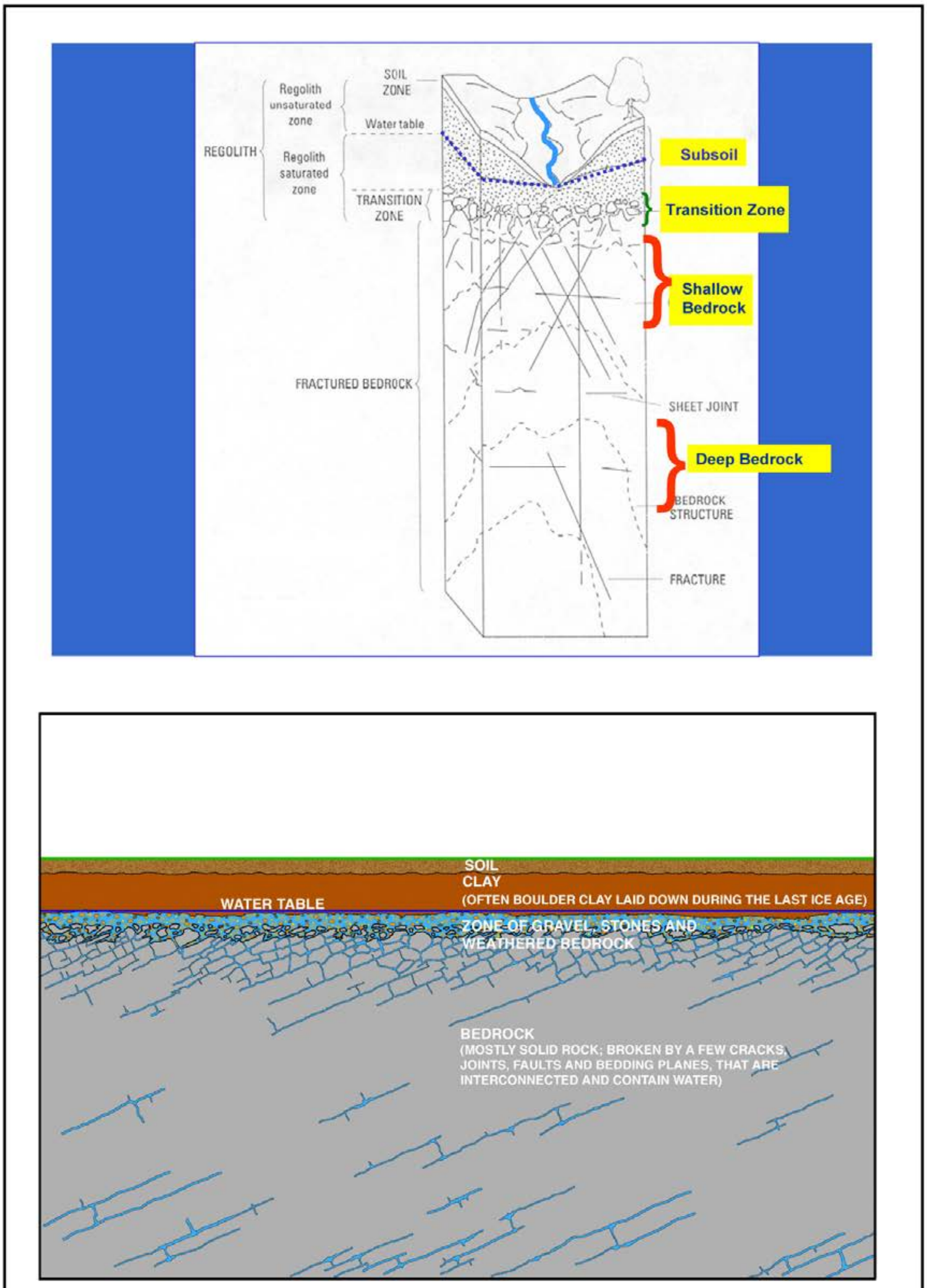
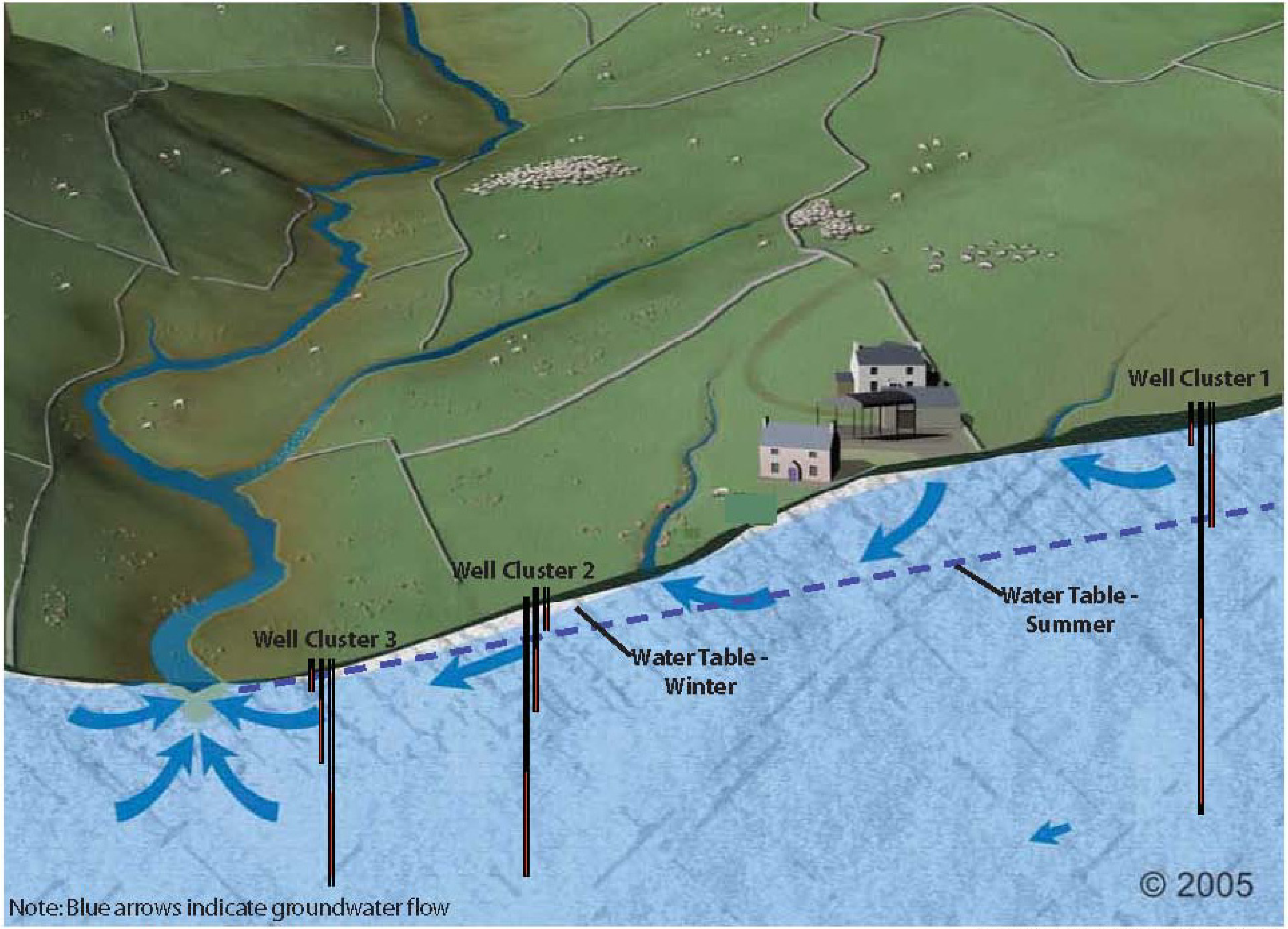


Diagram courtesy of David Ball

Figure 3: *Subsurface Pathways and Monitoring Targets*

Based on investigation results, depth-specific monitoring wells were constructed according to where groundwater movement is demonstrated or interpreted to take place. As shown in **Figure 4**, this involves the construction of well clusters along a transect between a recharge area (high up in the catchment) and a discharge area (near streams, rivers or lakes).



Adapted by Daly from www.wfdvisual.com

Figure 4: *Conceptual Diagram of Well Clusters Along a Transect*

For the purposes of the GWP, and to initiate the process of monitoring PPAs, up to twelve monitoring wells were installed at three clusters (sites) located along a transect which runs perpendicularly to the alignment of a nearby river or stream. The final depths of individual wells vary from one site to another based on findings during drilling.

A key concept to the monitoring of PPAs is to ensure that (vertical) monitoring intervals do not overlap. This is regarded as vital to the representativity of each monitoring interval – i.e., each interval provides a unique signature both in terms of hydraulic (water level) response and water chemistry. Care must therefore be taken to ensure that monitoring intervals are unique to individual wells and that chances for cross-flow between monitoring intervals in any given well cluster is avoided. This is accomplished in two ways:

- Allowing sufficient vertical separation between monitoring intervals;
- Following proper well construction practices (IGI 2007), including grouting of PVC casing at each well.

In addition, successively deeper wells in a cluster are constructed in the presumed downgradient direction in order to minimise the chances of grout penetrating and affecting the water quality of shallower wells in the same cluster.

Transition zone at Newvillage, Galway

3. Well Drilling and Construction

Table 2 summarises the wells constructed in each of the 6 catchments. A total of 61 wells were constructed:

- Nine (9) in subsoils;
- Fourteen (14) in the transition zone;
- Twenty (20) in shallow bedrock; and
- Eighteen (18) in deep bedrock.

Subsoil wells could not be constructed at all drill sites either because subsoils were absent altogether (e.g., Newvillage) or too thin to be able to construct a well (e.g., Gortinlieve). Overall, the important transition zone was evident at 75% of the selected drill sites (the main exception being the Mattock catchment).

All boreholes were developed by air-lifting upon completion, and development was continued until the formation water, as observed at the surface, became free of sediment. Subsoil wells were developed using an above ground pump and attached suction hose.

Deep Bedrock Wells

The deep bedrock wells were constructed as follows:

- A 304 mm (12 inch) or 254 mm (10 inch) nominal diameter air hammer was advanced approximately 0.5 m into the top of bedrock.
- A permanent 254 mm outer diameter steel casing was driven and installed from the ground surface to about 0.5 m into the top of bedrock.
- The 254 mm nominal diameter air hammer was advanced from the bottom of the permanent 254 mm casing to total depth (site-specific).
- 152 mm diameter unplasticised Polyvinyl Chloride (uPVC) riser pipes (casing) were lowered and grouted into place in each of the boreholes.
- Borings were advanced through the 152 mm riser pipes (casing) with a 149 mm (5-7/8 inch) nominal diameter air hammer to the total depth of the borings (site-specific).
- The wells were completed as open borehole sections below the riser pipes. No screens or filter pack were installed.

Shallow Bedrock Wells

Shallow bedrock wells were constructed as follows:

Table 2: *Summary of Construction Details of All Monitoring Wells*

Monitoring Well ID	Depth (m)	152 mm uPVC Riser	Completion of Screen/Open Interval	6 in. PVC Sump	Screen / Uncased Borehole			Screened Interval
					Depth		Length (m)	
					Top (m)	Bottom (m)		
Newvillage, Co. Galway								
NV1-Deep	64.00	0.6m ags to 21.6m bgs	Open 6 in. borehole	N/A	21.60	64.00	42.40	Deep Bedrock
NV1-Shallow(1)	21.60	0.63m ags to 9.7m bgs	Open 6 in. borehole	N/A	9.70	21.60	11.90	Shallow Bedrock
NV1-Shallow(2)	20.70	0.55m ags to 9.3m bgs	Open 6 in. borehole	N/A	9.30	20.70	11.40	Shallow Bedrock
NV1-Transition	2.95	0.45m ags to 0.75m bgs	6 in. PVC screen with 2mm slots, screen covered with 300 micron filter fabric	2.75 to 2.95m bgs	0.75	2.75	2.00	Transition Zone
NV2-Deep	64.00	0.57m ags to 21.6m bgs	Open 6 in. borehole	N/A	21.60	64.00	42.40	Deep Bedrock
NV2-Shallow	10.70	0.2m ags to 2.4m bgs	Open 6 in. borehole	N/A	2.40	10.70	8.30	Shallow Bedrock
NV2-Transition	1.50	0.5m ags to 0.5m bgs	6 in. PVC screen with 2mm slots, screen covered with 300 micron filter fabric	1.3 to 1.5m bgs	0.50	1.30	0.80	Transition Zone
NV3-Deep	64.00	1.2m ags to 19.5m bgs	Open 6 in. borehole	N/A	19.50	64.00	44.50	Deep Bedrock
NV3-Shallow	12.70	0.52m ags to 4.5m bgs	Open 6 in. borehole	N/A	4.50	12.70	8.20	Shallow Bedrock
NV3-Transition	2.90	0.52m ags to 0.4m bgs	6 in. PVC screen with 2mm slots, screen covered with 300 micron filter fabric	2.7 to 2.9m bgs	0.40	2.70	2.30	Transition Zone
Mattock, Co. Meath								
MK1-Deep	70.10	0.3m ags to 30.2m bgs	Open 6 in. borehole	N/A	30.20	70.10	39.90	Deep Bedrock

Monitoring Well ID	Depth (m)	152 mm uPVC Riser	Completion of Screen/Open Interval	6 in. PVC Sump	Screen / Uncased Borehole			Screened Interval
					Depth		Length (m)	
					Top (m)	Bottom (m)		
MK1-Shallow	22.90	0.3m ags to 6.7m bgs	Open 6 in. borehole	N/A	6.70	22.90	16.20	Shallow Bedrock
MK1-Subsoil	1.80	0.3m ags to 1.2m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter fabric	1.8 to 2.1m bgs	1.20	1.80	0.60	Subsoil and top of Bedrock
MK2-Deep	61.00	0.33m ags to 27.4m bgs	Open 6 in. borehole	N/A	27.40	61.00	33.60	Deep Bedrock
MK2-Shallow	22.90	0.32m ags to 7.9m bgs	Open 6 in. borehole	N/A	7.90	22.90	15.00	Shallow Bedrock
MK3-Deep	57.90	0.33m ags to 36.6m bgs	Open 6 in. borehole	N/A	36.60	57.90	21.30	Deep Bedrock
MK3-Shallow	27.70	0.16m ags to 21.6m bgs	Open 6 in. borehole	N/A	21.60	27.70	6.10	Shallow Bedrock
MK3-Subsoil1	2.75	2.5 inch uPVC Riser Pipe:0.35m ags to 1.25m bgs	2.5 in. uPVC slotted screen, screen covered with 300 micron filter fabric	N/A	1.25	2.75	1.50	Subsoil (Alluvium)
MK3-Subsoil2	8.70	2.5 inch uPVC Riser Pipe:0.35m ags to 7.2m bgs	2.5 in. uPVC slotted screen, screen covered with 300 micron filter fabric	N/A	7.20	8.70	1.50	Subsoil (Alluvium)
Glencastle, Co. Mayo								
GC1-Deep	61.00	0.4m ags to 24.4m bgs	Open 6 in. borehole	N/A	24.40	61.00	36.60	Deep Bedrock
GC1-Shallow	22.90	0.35m ags to 7m bgs	Open 6 in. borehole	N/A	7.00	22.90	15.90	Shallow Bedrock
GC1-Subsoil	2.15	0.55m ags to 0.45m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter	1.95 to 2.15m bgs	0.45	1.95	1.50	Subsoil
GC2-Deep	64.00	0.35m ags to 21.3m bgs	Open 6 in. borehole	N/A	21.30	64.00	42.70	Deep Bedrock

Monitoring Well ID	Depth (m)	152 mm uPVC Riser	Completion of Screen/Open Interval	6 in. PVC Sump	Screen / Uncased Borehole Depth			Screened Interval
					Top (m)	Bottom (m)	Length (m)	
GC2-Shallow	20.40	0.35m ags to 7.2m bgs	Open 6 in. borehole	N/A	7.20	20.40	13.20	Shallow Bedrock
GC2-Transition	7.10	0.22m ags to 4.9m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter	6.9 to 7.1m bgs	4.90	6.90	2.00	Transition Zone
GC2-Subsoil	4.00	0.3m ags to 2m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter	3.8 to 4.0m bgs	2.00	3.80	1.80	Subsoil
GC3-Deep	78.90	~0.75m ags to 21.6m bgs	Open 6 in. borehole	N/A	21.60	78.90	57.30	Deep Bedrock
GC3-Shallow	16.20	~0.5m ags to 10.4m bgs	Open 6 in. borehole	N/A	10.40	16.20	5.80	Shallow Bedrock
GC3-Transition	6.70	~0.5m ags to 4.4m bgs	Open 6 in. borehole	N/A	4.40	6.70	2.30	Transition Zone
GC3-Subsoil	3.10	~0.5m ags to 0.9m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter	2.9 to 3.1m bgs	0.90	2.90	2.00	Subsoil
Dripsey, Co. Cork								
DR1-Deep	70.10	~0.2m ags to 26.82m bgs	Open 6 in. borehole	N/A	26.82	70.10	43.28	Deep Bedrock
DR1-Intermediate	22.86	~0.1m ags to 15.54m bgs	Open 6 in. borehole	N/A	15.54	22.86	7.32	Intermediate Bedrock
DR1-Shallow	12.20	~0.3m ags to 5.48m bgs	Open 6 in. borehole	N/A	5.48	12.20	6.72	Shallow Bedrock
DR1-Transition	1.80	~0.1m ags to 0.9m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter fabric	1.8m to 2m bgs	0.90	1.80	0.90	Transition Zone
DR2-Deep	60.96	~0.2m ags to 21.94m bgs	Open 6 in. borehole	N/A	21.94	60.96	39.02	Deep Bedrock
DR2-Shallow	16.15	~0.35m ags to 6.7m bgs	Open 6 in. borehole	N/A	6.70	16.15	9.45	Shallow Bedrock

Monitoring Well ID	Depth (m)	152 mm uPVC Riser	Completion of Screen/Open Interval	6 in. PVC Sump	Screen / Uncased Borehole			Screened Interval
					Depth		Length (m)	
					Top (m)	Bottom (m)		
DR2-Transition	5.90	~0.8m ags to 2m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter	5.9 to 6.1m bgs	2.00	5.90	3.90	Transition Zone
DR3-Deep	60.96	~0.2m ags to 21.95m bgs	Open 6 in. borehole	N/A	21.95	60.96	39.01	Deep Bedrock
DR3-Shallow	15.24	~0.25m ags to 8.22m bgs	Open 6 in. borehole	N/A	8.22	15.24	7.02	Shallow Bedrock
DR3-Transition	6.71	0.35m ags to 2.43m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter fabric	6.5 to 6.7m bgs	2.43	6.71	4.28	Transition Zone
DR3-Subsoil	1.80	~0.1m ags to 0.9m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter fabric	1.8 to 2.0m bgs	0.90	1.80	0.90	Subsoil
Ryewater, Co. Meath								
RW1-Deep	67.40	0.3 m ags to 34.4m bgs	Open 6 in. borehole	N/a	34.40	67.40	33.00	Deep Bedrock
RW1-Shallow	30.00	0.4 m ags to 9.5 m bgs	Open 6 in. borehole	N/a	9.50	30.00	20.50	Shallow Bedrock
RW1-Transition	3.20	0.2 m ags to 2.3m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter	N/a	2.30	3.20	0.90	Weathered zone at top of bedrock
RW2-Deep	70.40	0.7 m ags to 34.4m bgs	Open 6 in. borehole	N/a	34.40	70.40	36.00	Deep Bedrock
RW2-Shallow	27.40	0.8m ags to 5.2m bgs	Open 6 in. borehole	N/a	5.20	27.40	22.20	Shallow Bedrock
RW2-Transition	2.90	1 m ags to 1.98 m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter	N/a	1.98	2.90	0.92	Weathered zone at top of Bedrock
RW3-Deep	82.30	0.70m ags to 39.2m bgs	Open 6 in. borehole	N/a	39.20	82.30	43.10	Deep Bedrock
RW3-Shallow	27.40	0.8m ags to 16.8m bgs	Open 6 in. borehole	N/a	16.80	27.40	10.60	Shallow Bedrock

Monitoring Well ID	Depth (m)	152 mm uPVC Riser	Completion of Screen/Open Interval	6 in. PVC Sump	Screen / Uncased Borehole			Screened Interval
					Depth		Length (m)	
					Top (m)	Bottom (m)		
RW3-Transition	14.50	1.1m ags to 13.5m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter fabric	14.4 to 14.5 m bgs	13.50	14.40	0.90	Pebble bed at top of bedrock
RW3-Subsoil	6.40	0.65m ags to 4m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter fabric	6.3 to 6.4 m bgs	4.00	6.30	2.30	Subsoil (Alluvium)
Gortinlieve, Co. Donegal								
GO1-Deep	76.20	0.2m ags to 46.6m bgs	Open 6 in. borehole	N/A	46.80	76.20	29.60	Deep Bedrock
GO1-Shallow	13.11	0.2m ags to 4.7m bgs	Open 6 in. borehole	N/A	4.72	13.11	8.38	Shallow Bedrock
GO1-Transition	2.44	0.46m ags to 0.65m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter fabric	2.21 to 2.44m bgs	0.65	2.20	1.55	Transition Zone
GO2-Deep	67.06	0.2m ags to 29.3m bgs	Open 6 in. borehole	NA	29.26	67.06	37.80	Deep Bedrock
GO2-Shallow	15.24	0.3m ags to 7.9m bgs	Open 6 in. borehole	N/A	7.92	15.24	7.32	Shallow Bedrock
GO2-Transition	3.05	0.4m ags to 0.63m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter fabric	2.85 to 3.05m bgs	0.63	2.85	2.22	Transition Zone
GO3-Deep	53.34	0.4m ags to 36.27m bgs	Open 6 in. borehole	N/A	36.27	53.34	17.07	Deep Bedrock
GO3-Shallow	23.77	0.36m ags to 12.19m bgs	Open 6 in. borehole	N/A	12.19	23.77	11.58	Shallow Bedrock
GO3-Transition	7.15	0.35m ags to 4.73m bgs	6 in. uPVC screen with 2mm slots, screen covered with 300 micron filter fabric	6.95 to 7.15m bgs	4.73	6.95	2.22	Transition Zone

- A 304 mm (12 inch) or 254 mm nominal diameter air hammer was advanced approximately 0.5 m into the top of bedrock.

- A permanent 254 mm (outer diameter) diameter steel casing was driven from the ground surface to about 0.5 m into the top of bedrock.

- A 254 mm nominal diameter air hammer was advanced from the bottom of the permanent steel casing to the total depth (site-specific).

- 152 mm diameter uPVC riser pipes (casing) were lowered and grouted into place in each of the boreholes.

- Borings were advanced with a 149 mm nominal diameter air hammer from the bottom of the uPVC riser pipe to the total depth (site-specific).

- The wells were completed with open borehole sections below the riser pipes. No screens or filter pack were installed.

Dust from percussion drilling at Ryewater

Transition Zone Wells

Transition Zone wells were constructed at the contact (boundary) between the subsoils and the weathered bedrock as follows:

- A 10 inch nominal diameter air hammer was advanced through the overburden and into the top of weathered bedrock.

- A temporary 10 inch steel casing was used to stabilise the borehole.

- Six (6) inch diameter PVC riser pipe and screen (with a 0.3 m long capped bottom plug) were lowered into the 10 inch diameter borehole.

- Filter pack sand was lowered into the annular space as the 10 inch steel casing was retracted carefully, exposing the filter pack against the PVC screen. The screen had been covered with a 300 micron textile prior to emplacement. The filter pack was introduced to a level approximately 0.3 m above the top of screen. The filter material was sourced from a sand and gravel quarry in Carlow. Limestone was not allowed to be used as filter pack for any of the wells constructed as part of the GWP due to its possible influence as a buffering agent on water quality.

- A 0.2 m thick interval of builders' sand was emplaced on top of the filter pack, again carefully as the 10 inch temporary steel casing was being retracted.

- The remainder of the annular space between the drilled borehole and the 6 inch PVS riser pipe was grouted.

- All filter/sand materials were emplaced with tremie pipes, from the bottom up. The tremie pipe was retracted in line with infilling of materials in the annular space. Fill depths were frequently checked with a weighted tape measure, or with the tremie pipe assembly itself.

Subsoil Wells

A 254 mm nominal diameter air hammer was advanced through the subsoils to the top of bedrock. A temporary 254 mm steel casing was inserted to stabilise the borehole. A 149 mm diameter uPVC riser pipe and screen assembly was lowered inside the steel casing. The 2 mm slot screen was fitted with a 300 micron filter fabric mesh prior to emplacement. The assembly also included a 0.3 m long bottom sump and plug.

Using a tremie pipe, the annular space between the screen and steel casing was backfilled with a filter pack consisting of quartz sand sourced from a known sand and gravel quarry. The steel casing was slowly retracted during the emplacement of the filter pack to a depth approximately 0.4 m above the filter pack. The riser sections were then grouted in place.

Grouting

Proper grouting was a central element of the well design that was followed during the works programme. All 150 mm (6 inch) and 50 mm (2 inch) uPVC riser pipes, as well as riser/screen assemblies, were grouted in place. The purpose of grouting was three-fold:

- To enhance the physical integrity of the completed wells;

- To prevent surface pollutants from running down the annular spaces outside the riser pipe (casing) and "contaminating" the monitoring interval;

- To ensure that the different hydrogeological units targeted for monitoring were hydraulically isolated from one another.

The latter is considered crucial to the programme in terms of ensuring that the hydraulic responses and water chemistry are unique to the interval monitored.

Locally sourced, standard Portland-type cement was used. The grout was emplaced using a tremie pipe which was initially set a small distance above the total depth to be grouted, and successively retracted as grout filled up the annular space of each borehole. The grout was pumped through the tremie pipe from a grout mixing plant. The specific gravity of the cement grout that was targeted during mixing was approximately 1.7–1.8.

Grouting 6-inch PVC casing in place

Cement grout was allowed to set for a period of 18-24 hours prior to the commencement of further work. In some cases, the setting time was accelerated by adding calcium chloride to the cement (not exceeding 4% by weight of the dry cement in each batch of grout). Testing of the grout indicated that the setting time could be reduced to approximately 12 hours. Work was therefore planned in such a way that grouting operations would take place at the end of a given day, so that drilling work could resume the following morning.

As part of the grouting operation, the PVC casings were filled with water on the inside to balance pressure and dissipate heat from the curing of the cement grout. Drill-rod was also placed on top of the casing/screen assembly to prevent it from "lifting" during the grout emplacement and curing period.

Bentonite products were not used in any of the constructed wells.

Wellhead Completion

Each well was completed with a concrete plinth measuring (generally) 0.8 m (W) x 0.8 m (D) x 0.5 m (H). The height of the concrete plinth above ground surface is generally 0.2 m, sloping gently from the steel casing to its edge.

A nameplate for each well was embedded in the concrete identifying the name of the well along with the insignias of the EPA and the Local Authority as the well owner.

A lockable metal cap was welded to each of the protective 10 inch casings at each well. The protective steel casing was subsequently finished with two coats of epoxy paint.

The stick-ups of the 10 inch protective casing are approximately 0.5 m above ground level. The stick-up of the 6 inch PVC casing inside the 10 inch steel casing was left approximately 0.4 m lower, to allow the EPA to suspend their pressure transducer equipment inside each well.

Upon wellhead completion, each drill site was restored to pre-construction conditions, per agreements with landowners.

Completed well cluster at Ryewater with data loggers installed

Artesian Wells

One monitoring well in the Newvillage catchment and three monitoring wells in the Ryewater catchment (all associated with the lowest cluster nearest a river) were artesian at the time of well completion, and water overflowed the 6 inch PVC casing in each case.

As the artesian heads represent a natural condition, continuously overflowing water would flood the lands surrounding the wells. To prevent this situation from occurring, specially-designed wellcaps were constructed to hermetically seal each of the wells in question. The photograph below shows the solution that was arrived at after discussions between the drillers and the hydrometric technicians at EPA who carry out EPA’s long-term monitoring activities. It consists of a wellhead assembly with three different ports that are designed to allow for flexibility in sampling and water level measurement during both artesian and non-artesian conditions.

The assembly is connected to a short piece of 6 inch casing which is threaded onto the main 6 inch PVC casing in the borehole. The whole assembly fits inside the capped 10 inch protective casing/wellhead. The functions of the three ports are as follows:

1. A 25 mm diameter port that can be used for installing a pressure transducer should the groundwater levels become non-artesian in the future.

2. A 100 mm diameter port that can be opened to lower plastic PVC bailers for sampling purposes, should groundwater levels become non-artesian in the future.

3. A 25 mm diameter port equipped with a stop valve and opportunity to install a pressure-meter as well as flexible hosing for pressure and water levels respectively. Whilst the well remains artesian, the idea is that a clear flexible hose can be slid onto the blue end piece and water levels can be measured as a function of the rise in water level inside the clear hose. The same port can also be used for sampling purposes.

1. Port for pressure transducer.
2. Port for PVC bailer.
3. Multi-port for sampling and water level measurement during artesian conditions

4. Hydrogeological Characteristics

Water-Bearing Fractures

Distinct water bearing intervals were noted during drilling. Each borehole was drilled 'dry' (with no added water or additive) in order to be able to clearly identify water bearing fractures or permeable zones. A considerable amount of dust is generated and reduced or eliminated when a water-bearing fracture is encountered, depending on the quantities of water that are encountered. This is vital information, as it is ultimately used to guide decisions about well construction.

During air-lifting, water at the surface was contained by hanging a heavy-duty rubber "skirt" over the drilling platform and channelling the water away from the borehole so that approximate measurements of water volumes (e.g., as litres per minute) could be made. In this way, the supervising hydrogeologist (SH) could assess the relative significance of water strikes at different depths during the course of the drilling.

In the drilling process, the SH would occasionally request the driller to pause the drilling and simply circulate air in the borehole to try to detect possible inflows of water into the borehole. Such inflows would subsequently be air-lifted and measured at the surface. At selected fracture intervals during drilling, the SH would also request the driller to air-surge the borehole at high pressures to remove dust, sediments, or cuttings which can clog fractures and reduce the inflow into the borehole.

The identification of discrete water bearing fractures were subsequently enhanced with geophysical logging tools, which were also used run to:

- Verify final construction details;
- Obtain information on the physical properties of the groundwater and rocks exposed.

Lowering the acoustic televiewer

Although drill cuttings and other rig observations provide clues and evidence of stratigraphic changes and water strikes, the resolution of data are greatly improved with geophysical logging. The following suite of tools was run (in order):

- Fluid conductivity and temperature;
- Three-arm Calliper;
- Natural gamma;
- Short- and long-normal resistivity (including self-potential and single-point resistivity);
- High-resolution flowmeter;
- High resolution acoustic televiewer (HiRAT) and/or downhole video camera.

The HiRAT and video surveys provided the most insightful results in terms of identifying and describing fractures in the open boreholes. The HiRAT remains the only tool that can accurately quantify fractures in terms of their depth, dip, orientation, and aperture. Future investigations of fracture-controlled groundwater flow are therefore well served by HiRAT logs.

Figure 5 shows an example of how, combined with the fluid conductivity and temperature logs, the short- and long-normal resistivity logs were useful in identifying potential groundwater inflow points in a borehole in the Ryewater catchment. Inflection points and cross-overs between the short-and-long normal resistivity responses point to the presence of inflow points.

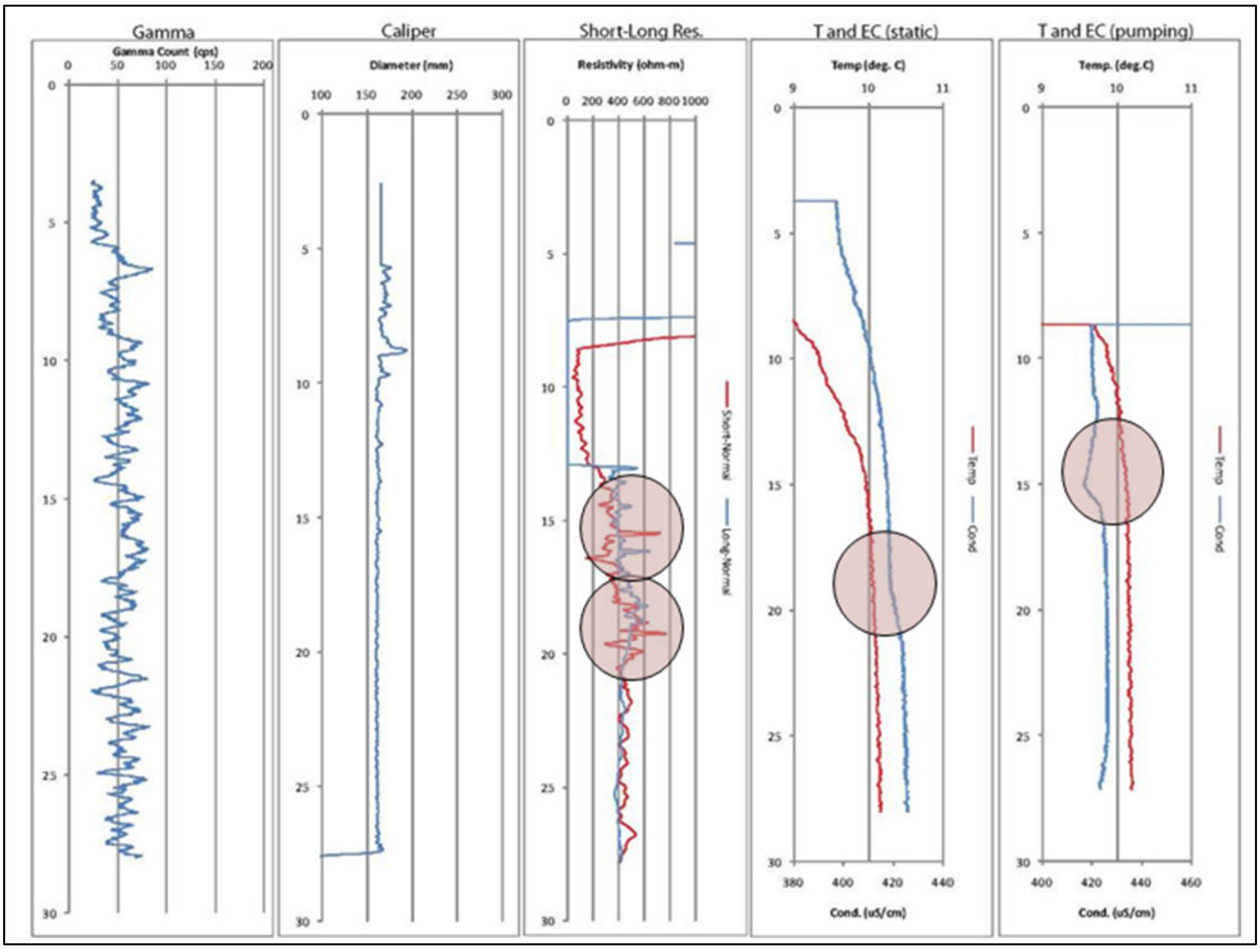


Figure 5: *Combined Use of Geophysical Logs to Identify Inflows*

Figure 6 shows an example of a HiRAT image (logging by Queens University Belfast) and its use in fracture identification. Overall, the HiRAT images indicated a decrease in the presence of fractures with depth, which is consistent with the conceptual models of PPAs, but this generalisation did not apply to two catchments where, albeit as isolated fractures, higher-yielding fractures were detected at depths exceeding 60 m bgs.

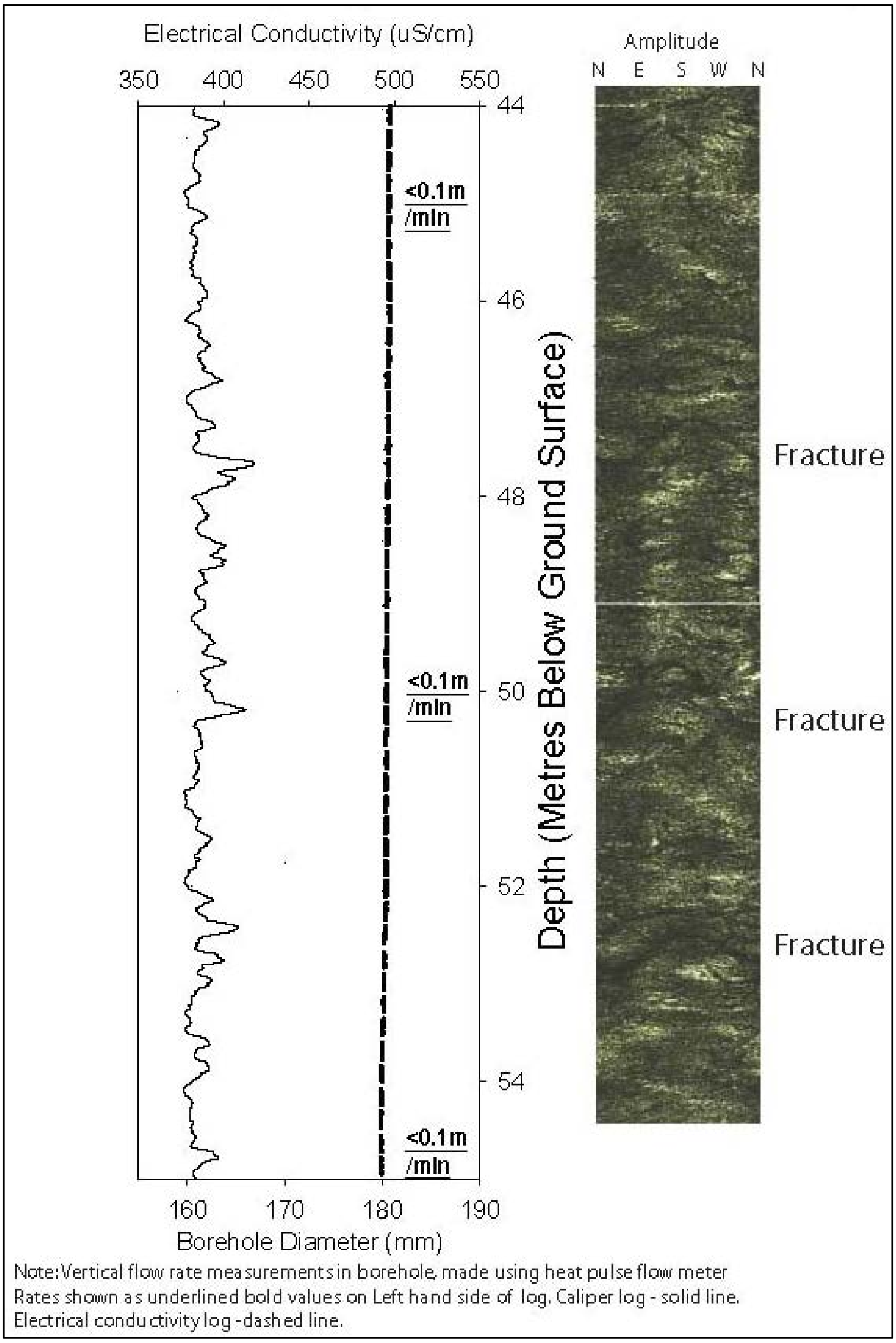


Figure 6: *HiRAT Image*

Hydraulic Testing

Rising head tests (RHTs) and/or falling head tests (FHTs) were carried out on all bedrock wells during drilling and at the completion of well construction. In some boreholes, several RHTs were carried out as the borehole was advanced, whenever noticeable water-yielding fractures were encountered.

For all RHTs and FHTs, the Hvorslev method was used to estimate the hydraulic conductivity of the formation in the open or screened borehole intervals.

Short-duration pump tests were carried out in some wells deemed to be “pumpable”: Because of the generally low permeability characteristics of most boreholes, pumping was carried out with a low-capacity pump capable of lifting approximately 15-20 L/min from approximately 35 m depth. Pumping durations ranged from 30-90 minutes, depending on the measured response to pumping. Water levels were measured during both pumping and recovery phases.

Test results are summarised in **Table 3**. Although the total number of tests for each interval is different, the results nonetheless point to a contrast in hydraulic conductivity between the four intervals, with a large overall range in values, and with higher mean values for the transition zone.

Table 3: *Estimated Hydraulic Conductivity Values (m/d)*

Interval	Minimum	Maximum	Average	Geometric Mean	n
Deep	1.12E-06	6.20E-02	7.71E-03	1.29E-03	26
Shallow	3.34E-05	8.51E-01	1.00E-01	7.53E-03	28
Transition	1.87E-03	2.57E-01	1.25E-01	4.41E-02	6
Subsoil	4.55E-02	6.68E-02	5.62E-02	5.51E-02	2

Corresponding pump test results generally indicated specific capacity values of less than 1 m^3/d per meter of drawdown. Due to the short duration of each pump test (approx 60 minutes), meaningful transmissivity or hydraulic conductivity values were not produced.

Measured Water Levels

At the time of well completion, all but two wells produced a measurable groundwater level. One subsoil well in Glencastle and one shallow bedrock well in Mattock remained dry. Subsequently, the subsoil well in Glencastle has shown a periodic water table following heavy rains, indicative of a perched and temporary groundwater table in the subsoils.

Following well completion, the EPA equipped most of the monitoring wells with automatic data loggers to continuously monitor groundwater levels and temperature. Measurable vertical gradients exist in nearly all well clusters in all catchments, and groundwater levels within well clusters may respond differently to recharge and recession events. As expected, downward gradients are often measured at the top of the catchment whereas upward gradients are measured at the bottom of the catchment nearest the stream.

An example of measured groundwater levels is presented in **Figure 7** for a well cluster in the Ryewater catchment near the Ryewater River**.** Measured water levels in the RW3 well cluster show an upward gradient from bedrock to subsoil and a contrast in hydraulic response between the deep bedrock well and shallower wells in the same cluster. The measured water levels in the transition and bedrock wells are also artesian.

Water level data will be subject to detailed study by the EPA and academic institutions as part of the GSI- and EPA-funded Griffiths and STRIVE research programmes respectively.

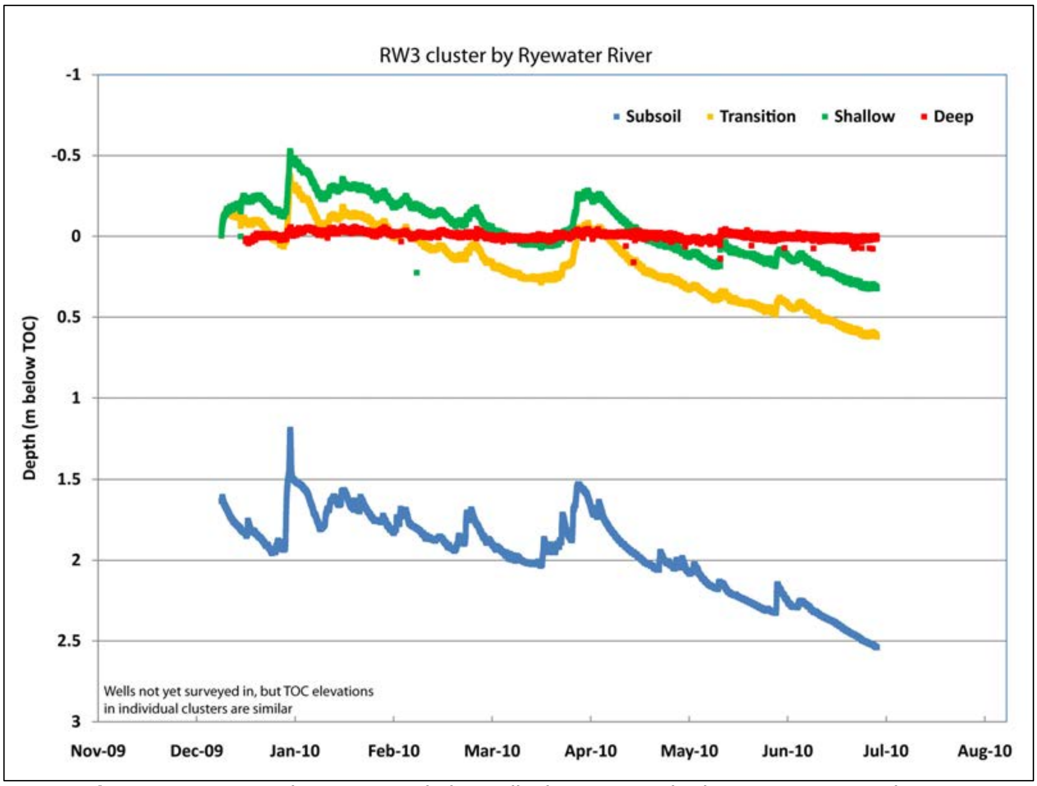


Figure* 7: Measured Water Levels in Well Cluster RW3 in the Ryewater Catchment*

Verification of Conceptual Model

The conceptual model that served as the basis for site investigation and monitoring stipulates the following general hydrogeological conditions in PPAs:

- Generally low-permeability characteristics of bedrock;
- Discrete inflows of groundwater to wells through fractures or fissures;
- The potential presence of a transition zone at the contact between bedrock and overlying subsoils;
- The existence of vertical hydraulic gradients between different monitoring intervals, as a function of well depth and the well's position in a groundwater flow system;
- Upward hydraulic gradients in wells nearest to the streams in each catchment.

As shown in **Table 4**, these conditions were present in most or indeed all of the catchments investigated. The transition zone was more pronounced and noticeable in some catchments compared to others. It appeared to be absent altogether in the Mattock catchment, situated on Ordovician age greywackes.

Table 4: *Verification of Conceptual Model in Each Catchment*

Characteristic	Newvillage	Glencastle	Dripsey	Mattock	Ryewater	Gortinleive
Low-permeability	✓	✓	✓	✓	✓	✓
Discrete inflows	✓	✓	✓	✓	✓	✓
Transition zone	✓	✓	✓	No	Partly	✓
Vertical gradients	✓	✓	✓	✓	✓	✓
Upward gradients near stream	✓	✓	✓	No	✓	✓

Although the study findings generally verify the conceptual model for PPAs, each site had its own set of defining features, whereby hydrogeological features specific to a site were noted in each catchment. These are summarised in **Table 5**.

The presence of these defining features raises the cautionary note that, although PPA catchments display many overriding similarities, site-specific hydrogeology applies in all cases, and there is a danger of perhaps over-generalising the hydrogeology of PPA catchments.

What is apparent, however, is that the technical approach has proven to be correct and appropriate for PPA monitoring purposes.

Groundwater Chemistry

Since well completion, each monitoring well has been sampled on a quarterly basis by the EPA. Samples have undergone full chemical analysis which includes general chemistry, metals and priority pollutants.

Although a groundwater quality study was not part of the GWP, a cursory review of the available data to date indicates that most samples from the 6 catchments tend to be dominated by calcium-bicarbonate waters, as shown in the Piper diagram in **Figure 8** and the Durov plot in **Figure 9**.

There are regional differences, notably, samples from the granites of Newvillage (Galway) and the ortho-gneiss, pelitic schists and quartzites of Glencastle (Mayo) show a broader range of results, with a tendency towards sodium- and magnesium-bicarbonate waters. In fact, results from Glencastle shows distinct water chemistries between well clusters that in all likelihood reflect lithological variations within the catchment.

In terms of metals, the measured iron and manganese concentrations frequently exceed their respective EPA drinking water standards in all 6 catchments. Aluminum is occasionally exceeded at Newvillage and Glencastle. Arsenic is frequently exceeded in bedrock at Dripsey and occasionally exceeded at Newvillage, Mattock and Ryewater. The drinking water standard for barium is consistently exceeded at Newvillage.

In terms of radionuclides, the drinking water standard for uranium is only exceeded at Dripsey and Newvillage, with the highest concentrations occurring in deep bedrock wells at Newvillage. Strontium is frequently exceeded in all 6 catchments.

Table 5: *Distinguishing Characteristics of Each Catchment*

Catchment	Comment
Newvillage	• Deep (60 m+) weathering of granite; • Noticeable, higher-yielding fracture at 60 m bgs at site closest to river; • Artesian heads in deep bedrock well closest to the stream.
Glencastle	• Potential fault encountered – appears to act as a barrier to flow, with groundwater discharge apparent mid-way in catchment; • Intensely fractured and weathered dyke intersected near river – may increase bulk permeability and hydraulic connections between wells.
Dripsey	• Deep weathering of mudstone/sandstone/siltstone to 40 - 50 m bgs; • Deeply weathered/fractured shallow bedrock to 15m bgs.
Mattock	• No apparent transition zone present; • Highly permeable fracture zone (or fault) at 40 m bgs in bedrock near river; • Dry, but highly permeable, shallow bedrock at one drill site (i.e., water table below completion depth); • Downward head from alluvium to bedrock at river - bedrock head approx.12 m bgs at river; • Thicker than anticipated alluvial/till sequence near river - subglacial rivers may have etched out deeper channels in bedrock.
Ryewater	• Artesian heads in bedrock near river; • Presence of 0.5 m thick “pebble bed” between glacial till deposits and bedrock –interpreted to be of a glacio-fluvial origin, and does not represent a transition zone; • Possible faulting of bedrock near river; • Thick alluvial/till sequence near river.
Gortinleive	• Deep weathering of psammites to 50-60 m near stream.

EPA’s groundwater quality data will be subject to in-depth study and analyses by academic researchers, notably Queen’s University Belfast under the GSI- and EPA-funded Griffiths and STRIVE research programmes respectively, the latter being partnered by Trinity College Dublin (TCD) and University College Dublin (UCD).

These projects are expected to examine the migration and chemical evolution of groundwaters in PPAs and the possibility that some waters are naturally, chemically stratified, possibly as a function of the different hydraulic dynamics between shallow groundwater (e.g., in the transition zone) and deeper groundwater in bedrock. Possible stratification has been noted from data at Newvillage especially. Here, groundwater in the transition zone has an average electrical conductivity (EC) of 150-300 uS/cm, whereas in deep bedrock the average EC is approximately 700 uS/cm. There are similar relationships with other parameters such as temperature, hardness, alkalinity, and even pH (6.5 vs >7.5, shallow vs. deep).

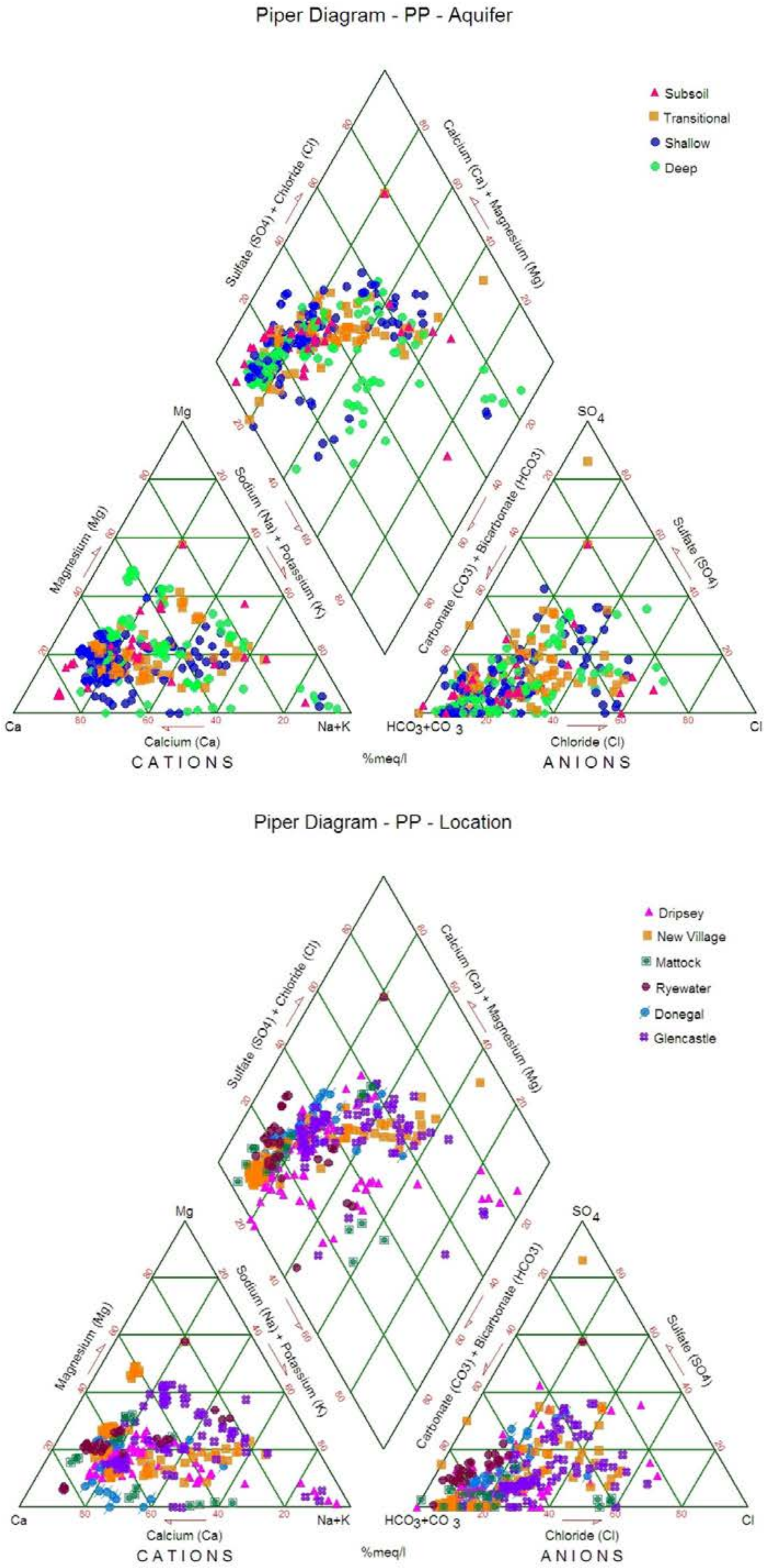


Figure 8: *Piper Diagrams of Groundwater Quality in Six Catchments*

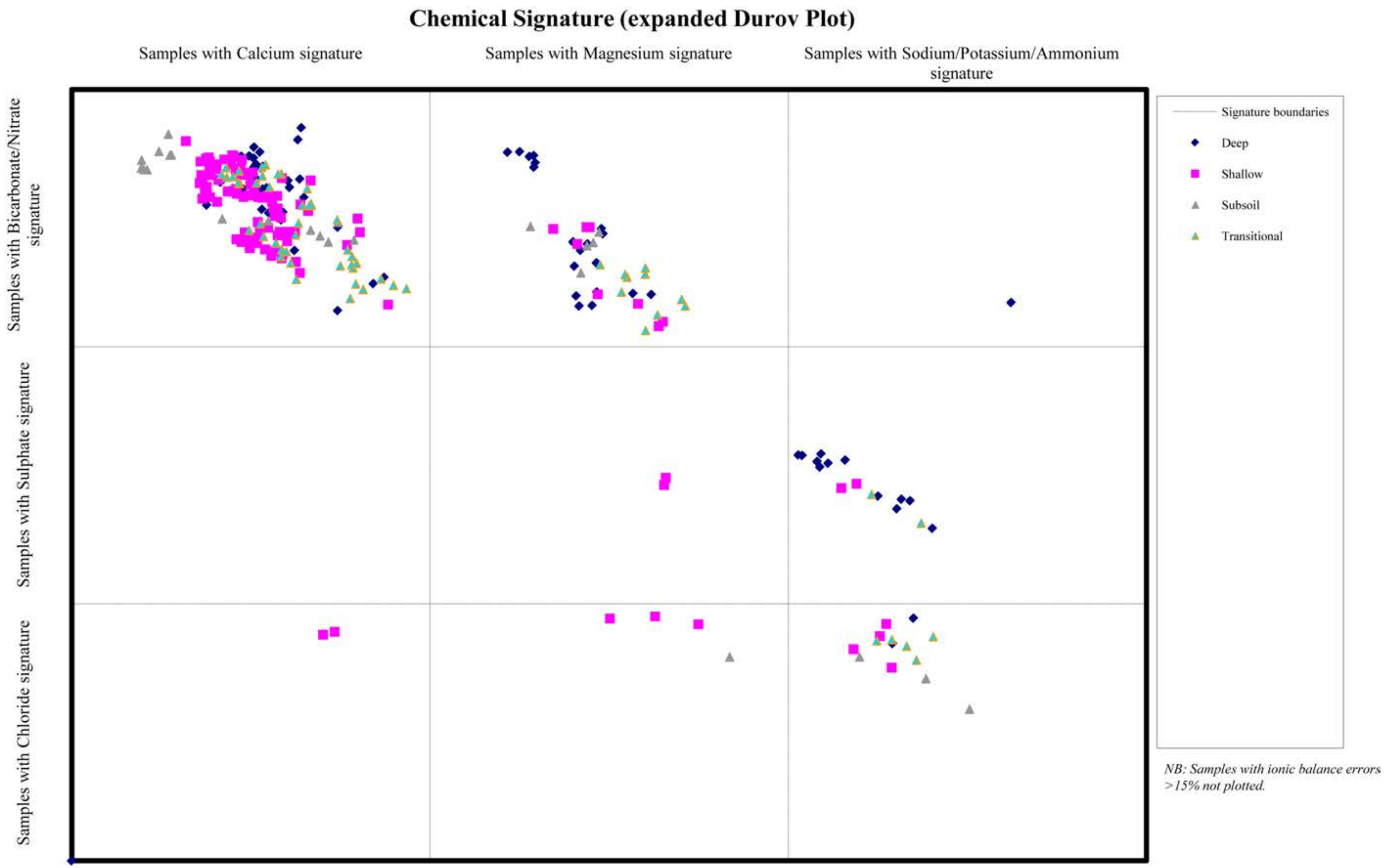


Figure 9: *Durov Plot of Groundwater Quality in Six Catchments*

5. Conclusions and Lessons Learned

The hydrogeological study of six PPA catchments has contributed towards an improved understanding of poorly productive rocks. New quantitative information has been developed in a systematic way to shed light on the hydrogeological characteristics and depth-specific water quality of PPAs.

Results highlight that different types of poorly productive rocks share many of the same hydrogeological characteristics, but importantly, differences apply at the catchment- and borehole-scales. At these smaller scales, extreme heterogeneities define PPAs. Nonetheless, PPAs transmit groundwater in smaller quantities and help to sustain stream flows in dry weather periods. This needs to be accounted for and monitored in the Water Framework Directive context.

Results from this study support the concept that shallow groundwater pathways, notably via the transition zone, can be important in delivering water, and therefore potential pollutants, to streams and groundwater-dependent ecosystems.

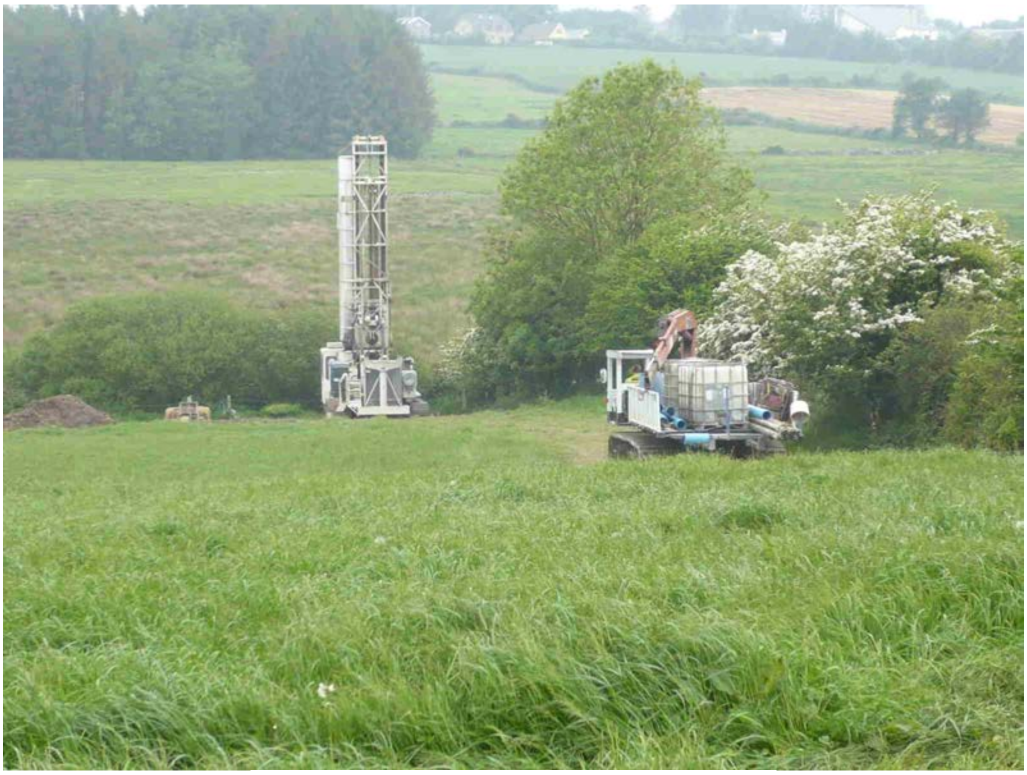
Moreover, the technical approach that has been applied for this study serves as an appropriate and useful guide to groundwater monitoring in PPA catchments throughout Ireland. The details of the approach are accessible from individual well completion reports prepared for each of the six catchments included in the GWP (CDM/OCM, 2010 a,b,c,d,e,f). Each well completion report includes notes on lessons learned that relate to different methodologies and logistical challenges posed by the work described herein, and which broadly summarised below.

Preparation for Drilling

Drilling on soft ground during winter months in Ireland can be hazardous. Adequate preparation of ground conditions was therefore a crucial success factor to the programme's implementation schedule and relationship with landowners. Access for drilling equipment, and adequate land

Track-mounted drill rig and service vehicle available to operate were key criteria for selecting drill sites within catchments.

Health and safety precautions and procedures were reviewed and adjusted on a frequent basis. The ability to complete the intended works were greatly aided by using a track-mounted drill rig and service vehicles. Not only were ground conditions soft, but some of the drill sites required the movement of equipment and materials across steep slopes. The use of a track-mounted drill rig was in fact critical to be able to complete the intended works.



Working on steep slopes

As some of the lands became significantly disturbed by site operations, great after care was taken and all restoration efforts were consulted, coordinated and approved with landowners.

Drilling

In several of the catchments, a thick subsoil sequence comprising alluvial sediments and glacial tills had to be drilled through, notably at sites closest to streams. When wet, clays within till layers tended to swell and stick to the 10 inch diameter steel casing. This made driving and retracting the steel casing very tricky. At some locations, the steel casing became stuck and permanently lodged at shallower or deeper depths than originally intended.

At one location in the Ryewater catchment, a 0.5 m thick but extremely permeable “pebble bed” caused numerous well construction problems. During attempts to isolate the pebble bed from the underlying bedrock, driving steel casing through the pebble bed proved extremely difficult. Several attempts were needed to keep the 10 inch boreholes open in order to be able to lower 6 inch PVC casing. The attempts involved repeated action of drilling out collapsed material, flushing the borehole, drilling collapsed materials, flushing, etc.

Nearly three full days of active rig time were spent trying to manoeuvre past the 0.5 m thick pebble bed and setting 6 inch PVC casing to its intended target depth. This type of problem would, under a normal pay-per-depth drilling contracts, result in claims by the drilling contractor. With foresight, this type of scenario was avoided by including a time-based “rig operation rate” in the drilling contract, whereby the drilling contractor was fairly compensated for the time, materials and efforts spent on securing the borehole as intended.

The same borehole also experienced a very different type of problem due to the subsurface conditions encountered – i.e., swelling clays and the presence of the pebble bed. During drilling of the shallow bedrock borehole, the target depth for the 6 inch PVC casing was 16.0 m bgs. Due to the swelling clays, it was not possible to drive the 10 inch steel casing beyond 10.6 m. Upon subsequent 10 inch drilling into bedrock, the open borehole below the steel casing exposed sections of clay, the pebble layer, and bedrock. As such, the 10 inch borehole kept collapsing, primarily with materials from the pebble layer and clay. These were subsequently drilled and flushed out, the process being repeated several times.

After several failed attempts to keep the borehole open to the intended depth of 16.0 m, a decision was taken to overdrill the 10 inch borehole and allow some materials to collapse back in. The 10 inch borehole was subsequently deepened to 20.3 m. Frequent measurements of the total depth of the borehole were subsequently made in the process of drilling and flushing. Just before the 6 inch PVC was lowered, the total depth of the borehole was measured at 16.4 m. A total of 17.2 m of PVC was actually inserted below ground level, suggesting that the borehole had “settled” by 0.8 m from the time that the last depth measurement had been taken.

After grouting, and after continuing to drill through the bottom plug on the 6 inch PVC casing, the loose collapsed materials in the 10 inch borehole below the 6 inch casing were flushed out by the 6 inch drilling action. The subsequent calliper log therefore shows a 10 inch diameter borehole to 20.3 m, beneath the 6 inch casing. On the video log, this has the appearance of a PVC casing that is freely suspended, when in fact it is solidly grouted in place.

As suggested by the subsequent grouting operation, the repeated collapse, drilling, and flushing action is believed to have created large voids surrounding the 10 inch borehole. Considerable quantities of grout were injected before it overflowed at the surface. Sixty-six bags of cement were used on Day 1 of the grouting operation, an operation that would normally take 3-4 hours for a deep borehole. As the grout did not reach the surface on Day 1, an additional 54 bags were used on Day 2. A total of 119 bags of cement were needed before the project team was satisfied that the borehole had been properly grouted. This exceeded by far the quantity that would theoretically be needed to fill the annular space between a 6 inch casing and a 10 inch borehole.

The massive quantity of grout needed could only have gone two places: a) either it was washed away through the permeable pebble layer; or b) it was needed to fill up void spaces that may have resulted from the airlifting of collapsed materials. The latter option is considered more likely. Grout was not observed with cuttings or water washed from the pebble layer during the drilling of other wells in the same well cluster.

During the drilling of a subsequent transition zone well in the same cluster, similar challenges were faced but a different solution was arrived at based on the previous (bad) experiences from the shallow bedrock well. Upon the 10 inch steel casing becoming stuck as it was driven through the clay, rather than over-drilling, a smaller 8 inch steel casing was inserted inside the 10 inch casing and borehole, and was temporarily used to keep the borehole open while the 6 inch PVC was lowered. The 8 inch steel casing was easier to handle and was successfully withdrawn after the PVC casing was lowered.

Progress and decision-making was greatly facilitated by the fact that a SH was present on-site at all times, and there was good and continuous communication between the SH and the drillers. Without fulltime supervision and ability to make field-based decisions, the well construction activities would likely have failed resulting in a potential claim and counter-claim situation.

Grouting

Grouting operations should be carried out in one motion at the exact appropriate time. This became very apparent during the drilling of one well in the Mattock catchment. During well construction of a shallow bedrock well, the setting of the 150 mm diameter uPVC casing was completed late on a Friday, and too late in the day to be able to complete the required grouting of the casing on the same day. The 150 mm diameter uPVC casing was therefore left inside and through the outer (250 mm diameter) temporary steel casing over the weekend.

Upon returning on the Monday morning, it was found that subsurface clays had expanded/collapsed around the uPVC casing. It was basically impossible to lower the 37.5 mm diameter steel tremie pipe used for grouting to its intended depth in the annular space between uPVC casing and the borehole wall. The uPVC casing therefore had to be pulled back out of the borehole before reaming and clearing out the borehole to its originally drilled diameter. The uPVC casing was subsequently reinserted into the borehole and grouted in place. This sequence of events effectively resulted in an extra day of drilling/construction activity.

With the exception of the specific cases outlined above, grouting operations in all catchments proceeded without any specific problems or delays. The addition of calcium chloride as a curing accelerant worked well. The work was mostly timed such that grouting operations were conducted in the late afternoon on any given day, in order for work to be continued on the following morning. Compensation associated with stand-by time (for grout to cure) was therefore avoided. As observed at the wellhead, some settling (1-2 m) of cement grout occurred after each operation. Additional cement grout was subsequently added to the well at the end of the construction activity so that the annular spaces were completely filled with grout to ground surface.

The integrity of the grout seal was checked periodically and at the end of each setting period by measuring the total depth and water level inside the well, and ensuring that grout had not penetrated inside the casing (e.g., clarity of water, no grout residuals on a device lowered to the bottom of the PVC casing).

Adding calcium chloride to grout batch plant

Borehole Blockages

All boreholes in bedrock were constructed as open holes. Only one borehole, at Glencastle, experienced a blockage by a "borehole collapse" at a depth of 51 m depth. The blockage was noted during the lowering of a small diameter pump for test pumping purposes. A depth sounding device could be lowered past the blockage, which means the borehole did not completely collapse, but rather a larger piece of rock came loose and is now lodged against the borehole wall.

Difficulties arose when attempting to advance geophysical logging equipment in two of the deep boreholes at Gortinlieve, and it was feared that the borehole might have collapsed in the open borehole sections. Subsequent investigations established that the wells were not in fact blocked. Rather, it was established that a small ledge just below the end of the PVC casing prevented the logging tools from being lowered to the intended depths. The ledge is believed to be the result of a slight off-set from centre of the reduced borehole diameter below the PVC casing.

Not all of the drilled boreholes are perfectly straight. The deviation of the partially blocked borehole at Glencastle is significant, where based on plumbness tests, the bottom of the deep borehole could be offset by as many as 5 m from the top. Subsequent to this discovery, drill collars were used for all drilling activities.

Hydraulic Testing

The RHTs suffered one drawback. Water level measurements could only start once the drill-string assembly (DSA) was removed from the borehole after the preceding air-lift event. Where the DSA was long (>30 m), the time needed for removal could be 10-15 minutes. Each drill pipe in the DSA was 5.8 m long and had to be disassembled and staged in turn.

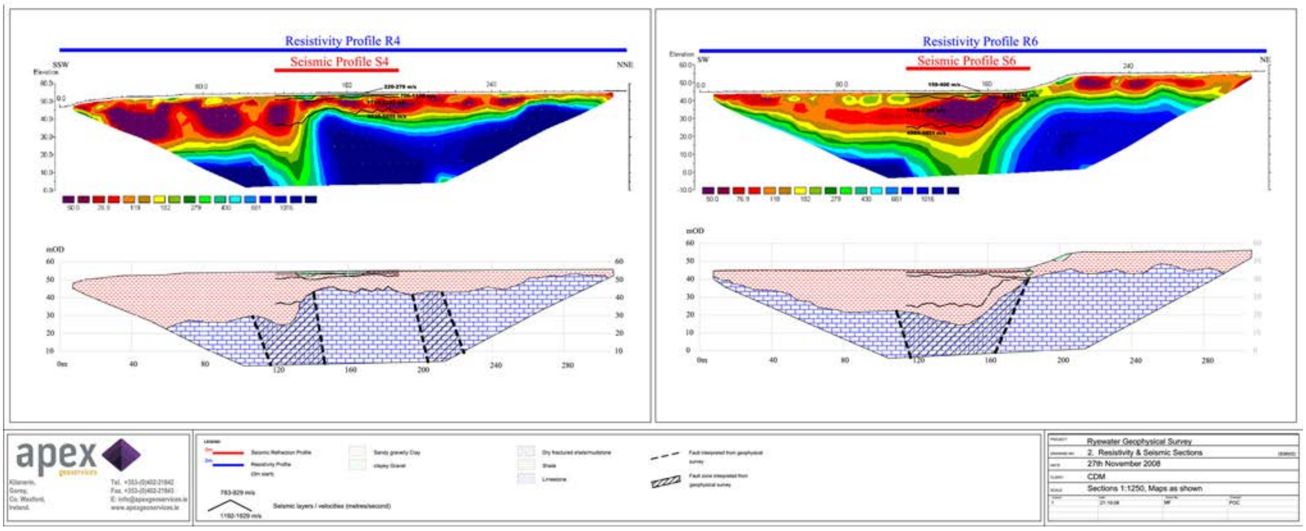
As a result, measurement of water level recovery could only start some minutes after blow-out.

The analytical calculations of hydraulic conductivity (K) from the recovery data requires an estimation of the water level at time =0 (i.e., start of recovery). This value has been assumed based on the observed rate or gradient of recovery during the earliest measurements that could be taken. This may impart a degree of “inaccuracy” in the calculations of K.

Pump testing was limited by the low permeability characteristics of the bedrock. Pump tests were stopped when measured water levels approached the pump setting depths. Pumps could have been set deeper to pump longer at lower rates, but the initial results were deemed sufficiently valid to prove the low-permeability nature of the encountered rocks and meet project objectives.

Surface Geophysics

2-D resistivity and seismic refraction surveys were mostly carried out, and induced polarisation measurements were added to verify the presence of clays. Both types of surveys added great value to the study. The seismic refraction data were particularly useful for refining estimates of depth to bedrock from 2-D resistivity surveys. 2-D resistivity surveys pointed out potential changes in bedrock type across the study area as well as potential faulting.



Example of 2D-resistivity and seismic refraction survey results

Borehole Geophysical Logging

Borehole geophysical logs added great value to the site investigations. Together with calliper logs, the high resolution acoustic televiewer was particularly useful for identifying and describing fractures with depth. Video logs were most helpful for examining stratigraphic changes, borehole integrity, and verifying well constriction details.

The high-resolution flowmeters (both impeller and heat pulse types) were not able to identify inflows or record vertical movements of water with any certainty. The resolution of the velocity of the heat pulse flow meter was 9 cm/min.

The combined use of fluid temperature, fluid conductivity, and electric logs were able to identify water inflow and higher-permeability (fracture) zones at discrete depths.

Video camera view of shale and limestone contact

Overall Implementation

Besides the expected practical problems associated with soft ground conditions, the overall schedule of works proceeded as intended.

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