
IRISH AQUIFER PROPERTIES – A REFERENCE MANUAL AND GUIDE

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Database

The database to which this report refers is managed by the GSI. The summary 'look up tables' are contained within this report/manual.

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PART 1

1 INTRODUCTION

1.1 BACKGROUND

The Environmental Protection Agency (EPA) is an independent public body with statutory duties and powers under the Environmental Protection Act. The Geological Survey of Ireland (GSI) is the National Earth Science Agency, with responsibilities that include gathering data and providing geological advice and information. Both agencies work alongside each other under different themes and in the context of groundwater protection, this document represents a collaborative project, initiated by the EPA in co-operation with the GSI, and undertaken by Tobin Consulting Engineers.

For the purposes of assisting compliance with the legislation, and managing contaminated land and groundwater, guidance for Contaminated Land and Groundwater Assessment in Ireland at EPA licensed sites has been established and published, which sets out the approach to be adopted to assess sites (EPA, 2013).

Hydrogeological risk assessments are routine tasks and generally comprise a progressive tiered approach built around site investigation data and a conceptual model. Such assessments require hydrogeological data that can be consistently applied for a variety of risk assessments. Ford Consulting Group¹ (2010) prepared a briefing note for EPA evaluating specific needs in the regulation and support of groundwater risk assessment at contaminated sites, and concluded that an *'aquifer properties manual with specific reference and appropriate to Ireland would be beneficial and a 'useful tool'*.

Building on the briefing note and the establishment of a framework for Contaminated Land and Groundwater Assessment, the EPA in partnership with the GSI, required that a database of aquifer parameters and guidance document would be established. The role of the GSI was to provide access to their hydrogeological data, advice and support, and technical assistance to the development of an aquifer parameters database. The GSI will host the database and is continuing to manage it, and may provide further updates as necessary to this report and the database.

1.2 THE NEED FOR AN AQUIFER PARAMETER DATABASE

An aquifer parameters database will provide a reference point, assist methodologies utilised in hydrogeological assessments, inform preliminary site assessments and initial conceptual site models and subsequent site investigations and modelling. The main needs and uses are to:

- 1) Inform quantitative hydrogeological risk assessments and groundwater modelling.** The database provides representative parameter values that can be used in risk assessment/modelling until site-specific data are available, and also for verifying reported data. In a briefing note to the EPA, Ford (2010) concluded that an Ireland-based appropriate 'properties' manual would be important for both regulators and industries for risk assessments, and in particular contaminated land tier 1/2 assessments that may involve impact prediction.
- 2) Aid aquifer classification.** Aquifer classifications for different rock types have been determined in a holistic manner by using the available data, for example, lithology, structure, presence/absence of large or small springs, 'productivity', yield, karst features, baseflow signals and hydrographs (GSI, 2006). Specific aquifer parameter information

¹ Geosyntec consultants acquired Ford Consulting in 2012.

such as transmissivity is quite sparse and therefore the database will assist the classification process by providing individual records and facilitating statistical analysis on the data for individual aquifers. In addition there is a continual requirement for data and it is anticipated that the database will provide further additional data.

- 3) **Inform quantitative groundwater discharge assessments.** A key question in many site assessments is whether or not the geological material can accept, and hydraulically attenuate, the additional loadings from a system that is discharging to ground. High quality data on the subsoils and/or the transition zone and/or the shallow bedrock could assist in predicting the response to a loading in a particular hydrogeological setting, which is useful with respect to the guidance on the technical assessments relating to groundwater discharges provided by the EPA in a manual - 'Guidance on the Authorisation of Discharges to Groundwater' (EPA, 2011).
- 4) **Informing groundwater resource developments.** Users will be assisted by having information on areas previously drilled and the expected water strike depths and typical yields. In addition, the data could assist in providing information on previous test pumping regimes conducted in a particular rock type or area.

1.3 THE OBJECTIVES OF THE PROJECT

The primary objectives for the project are to:

- Establish a framework under which a database of aquifer parameters can be determined, maintained and updated.
- Compile and publish aquifer parameters, and relate them to the nine GSI aquifer categories and the twenty-seven Rock Unit Groups (RUGs) used by GSI in aquifer classification (Groundwater Working Group, 2003).
- Determine and summarise best international practice in the determination of aquifer parameters using site specific data.

To meet with the project objectives and to provide a database that meets the needs outlined above it was considered that the database needed to account for aquifer heterogeneity, pathways and scale; and be as large as possible, representative and reliable. It is termed '**An Irish Aquifer Parameters Database**'.

1.4 CONTENT AND STRUCTURE OF THIS REPORT

The following report:

- Outlines the main findings from the literature review which includes the main definitions that apply to the aquifers and the RUGs and to aquifer properties, and the current understanding of groundwater flow systems in Ireland. It also briefly describes relevant work and research.
- Outlines the structure of both the aquifer parameter databases and summary tables.
- Provides guidance on parameter estimation, and outlines inter-relationships between aquifer properties.
- Provides general guidance on how to use the summary tables and the aquifer parameter databases, and how to assess practitioners' own data.

- Provides a practitioner with summary information for a particular RUGs and aquifer type.
- Outlines data caveats and background information on the hydraulic test type: for instance, laboratory tests provide information at a much smaller scale than a large scale pumping test and aquifer parameter values are commonly a couple of orders of magnitude less.
- Explains aspects of the data such as the regional differences in hydraulic properties of the different RUGs.

The data collated, presented and assessed in this report and database are primarily the groundwater transport parameter ‘transmissivity’ (or its proxies). This is for two reasons: transmissivity is a bulk transport parameter and is the one that is generally collected by Irish hydrogeologists during groundwater studies and therefore the most readily available. The distribution and volume of the data enables estimates for transmissivity to be established across the entire country. Secondly, Irish fractured bedrock aquifers are highly heterogeneous, and the whole-well aquifer tests that are typically undertaken integrate fracture flows along the length of the generally unscreened well, rather than measuring individual fracture inflows.

Available hydraulic conductivity data are limited in number and regional distribution. Also limited are storativity, specific yield and effective porosity data. No attenuation/dispersivity data were available to the study. (For definitions of parameters describing aquifer behaviour and contaminant fate and transport, see Section 3.)

The data that were available to this study, including transmissivity (and proxies), hydraulic conductivity, and storage parameters, are held in the parameters database and are summarised in Section 6. Contaminated land and contaminant fate and transport studies may need to consider first arrival times and dispersion/attenuation, requiring permeability, porosity, diffusivity and attenuation data, and this should be borne in mind when using data from this study. The conceptual models outlined in this report describing the main types of groundwater flow and flow pathways should also be borne in mind when applying data, and also when acquiring and interpreting site-specific data.

The document is organised into two parts.

Part 1 comprises:

- Methodology and data sources.
- Hydrogeological framework for the parameters database.
- Aquifer parameter estimation methods.

Part 2 comprises:

- Aquifer parameters database structure.
- Data analysis and discussion of results.
- Summary and conclusions.

2 METHODOLOGY AND DATA SOURCES

2.1 METHODOLOGY

The following tasks were undertaken to create the structure of the parameters database, to input data and prepare the summary parameters tables and accompanying report.

- Obtained advice and support from a selected nominated 'steering group'.
- Reviewed relevant literature and current and previous studies.
- Identified appropriate hydraulic parameters.
- Designed database structure and fields.
- Identified sources of high quality data.
- Collected data, including additional data from Geological Survey of Ireland's (GSI) well database (Geodata, specifically, specific capacity data) to augment data analysis.
- Assessed data (with an emphasis on quality control).
- Inputted data.
- Analysed data within two frameworks: the bedrock aquifers and the sand and gravel aquifers, and the Rock Unit Groups (RUGs).
- Prepared summary tables for the bedrock aquifers, the sand and gravels aquifers, and for RUGs.
- Circulated database for trialling.
- Prepared synthesis report.

2.2 CURRENT RESEARCH AND GROUNDWATER STUDIES IN IRELAND

GSI – Aquifer Classification

One role held by the GSI is the mapping, characterisation and classification of the country's aquifers and groundwater systems. This is dependent on the acquisition, analysis and interpretation of hydrogeological data. The Aquifer map is of primary importance to the GSI, and it is employed in many important risk assessments and groundwater studies (e.g. county Groundwater Protection Schemes, Water Framework Directive, on-site wastewater site suitability assessments, groundwater source protection studies, etc.). For several decades, the GSI have been investigating, locating, assessing, characterising and mapping Irish aquifers (GSI, 2006). The GSI is continuing this work with a concurrent programme detailing, defining and summarising the behaviour and location of all Irish bedrock and sand/gravel aquifers in a forthcoming document "Aquifer Classifications in the Republic of Ireland" (GSI, *in prep*). The GSI will host, maintain and update the aquifer parameters database through a separate project. As such, work on the Aquifer Parameters database builds on existing work, and is being built on and continued by the GSI.

GSI/EPA – Source Protection Zone work

Groundwater source protection studies are conducted by/on behalf of GSI, EPA and local authorities, and require an assessment of aquifer properties in the zone of contribution to the source in question. This work provides many high quality test pumping data, which are an important source of data for the aquifer parameters database.

EPA – Guidance Document on Authorising Groundwater Discharges

The EPA have published a guidance document providing advice on the technical assessments needed to authorise groundwater discharges, either new discharges seeking consent or older ones under review (EPA, 2011). Thus the guidance document assists both those in Local Authorities or environmental consultants preparing applications. This document is a useful

reference document for assessing subsoils in terms of hydraulic performance and offers broad permeability ranges for different subsoil textural classes as per British Standards 5930 Code of Practice for Site Investigations.

GSI/EPA – Research

The EPA and GSI have a strong tradition in research and linking with academic institutions and other organisations. Much of the research allows for continued investigation into aquifer assessment. Several research programme areas are as follows:

- **EPA – Monitoring of Poorly Productive Aquifers**

The EPA are tasked with the responsibility and primary role of monitoring groundwater in Ireland, which includes the implementation of a representative and comprehensive monitoring programme to fulfil the objectives and aims of the Water Framework Directive (WFD). Previously, most of the monitoring points were located in the ‘Productive Aquifers’, although ‘Poorly Productive Aquifers’ occupy approximately two-thirds of Ireland’s landmass (Moe *et al.*, 2010). Furthermore, these aquifers contribute a significant amount of water to surface water flows, and therefore further characterisation of the delivery mechanisms is required to enable better management of them. The EPA have incorporated the ‘Poorly Productive Aquifers’ into the monitoring programme by establishing and constructing a suite of high quality monitoring boreholes in a number of unique catchments underlain by ‘Poorly Productive Aquifers’. This work established much needed data and understanding of the storage and transmission properties of the aquifers (Moe *et al.*, 2010). Importantly, this work has allowed for research to be conducted assisting in the development and understanding of the conceptual models (see below), and particularly has focussed on understanding the principal groundwater pathways outlined in Section 3.7.

- **Griffiths funded Research on the Poorly Productive Aquifers**

The EPA Groundwater Works Programme described above has enabled hydrogeological research on the ‘Poorly Productive Aquifers’. The Groundwater Research Group from Queens University Belfast (QUB) is investigating flow and transport mechanisms, and the research includes pumping tests that provide data on the aquifer properties. The research, which is funded by DCENR/GSI, ties in with the ‘Pathways’ project described below.

- **EPA Strive funded ‘Pathways Project’**

The ‘Contaminant Movement along Pathways Project’ is an EPA STRIVE funded project led by QUB, partnered with Trinity College Dublin (TCD) and University College Dublin (UCD). The pathways being investigated are overland flow, interflow, shallow and deep groundwater. Field work is being carried out in four study catchments, three of which are underlain by poorly productive aquifers and the fourth by a regionally important aquifer. The studies include simulation of flows along the pathways using a lumped modelling approach. The main aim of the project is to develop a catchment management tool.

- **EPA Strive funded project investigating fracture systems**

This is a project led by the Fault Analysis Group at UCD. Fault and fracture systems in different rock types and at different depths are being investigated and linked to observed groundwater behaviour. Fracture orientations, densities, spacing/clustering, sizes, scaling and connectivity will be used to characterise and conceptualise structural models and domains, which in turn will be linked to Irish fractured groundwater flow and transport conceptual models.

- **EPA Strive funded project “CONNECT” (COMbiNed Earth Observation and GEOchemiCal Tracing for Groundwater Detection and Evaluation in Ireland)**

This research project by TCD involves developing remote sensing as a tool for detection, quantification and evaluation of submarine groundwater discharge (SGD) principally to lakes and coastal water. It has been shown to indicate large fluxes of groundwater discharging to Lough Mask.

- **Teagasc – Agricultural Catchments Programme**

Teagasc are conducting research under the Agricultural Catchments Programme (<http://www.teagasc.ie/agcatchments/>), consisting of several linked themes: nutrient sources, nutrient delivery, nutrient pathways (linking the source to the streams via the pathways (soils, subsoil, rock). The research is being conducted across six different catchments characterised by different geological settings to evaluate the environmental and economic effects of measures implemented under the Nitrates Directive. There is an extensive list of publications available on the Teagasc website (<http://www.teagasc.ie/agcatchments/publications/>).

- **IRETHERM (www.iretherm.ie) – A multi-disciplinary investigation into Ireland’s warm springs.**

This is a Science Foundation Ireland funded collaborative project comprising the Dublin Institute of Advanced Studies (DIAS), Earth and Ocean Sciences, NUI Galway and the School of BEES, University College Cork and Mark Muller, an independent geophysical consultant. They are investigating Irish warm springs and their potential for geothermal energy provision, using geophysical and hydrochemical methods. This study will enable a better understanding of the aquifer characteristics in the vicinity of the springs and associated delivery mechanisms (Blake *et al.*, 2013).

2.3 SOURCES OF DATA

Sources of data included the following:

Geological Survey of Ireland

In house data sources including:

- Document management system.
- Scanned files and reports.
- Pumping tests.
- GSI Source reports, source folders and digital files.
- Geodata.
- Geotech database.

Exploration and Mining Division

Environmental Impact Statements (EISs) for working mines (i.e., Lisheen, Tara and Galmoy mines).

EPA

- EISs / Landfills (Waste licence files).
- Groundwater Source Protection Zone reports for the national groundwater monitoring points on behalf of EPA.

- Groundwater Works Programme.

Research Institutes: Trinity College Dublin, Queens University Belfast, Teagasc.

Consultants' reports provided in response to a request to assist the establishment of the aquifer parameters database, plus those already in-house within GSI.

3 HYDROGEOLOGICAL FRAMEWORK FOR THE PARAMETERS DATABASE

3.1 OVERVIEW

Groundwater is an important resource in Ireland, supplying drinking water to public water and private water supplies and supporting rivers, lakes and groundwater dependent ecosystems via baseflow contribution. The GSI fulfils a mapping and advisory role, and has an important role in characterising the groundwater resource, developing hydrogeological concepts relevant to Ireland's hydrogeology, and providing groundwater information. The GSI have been developing an understanding of the hydrogeology of the country via the acquisition, collation and analyses of hydrogeological data, for several decades. The EPA holds a regulatory and enforcement role, manages the national water (ground, river, lake, coastal/transitional waters) monitoring networks, and has oversight of public drinking water supply quality. Since the 2000's, EPA's groundwater group has grown in response to the requirements of the Water Framework Directive, and it has funded several key aquifer characterisation studies (see section 2.2 above).

This section briefly outlines the hydrogeological framework under the following headings:

- Bedrock and subsoils
- Rock Unit Groups (RUGs)
- Aquifer categories
- Flow types
- Groundwater storage, flow and transport
- Irish groundwater flow conceptual models.

3.2 BEDROCK AND SUBSOILS

Bedrock units of sedimentary, metamorphic and igneous rocks occur within Ireland. Limestones are the most common rock type, underlying almost half of the country (Hickey, 2010, 2008). Nearly all rocks have only secondary porosity and permeability. The more than 1,000 bedrock formations and members are characterised, classified and mapped in terms of their aquifer potential.

Subsoils comprise different sediment types of which peat, glacial till and sand and gravel are the most dominant. The subsoils mantle the bedrock to varying degrees of thickness and the bulk textural characteristics and patterns are mapped in terms of broad qualitative permeability ranges. Sand and gravel deposits are defined as aquifers once they meet certain criteria (GSI, 2006). The parameters database focuses principally on hydraulic properties of the aquifers. Recommended values for the main subsoil textural classes are given.

3.3 ROCK UNIT GROUPS

To enable and assist the aquifer classification work, the more than a thousand bedrock formations and members were simplified to a more readily useable and identifiable hydrostratigraphy based on similar properties and age. This generalised grouping is known as the Rock Unit Group (RUG), and comprises twenty seven distinct RUGs, shown in [Figure 1](#).

The RUGs were overlain with a broad structural zone map (Dunphy, 2004) which incorporated the impact of major structural zones. The RUG map together with the structural zones, and indicators of hydrogeological characteristics such as productivity and spring flow, provided the basic aquifer boundaries and compartments for aquifer classification.

3.4 AQUIFERS

Aquifers are bodies of saturated geological materials that both store and transmit important quantities of water (e.g., Younger, 2007). The GSI developed a classification scheme defined in the Groundwater Protection Schemes document (DELG/EPA/GSI, 1999), which is further detailed in the various published County Groundwater Protection Schemes and in a paper titled “*Rock type versus Fractures*” – *Current Understanding of Irish Aquifers* (Fitzsimons *et al.*, 2005), and revised and updated for the purposes of the WFD. The WFD required a national aquifer map to be prepared to allow for a national characterisation of groundwater bodies to fulfil the tasks and objectives of the WFD described in “The Characterisation and Analysis of Ireland’s River Basin Districts” (EPA, 2005).

In Ireland, nearly all bedrock types provide enough water for a domestic supply. Given the dispersed, rural population, this is considered to be an ‘important’ use. Therefore, almost the entire country is classified as an aquifer (Fitzsimons, *et al.*, 2005). **Figure 2** shows the national aquifer map. The criteria for aquifer classification can be obtained from the GSI website: <http://www.gsi.ie/Programmes/Groundwater/Aquifer+Classification.htm>, and are also described in Fitzsimons *et al.* (2005). Criteria used to determine aquifer categories are hydrogeological data (productivity, transmissivity, and borehole yields), presence of large springs, presence of many small springs, lithology, structure, stream density. If there are enough data across a particular rock unit area and the pattern is definable, then this is normally sufficient to conclude on a category.

Box 3.1 The GSI aquifer classification scheme:

Regionally Important (R) Aquifers

- Karstified bedrock (Rk, Rk^c, Rk^d).
- Fissured bedrock (Rf).
- Extensive sand & gravel (Rg).

Regionally Important Karst Aquifers are distinguished in places where possible as either conduit flow dominated (Rk^c) or diffuse flow dominated (Rk^d).

Locally Important (L) Aquifers

- Sand & gravel (Lg).
- Karstified bedrock (Lk).
- Bedrock which is Generally Moderately Productive (Lm).
- Bedrock which is Moderately Productive only in Local Zones (LI).

Poor (P) Aquifers

- Bedrock which is Generally Unproductive except for Local Zones (PI).
- Bedrock which is Generally Unproductive (Pu).

Regionally Important Aquifers:

- are generally dominated by relatively pure fractured limestones or clean sorted sands and gravels;
- tend to comprise regional groundwater flow systems;
- tend to be dominated by productive boreholes with yields greater than 400 m³/d;
- have a relatively low drainage density together with a high baseflow to rivers; and,

- often have large dependable springs present (i.e., flow rates greater than 25 litres/second) – mainly in the karst aquifers.

In contrast, with the exception of the sands and gravels, Locally Important and Poor Aquifers are:

- dominated by impure limestones, shales and sandstones, granites and other rock types;
- dominated by poor yielding boreholes (less than 40 m³/d), with fewer and fewer productive boreholes (which tend to be unsustainable over long pumping periods/dry weather spells);
- a high drainage density with low base flow; and,
- often many small springs and seepages present, that dry out in long periods.

Sand and gravel aquifers:

- are dominated by grain sizes of less than 7% fines;
- comprise a permeability greater than 10⁻⁴ m/s;
- comprise an areal extent greater than 1km²; and,
- if known, a saturated thickness of at least 5m, or a thickness of at least 10m if saturated thickness unknown.

If the areal extent is greater than 10 km², and the deposit is well-characterised and understood, then the classification moves from a Locally Important Sand and Gravel Aquifer (Lg) to a Regionally Important Sand and Gravel Aquifer (Rg). Occasionally there are saturated deposits that do not meet all the criteria but are nevertheless important for a local supply and are therefore defined as a Locally Important Sand and Gravel Aquifer (Lg).

3.5 GENERALISED AQUIFER TYPES

The aquifer categories are also considered in terms of generalised aquifer types (GW WG, 2003; Fitzsimons *et al*, 2005), as follows:

- Sand/gravel (Rg, Lg)
- Karstic (Rk, Lk, Rk^c, Rk^d)
- Productive fissured bedrock (Rf, Lm)
- Poorly productive bedrock (LI, PI, Pu).

This generalisation is based on similar properties such as groundwater flow type (conduit, fissure or intergranular) and expected attenuation, and groundwater flow path length. These general aquifer types can be considered as groundwater systems that have similar hydraulic properties with a good indication of resource, extent and risk. In terms of groundwater management, aquifer units within each aquifer type are likely to require the same measures and monitoring requirements.

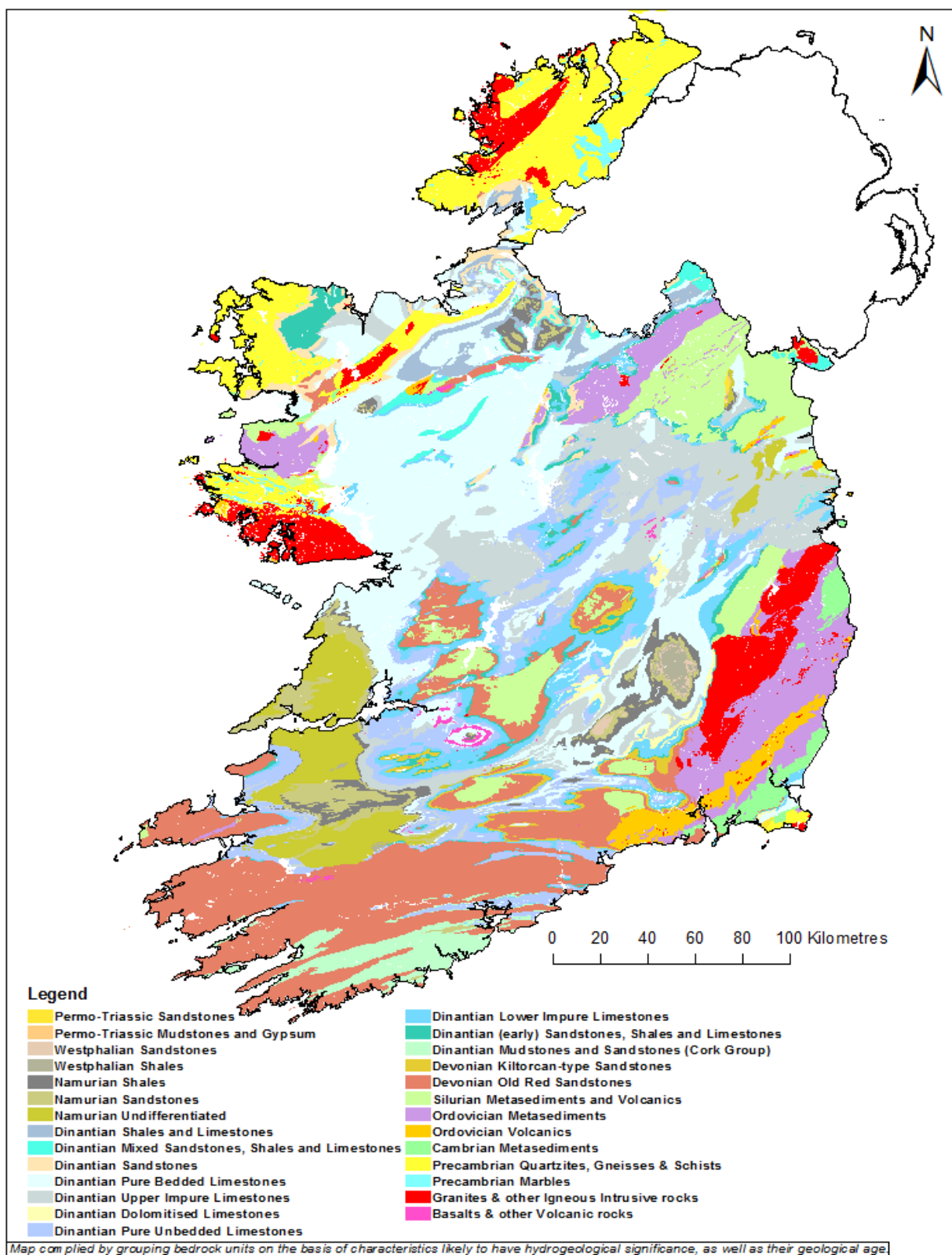


Figure 1 Rock Unit Group Map (GSI)

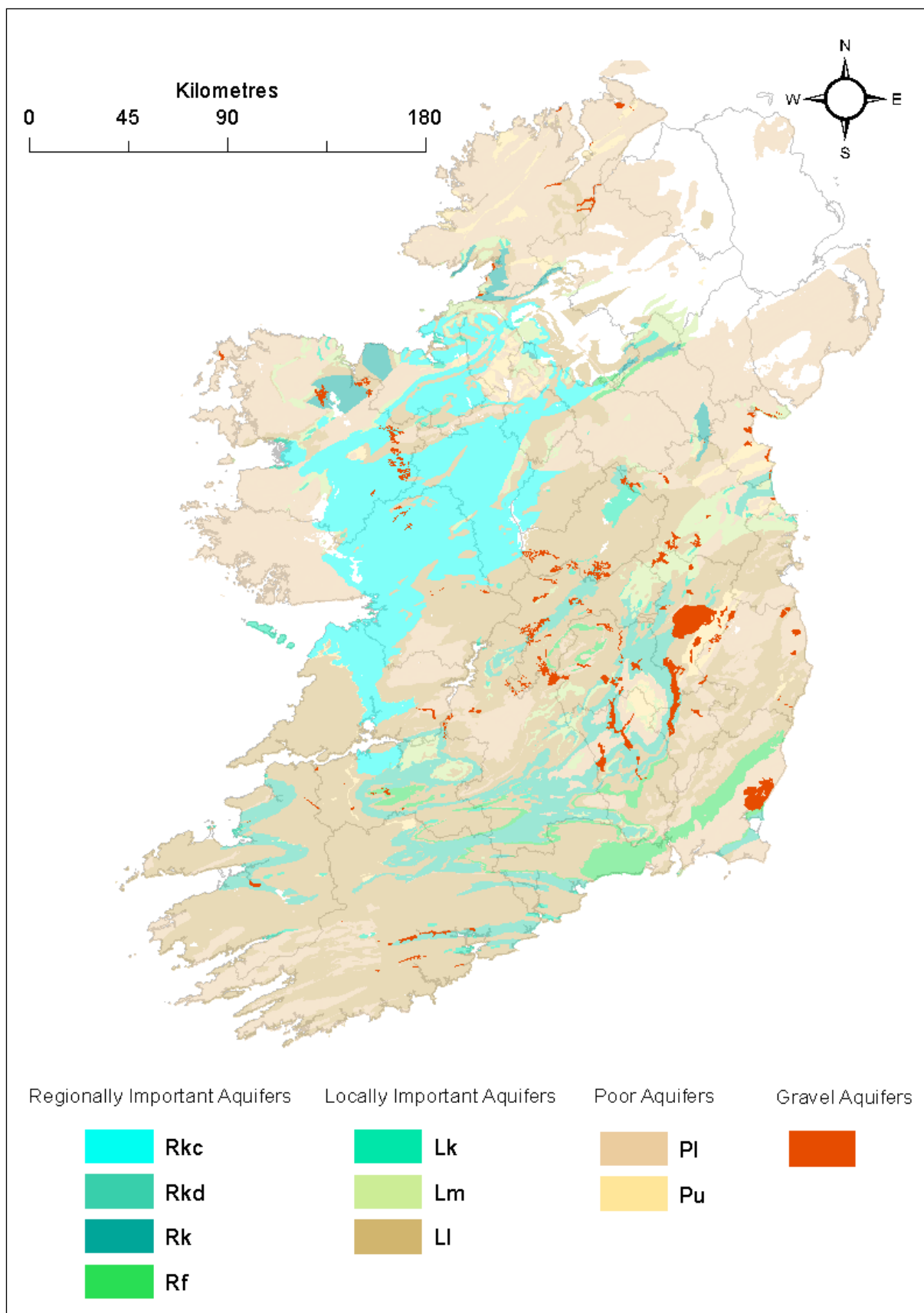


Figure 2 National Aquifer Map (GSI)

3.6 GROUNDWATER STORAGE, FLOW AND TRANSPORT

3.6.1 Introduction

The conceptualisation and characterising of groundwater systems requires quantification of the factors that govern the ability of the system to store and transmit groundwater. Thus a major task for hydrogeologists is the estimation or measurement of fundamental aquifer properties.

3.6.2 Groundwater storage

Porosity (n) is the proportion of a given volume of geological material that is occupied by pores.

- **Primary Porosity** comprises the voids between the individual grains in sediments and is a function of grain size, shape and sorting;
- **Secondary Porosity** refers to the spaces in consolidated and crystalline rocks that are formed due to fracturing and weathering. Secondary Porosity is usually much smaller than Primary Porosity.
- **Effective porosity (n_e)**: refers to the ratio of the volume of interconnected pores or spaces to the total volume and is a pre-requisite for groundwater flow. In Ireland primary effective porosity generally relates to sands and gravels and secondary effective porosity generally relates to fissure porosity. Effective porosity in fissured bedrock is generally equal or slightly more than the specific yield. Effective porosity in sand and gravel is generally significantly more than specific yield. In fine-grained deposits such as glacial tills, this relationship is even more pronounced.

Specific Yield (Sy): For unconfined aquifers specific yield is the amount of water which drains freely from a unit volume of initially saturated rock or subsoil per unit decline in water level and is normally greater than 0.01 (1×10^{-2}). The water retained by the bedrock or subsoil by capillary forces is called the **specific retention (Sr)**. The sum of Sy and Sr equals the effective porosity.

Storativity (S): For confined aquifers the water is under pressure and release of water from confined aquifers is due to release of elastic storage. Storativity is the amount of water which can be removed from a unit area of confined aquifer per unit decline in water level.

3.6.3 Groundwater flow

For groundwater to flow there needs to be effective porosity present. The size, shape and degree of interconnectedness of the void spaces in the rock or unconsolidated deposit together with the driving force (groundwater or hydraulic gradient) of groundwater control the rate of movement. In the current database the terms hydraulic conductivity and permeability, are often used interchangeably (as they are generally in Ireland).

Hydraulic Conductivity and Transmissivity: Groundwater flow through the aquifers is described by the Groundwater Flow Equation – Darcy's Law, which states that the flow rate is directly proportional to both the cross-section area and the hydraulic gradient. The resultant proportionality constant is the coefficient of **hydraulic conductivity (permeability) (K) [m/d]** which is an important aquifer characteristic. Equally important is the notion of hydraulic conductivity (permeability) over an entire saturated aquifer, a property which is captured by **transmissivity (T) [m^2/d]**: defined as the rate at which water can pass through the full aquifer thickness. Simply stated, it is the hydraulic conductivity multiplied by the saturated aquifer thickness.

There are two types of permeability:

- Intergranular permeability: the water moves between the grains of subsoils such as sand and gravel.
- Fracture/fissure permeability: the water moves through fractures or fissures or joints and along bedding planes. This is the dominant permeability in Ireland as the bedrock does not, in the main, exhibit primary porosity.

Groundwater flow to a well allows for parameter estimation and brings another useful concept and parameter to bear: **Specific Capacity (SC) [$\text{m}^3/\text{d}/\text{m}$]**, which is the pumping rate divided by the drawdown. This parameter gives an indication of how 'good' the yield is with respect to the corresponding drawdown.

The GSI Groundwater Programme (Wright, 2000; Wright, 1997) developed a useful metric to overcome a lack of fully recorded pumping test data by developing the Productivity Classification, which has become a very important tool in assisting with characterising Irish aquifers. It is considered a proxy for transmissivity (Fitzsimons *et al.*, 2005). It is described in Box 3.2.

Box 3.2 GSI Productivity Index

The Productivity Index is based on log-log plots of specific capacity (SC) [$\text{m}^3/\text{d}/\text{m}$] against pumping rate (Q) [m^3/d]. This plot is shown **Figure 3**, which shows all the data available to Wright (1997) at the time. There are five indices of productivity, I being the best and V being the worst. In general the productive aquifers are dominated by classes I, II and III, whilst the poorly productive aquifers are dominated by IV and V indices. There are cautions to be borne in mind with respect to the karst aquifers where there might be a high proportion of poorer productivity wells in addition to the very high yield wells intercepting conduits. The productivity graph is now widely used outside the GSI as a measure of both well and aquifer performance.

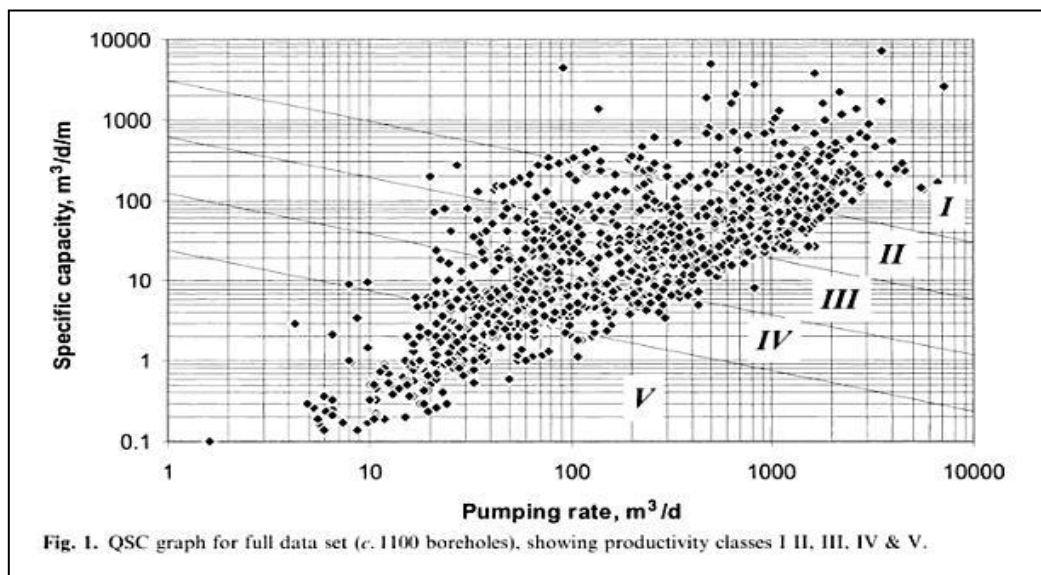


Figure 3 Productivity (QSC) graph by Wright (1997) Groundwater newsletter No. 32

Heterogeneity and anisotropy are two terms to describe variation in permeability. If permeability is the same throughout a geological unit and the same in all directions, it is both anisotropic and homogenous. If permeability varies with direction it is anisotropic. In fractured rock aquifers anisotropy is typically observed vertically and horizontally. Heterogeneity applies if permeability varies in magnitude from one place to another in the same geological unit.

Figure 4 illustrates the concepts of heterogeneity and anisotropy.

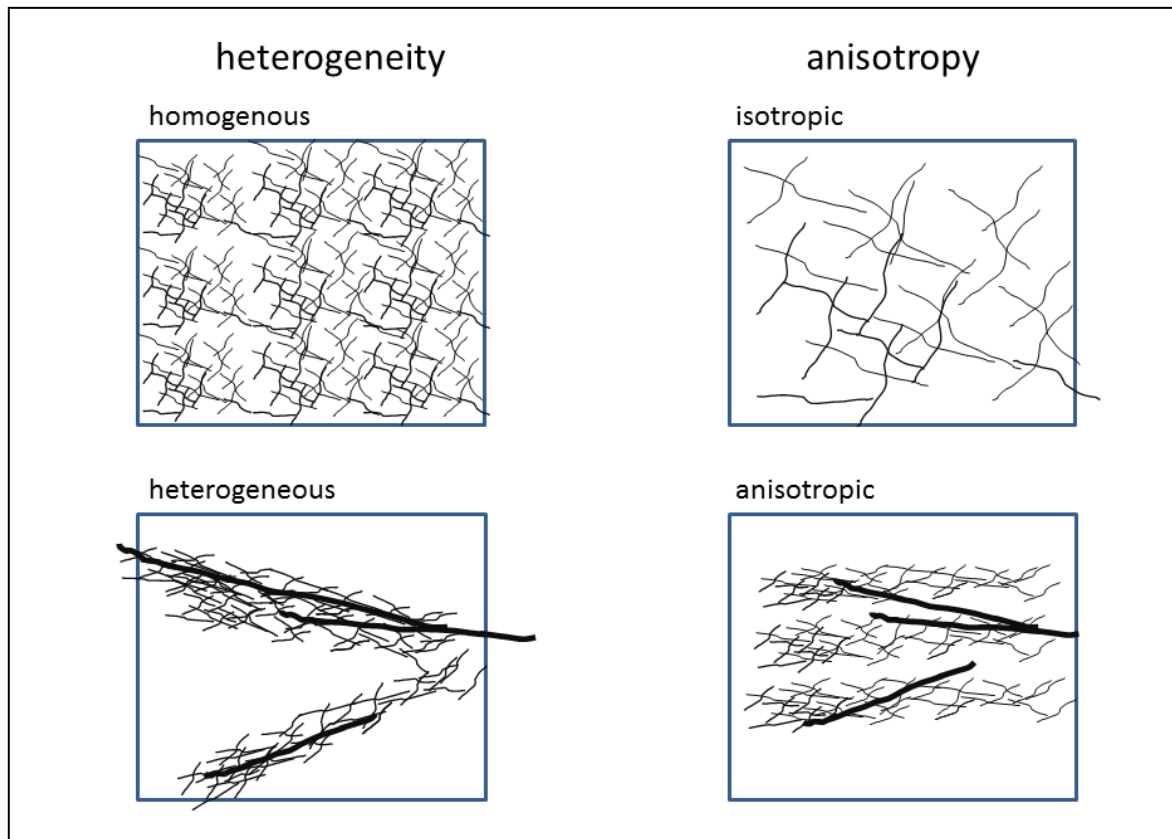


Figure 4 Illustrating heterogeneity and anisotropy

It is known that hard rock aquifers or fractured rock aquifers pose difficulties in characterising and predicting aquifer parameters. This is due to the inherently heterogeneous nature of fractured rock aquifers and the length scales of heterogeneity and the length scale of measurement. The length scale of the groundwater flow system or site under investigation needs also to be considered. Banks (2010) refers to a '**Representative Elementary Volume (REV)**', first introduced and defined by Bear (1972), "**as the volume/dimension at which there are only small changes in bulk hydraulic conductivity for small changes in sample size or sample location**". Zang *et al.* (2000) discuss the concept of REV, attempt to quantify the existence and size of REVs, and present the concept of a statistical REV, concluding that an REV is a volume above which the mean (of an aquifer property) is approximately constant. Neuman (2005) refers to the term 'support scale' which may be considered in similar terms to the REV.

3.6.4 Solute Transport

Characterising and predicting the distribution of solutes (contaminants) within groundwater flow systems is a commonly conducted hydrogeological task in contaminant hydrogeology. There are four main processes (advection, dispersion, retardation and degradation).

Advection is the most dominant process generally, a process where the contaminant is carried along by the bulk of groundwater flow, thus is quantified by the average linear velocity of groundwater flow.

Dispersion characterises the process of spreading during transportation, where a high concentration of solute spreads out to areas of groundwater with lower concentrations due to molecular diffusion and variations in velocity at different scales. There are two main components to dispersion (*hydrodynamic dispersion*): diffusion and mechanical mixing, which can be described in terms of **longitudinal** (parallel to dominant flow direction) and **transverse** dispersion (normal to the dominant flow direction) and **vertical** dispersion (Krešić *et al.*, 2013; Aziz *et al.*, 2000). The dispersive characteristic of rocks is very difficult to quantify and is scale dependent. Dispersion for a specific portion of aquifer is proportional to the sum of the velocity and the effective diffusion component.

$$D_L = \alpha_L V + D$$

$$D_T = \alpha_T V + D$$

$$D_z = \alpha_z V + D$$

Where,

D_L , D_T and D_z are longitudinal, transverse and vertical coefficients of hydrodynamic dispersion.

α_L , α_T and α_z are dispersivity (dynamic) constants (L).

D is coefficient of diffusion (L^2, T^{-1}).

V is the seepage velocity.

In most aquifers the mechanical mixing element dominates. The constant, termed **dispersivity**, is normally expressed as a 'length' in cm or m. It is an expression of the deviations from the mean linear velocity caused by mixing at all the different scales present in a given portion of aquifer. Some groundwater models call for inputs for the longitudinal and transverse components. As might be expected, due to advection, longitudinal dispersivity is greater than transverse dispersivity. Therefore contaminant plumes tend to be longer than they are wide. Field studies suggest that longitudinal dispersivity ranges from 10 to 100 m, and that transverse dispersivity ranges from 10-30% of the longitudinal dispersivity (Singhal *et al.*, 2010). Gelhar *et al.* (1992) and Neuman (1995) collated data from a variety geological environment, and from different tests at different scales, and demonstrate that the longitudinal dispersivity increases with the scale of observation, and at a rate greater than 1:1.5 on a log-log scale. Based on the work by Gelhar *et al.* (1992), initial estimates of 10% and 3% of the pathway length for the longitudinal and transverse dispersion components, respectively are commonly used (Aziz *et al.*, 2000; Krešić *et al.*, 2013). However, Gelhar *et al.*, (1992) also discusses the reliability of the data they used, and consequently advises caution with the use of the ratios presented. Krešić *et al.* (2013) outline the dangers of applying rules of thumb by way of example. Similarly US EPA guidance (Aziz *et al.*, 2000) advocates a conservative approach in selection of initial estimates.

Chemical processes include **retardation** where (mainly sorption processes) due to interactions between the geological media and the water slow down the solute transport; and **degradation** where certain solutes decay and biodegrade to other products. Note that sorption processes are mainly used when referring to organic contaminants, whilst ion exchange applies to inorganics.

3.7 GROUNDWATER PATHWAYS

In consideration of groundwater–surface water interactions for WFD purposes and obtaining a handle on quantifying flow to streams, the GSI developed the pathways concept, illustrated in **Figure 5**. The concept and definitions of the pathways are set out in Fitzsimons *et al.* (2005), RPS (2008) and Moe *et al.* (2010). The pathways concept is continually being developed under

the EPA Strive pathways project (e.g. Deakin *et al.*, 2010; O'Brien *et al.*, 2013) and the Griffiths Poorly Productive Aquifer study (Comte *et al.*, 2012).

There are four groundwater **pathways** considered, depicted in **Figure 5**. Examples are given in **Figure 6**, **Figure 7** which attempts to show the pathways at two contrasting scales, and **Figure 8**. These pathways require characterisation where groundwater is demonstrated to be present and flowing in these zones. Comte *et al.* (2010) describe an integrated approach to characterising catchments underpinned by fractured rock aquifers, and identify and assess the different pathways present.

The four pathways are:

- **Subsoils;**
- A “**transition zone**” between subsoils and underlying bedrock;
- **Shallow bedrock;** and,
- **Deep bedrock.**

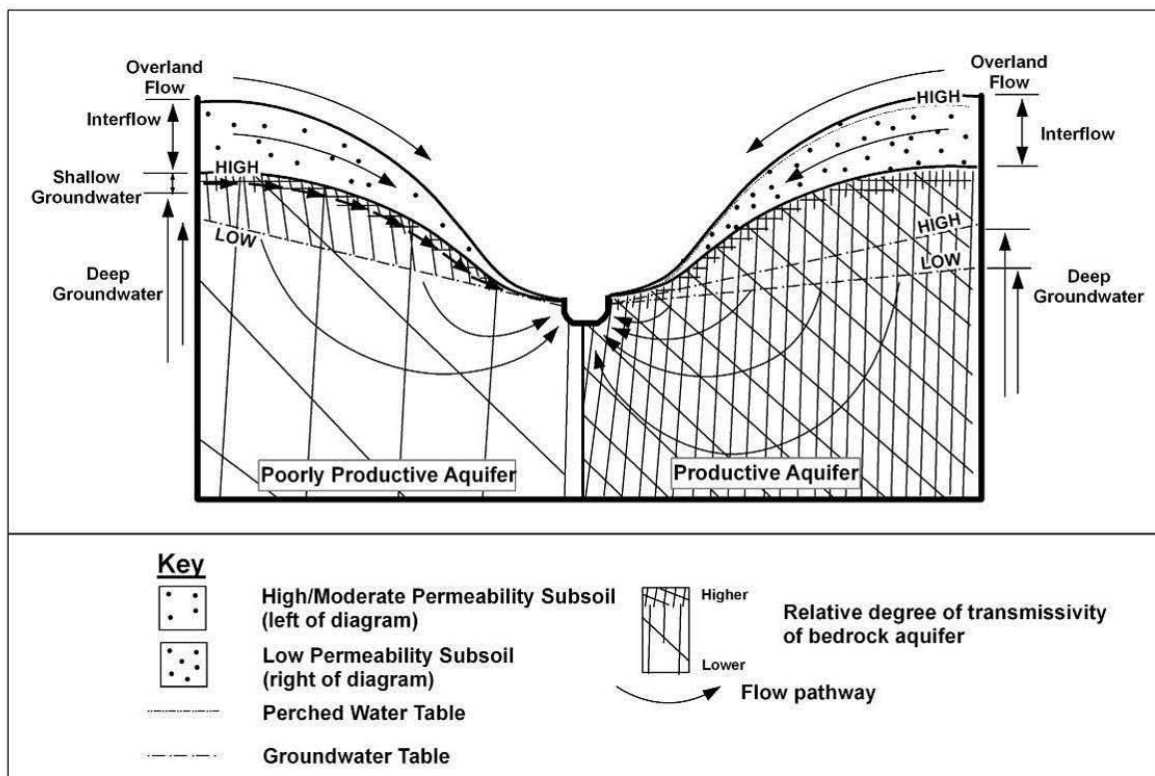


Figure 5 Groundwater pathways set in contrasting aquifer settings (original figure and concept by D. Daly and N. Hunter Williams, 2007, in RPS 2008).

The **transition zone** is a zone of broken/weathered bedrock that is located between the subsoil and competent unaltered bedrock. It is in many cases clast-supported. It can rapidly change in thickness over very short distances and may be absent in many cases, for example as shown in **Figure 6**, which is further along the same coastal section as shown in top photograph **Figure 7**. The boundaries with the subsoils and the underlying bedrock can be sharp, gradational, wavy, horizontal, and in some cases it is difficult to observe and define, particularly during drilling. As a pathway, where it is present, it is generally more permeable than the underlying bedrock. However, this is largely dependent on the underlying bedrock. For instance, shalier bedrock units may be expected to have less permeable transition zones consisting of matrix supported, highly

weathered and very fine grained material, making it difficult to distinguish from subsoil and the underlying bedrock.

Figure 8 **Figure 8** illustrates examples of different transition zones in a variety of rock types.



Figure 6 Subsoil directly on shallow bedrock – no transition zone present (photograph courtesy of Monika Kabza)

The **shallow bedrock zone** is located beneath the transition zone and generally comprises bedrock in which the inherent bedding and structure is clearly visible and unaltered and is a zone often characterised by a network of connected fissures, joints and fractures (**Figure 6**, **Figure 7**).

Beneath the shallow bedrock zone the fractures and fissures become less frequent and less connected. This zone is described as the **deep bedrock zone**, illustrated in **Figure 7**; in the lower photograph a single fissure close to the quarry floor is issuing groundwater. **Figure 7** attempts to illustrate the pathways at two different contrasting scales.

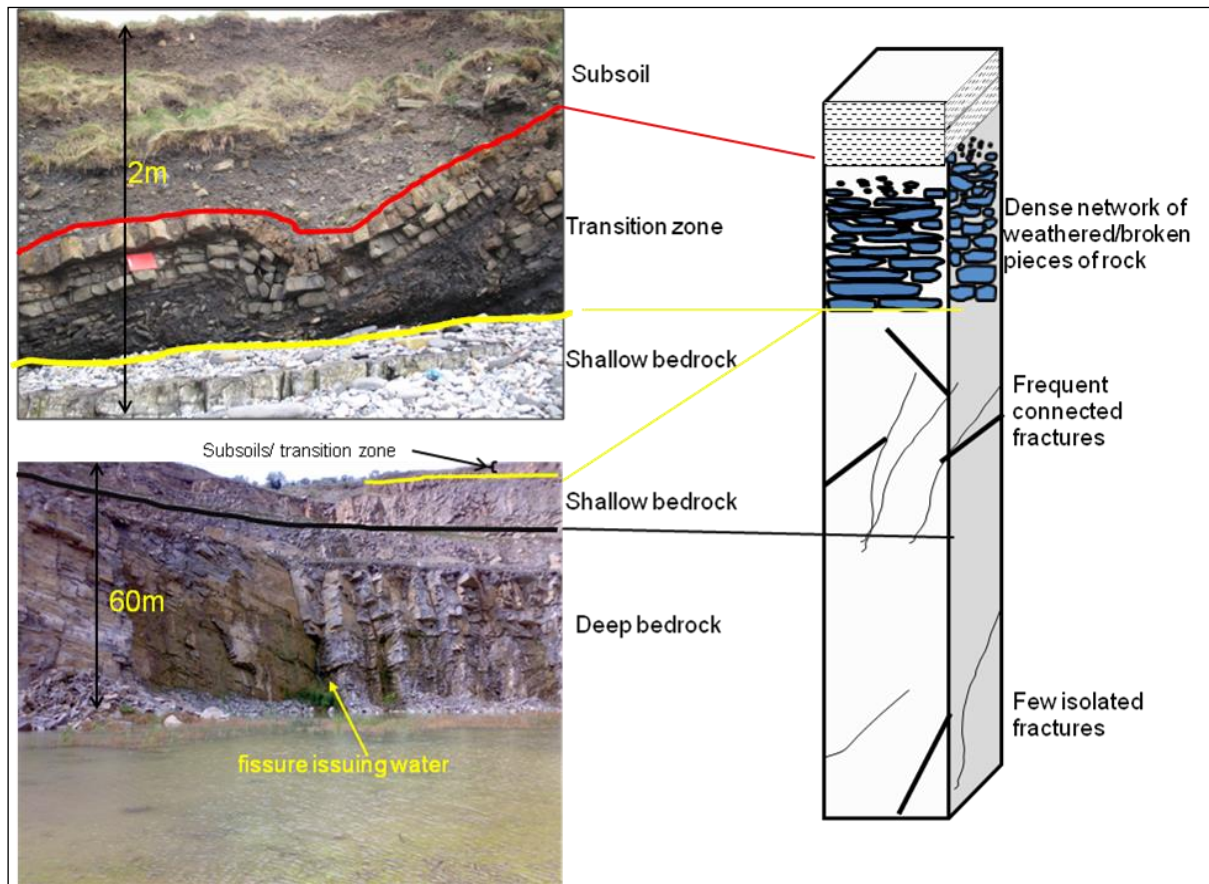


Figure 7 Groundwater pathways in fractured bedrock aquifers overlain by subsoils at two contrasting scales. Top photograph courtesy of Monika Kabza and bottom photograph courtesy of Robert Meehan. In the bottom photograph the subsoils and transition zone occupy 1-3m above the shallow rock zone.

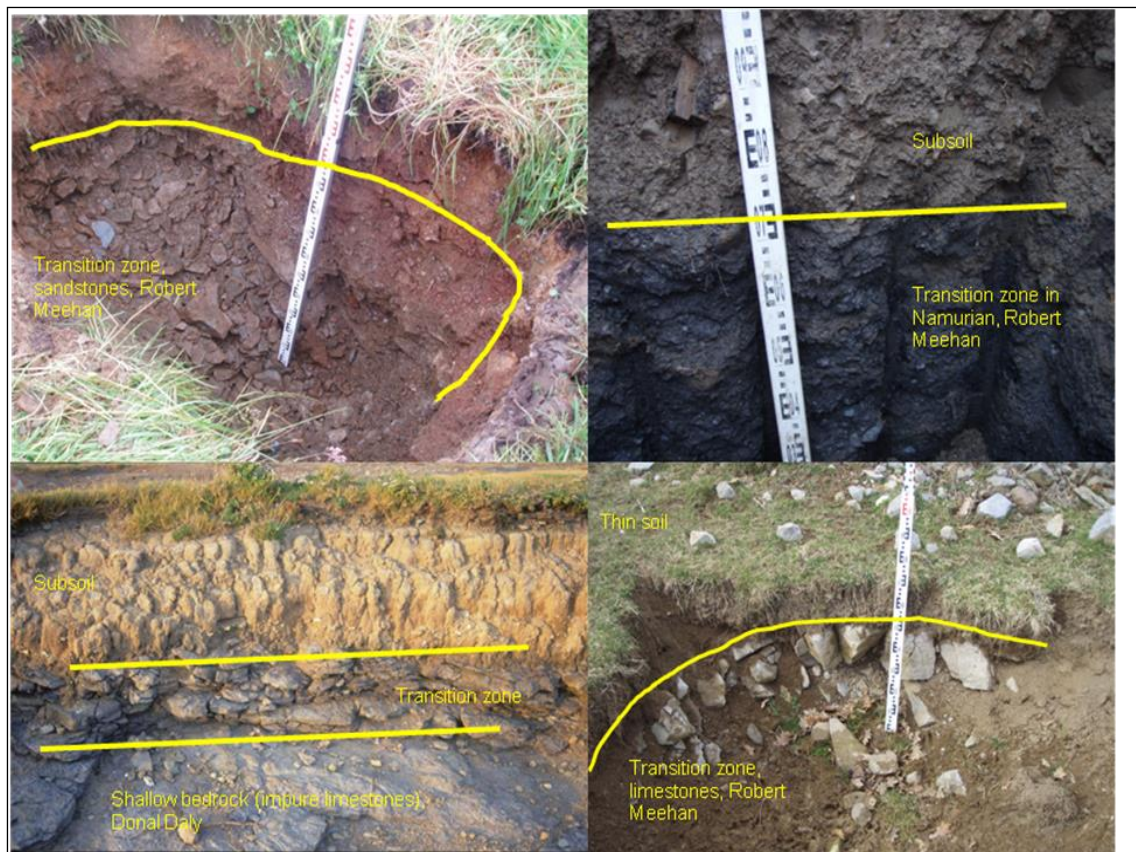


Figure 8 Examples of transition zones in different rock types

As described by Fitzsimons *et al.* (2005) and Daly (1995), fissure permeability is dominant in Ireland due to the fractured nature of the bedrock and lack of primary porosity. Fitzsimons *et al.* (2005) describe the typical relationship between fissure permeability and transmissivity with depth for a transmissive aquifer and a poorly transmissive aquifer (

Figure 9). Typically, fracture density and aperture, hence permeability and transmissivity, decrease with depth, although significant flowing fractures and fracture zones can be encountered at depth. Comte *et al.* (2012) show a significant reduction in permeability with depth. With reference to

Figure 9, it was found that permeability ranged from 0.1 m/d in the uppermost broken/weathered zone (Zone 1), to 0.01 m/d in Zone 2, to 0.001 m/d in Zone 3.

Missteart (2012) discusses well design in fractured bedrock aquifers where the uppermost zones are the most productive/transmissive, and yet often the most vulnerable to contamination. He points out the trade-off between providing sufficient length of grout-sealed casing(s) to reduce the susceptibility to contamination and maximising the yield.

Fitzsimons *et al.* (2005) conclude that “*permeabilities can be elevated in localised zones within even the poorest aquifers. The concept of poorly permeable aquifers is therefore not appropriate. Transmissivity or its proxy “productivity” are more appropriate terms to use, as they encapsulate the variation in fissure permeability with depth. In bedrock aquifers, higher transmissivity and productivity values are generally due to greater depths of interconnected fissuring*”. Hence the term “Poorly Productive Aquifers” that is used in Ireland.

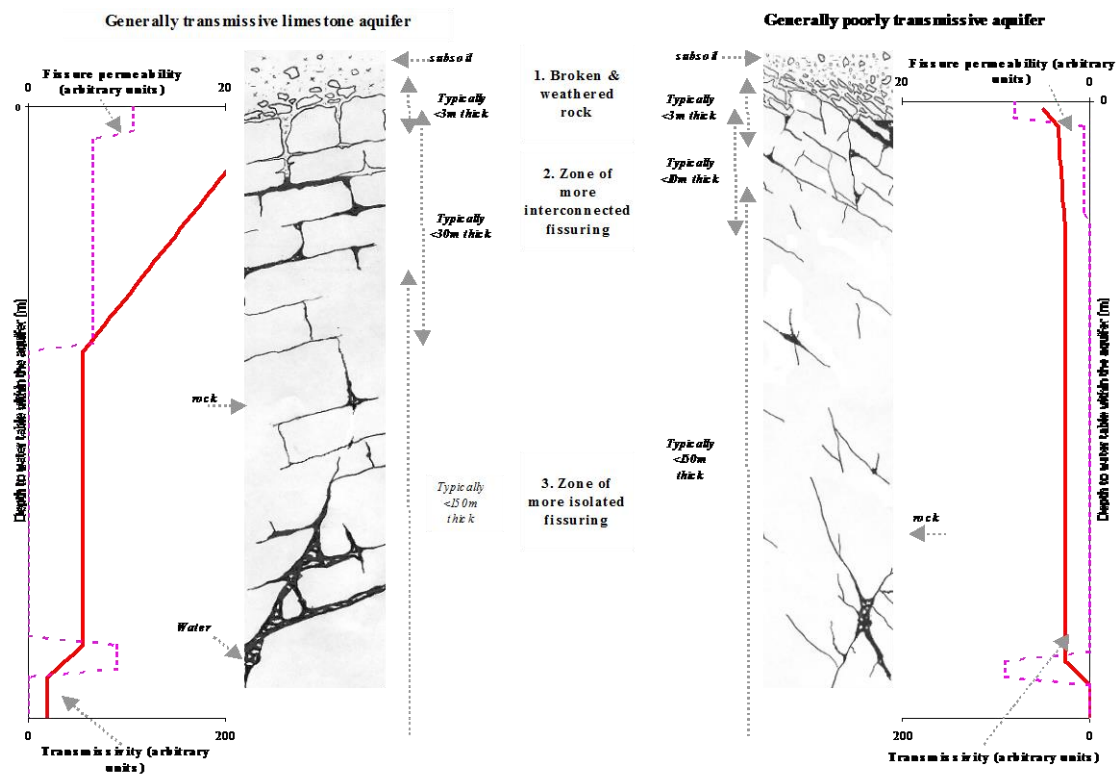


Figure 9 Fissure Permeability and Transmissivity (after Fitzsimons et al., 2005; GSI Aquifer report in preparation)

4 DERIVING ROBUST AQUIFER PARAMETER VALUES

4.1 APPROPRIATE AQUIFER PARAMETERS FOR IRISH AQUIFERS

The preferred parameter to assess hydraulic properties in hard rock aquifers or fractured rock aquifers is transmissivity due to its practical importance, availability of data and more reliable values as compared to hydraulic conductivity where data from well pumping tests usually reflect single or a handful of highly permeable fractures surrounded by massive blocks of impermeable rock. Banks (2010) advises caution when using bulk transmissivity to estimate hydraulic conductivity due to the strong depth dependence of hydraulic conductivity, and also because a single or handful of highly permeable fractures can be responsible for virtually all of the hydraulic conductivity.

In many countries, including Ireland, where fractured aquifers dominate, borehole yield and drawdown are often used to assess, predict and generalise aquifer hydraulic properties, since specific capacity is proportional to transmissivity (Wright, 1997; Banks, 2005). In the Czech Republic, transmissivity is the preferred hydraulic parameter due to the availability of data, and the fact that it is more reliable than hydraulic conductivity (Krasny, 1993).

In practical terms, the basic concept is about moving away from a single fracture to a sufficient volume of rock whose properties are representative of that rock unit as a whole. However, for contaminant fate and transport issues where first arrival is a key concern, then focussing on the fracture permeabilities may be most appropriate, particularly where the distance between contaminant and receptor/compliance point is small/similar compared to the fissure length scales.

4.2 METHODS FOR PARAMETER ESTIMATION

4.2.1 General

Quantifying hydraulic conductivity, transmissivity and the storage properties of aquifers is achieved primarily through hydraulic testing. Laboratory tests are used for direct measurement of hydraulic conductivity of the material, but the samples are usually very small, disturbed and groundwater generally flows in fractures which cannot be replicated easily in a laboratory. Therefore, in practice more reliable measures are conducted using field based tests. To establish groundwater storage parameters through site testing, an observation well is required. Effective porosity may be assessed from core samples in a laboratory, but for fractured bedrock or spatially variable subsoils, these samples are generally too small relative to the scale of heterogeneities, to establish effective porosity reliably. Effective porosity in fractured bedrock is generally taken to be approximately the same as specific yield.

There are standard site investigation technical guidance documents to prepare, set up and execute hydraulic tests.

Two of the main documents are:

- BS5930: 1999 Code of Practice for Site Investigations.
- BS ISO 14686: 2003 Hydrometric determinations. Pumping tests for water wells. Considerations and guidelines for design, performance and use.

In addition there are a number of popular text books, for example, Kruseman and De Ridder (1990), and Misstear *et al.* (2006) that provide background, practical information and worked examples.

There are a number of different hydraulic tests and each addresses a different purpose, a different scale of measurement and potentially different pathways or combination of pathways.

Typically hydraulic tests comprise:

- Falling/rising/constant head tests.
- Packer tests.
- Test pumping.

Figure 10 and

Figure 11 illustrate the scales of measurement of the different tests.

Figure 12 and

Figure 13 illustrate the scale of investigation – an important aspect when choosing the appropriate test method(s).

In

Figure 12 (upper diagram) smaller type tests may be appropriate to characterise the pathways. In the lower diagram a number of different tests may be required to fully characterise the fractured bedrock and pathways.

In

Figure 13 the anisotropy and the direction of groundwater flow and groundwater gradient testing will influence the testing most appropriate to determine aquifer parameters, and also the test interpretation methods chosen.

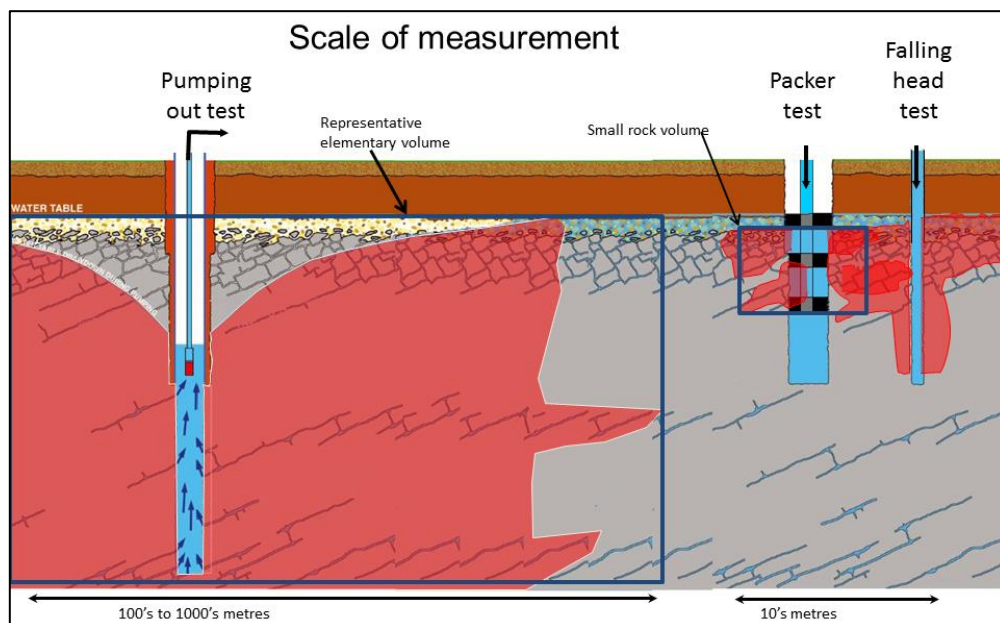


Figure 10 Different test types and scale of measurement and the representative elementary volume. (Diagram background adapted from IGI, 2007.)

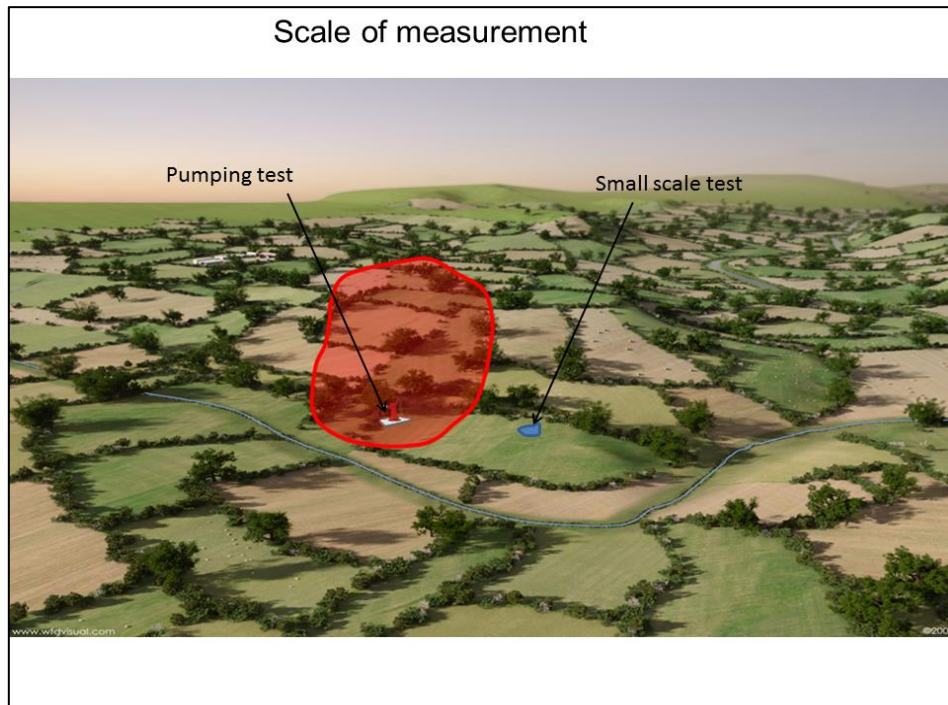


Figure 11 Schematic plan view illustrating different test types and scales of measurement

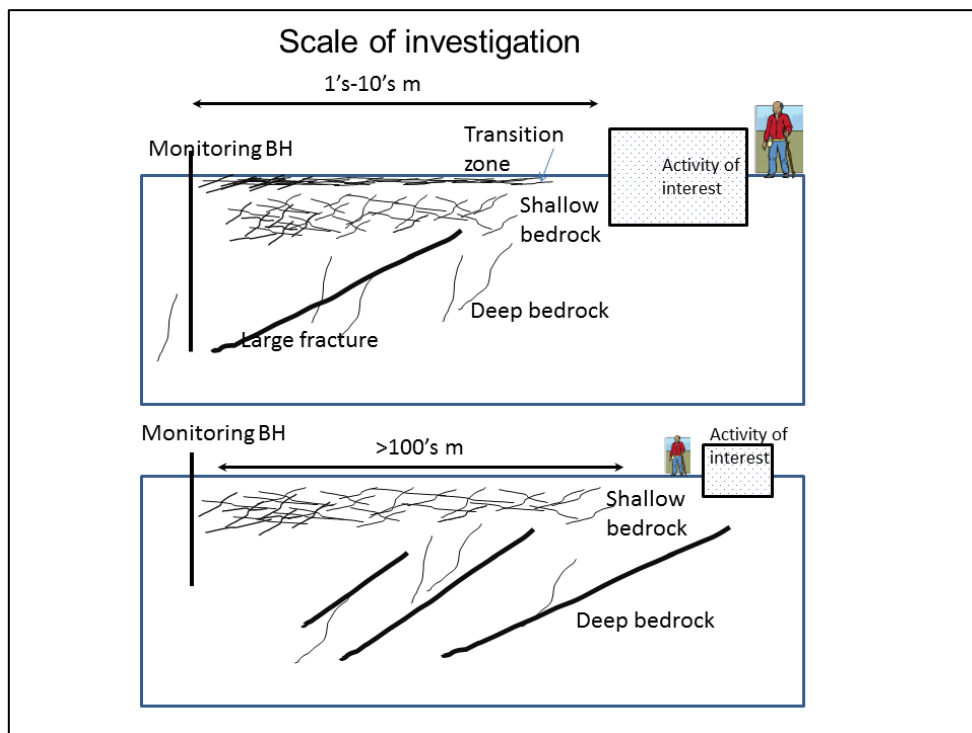


Figure 12 Schematic illustrating scale of investigation. In the upper diagram, smaller type tests may be appropriate to characterise the pathways. In the lower diagram a number of different tests may be required to fully characterise the fractured bedrock and pathways.

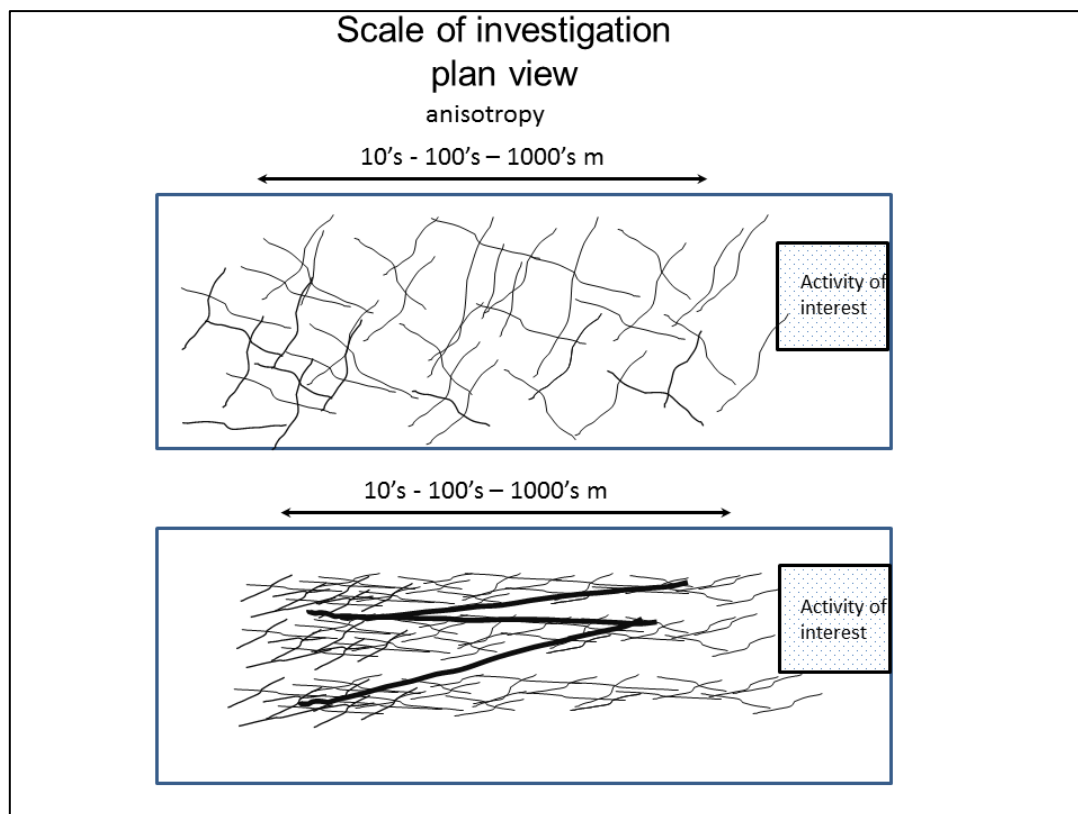


Figure 13 Schematic illustrating scale of investigation in plan view. Testing will need to take account of groundwater flow direction and gradient.

4.2.2 Permeability tests (falling/rising/constant head)

Permeability tests are generally used to determine hydraulic conductivity over short intervals or discrete identifiable fractures and are usually restricted to relatively shallow depths. They are often deployed for site investigations, for example, landfills, petrol stations or tunnels, and can be useful to characterise the hydraulic properties of, and assist in identifying any potential problematical, inflow zones. In Ireland, the data generally refer to the subsoils or the transition zone and/or the shallow groundwater pathway (up to 25–30 m deep below rock head) in the bedrock. The length scale of these tests is generally restricted to 'metres', in other words the representative volume of aquifer tested is relatively small – cubic metres to a few hundred cubic metres at most.

There are many methods available to analyse the results. Two of the more common methods are Hvorslev (1951) and Bower and Rice (1976). Butler (1998) provides a series of flow charts to facilitate selection of the most suitable analysis method. It is common practice to use the Hvorslev (1951) method/solution. For instance it was recently used in the EPA Groundwater Works Programme (Moe *et al.*, 2010), and also used by Swartz *et al.* (2003) to assess data from falling and constant head tests in subsoils. The Hvorslev (1951) solution was developed for confined aquifers with fully screened wells, and the Bouwer and Rice (1976) solution was developed for unconfined aquifers with partially screened wells (Butler, 1997).

There are assumptions and limitations to each method, and knowledge of the geology and a detailed log is required to deploy the most appropriate method. Anisotropy and the ratio between the length and radius of the screened interval or open interval determine the relative importance of axial and radial flow and therefore the model solutions used. For example, according to Butler

(1994), the Hvorslev (1951) method overestimates the conductivity where there is only partial penetration of the well and it also doesn't take into account the aquifer thickness. It also assumes an isotropic aquifer, performs poorly in the presence of well skin, has increasing errors in wells with small aspect ratios, i.e., the ratio of the length and the radius of the screened or open interval. Less reliable estimates can occur from the Bouwer and Rice (1976) method when the well screen decreases in length as this affects the flow geometry; the shorter the well screen the more the flow geometry deviates away from that of radial flow (Brown, 1995).

Permeability tests, in particular those conducted in the field, are often viewed with scepticism and considered unreliable (Black, 2010). Black (2010) indicates that the main issues surround leakage around the interval being tested and the test procedures in BS5930 (1999). He advocates and suggests a number of specifications that include:

- an 'elevation composite plot' – a plot that links the drawdown curve to borehole construction and geology;
- avoiding over-simple straight line analyses;
- careful measurement of the initial water level;
- small induced head changes;
- interval length:diameter ratio of 10 or more; and,
- the use of pressure transducers.

4.2.3 Packer tests

Packer tests involve isolating open/unscreened sections of a borehole to facilitate hydraulic and/or water quality testing. The packers are inflatable bladders that seal off the test section. There are a number of different assembly and testing arrangements. Commonly, water is then injected under pressure into the test section and the pressure (pounds per square inch) and flow recorded. Normally, for the section being tested, a cycle of three increasing pressure steps followed by decreasing steps (at the corresponding pressure steps used in the increasing steps) is carried out. Hydraulic conductivity can be calculated from the test information, often reported as Lugeons (gallons per minute of flow per foot of test section per psi of pressure). Lugeon testing is commonly deployed in engineering geology projects during drilling, whereby a single packer assembly is set up at the bottom of the advancing hole, consisting of an open test section 3-6 m from the bottom of the hole. A Lugeon can be converted into hydraulic conductivity units; 1 Lugeon is approximately 1.1×10^{-7} m/s.

4.2.4 Test pumping

The scope of this section does not cover the entirety of test pumping. For greater detail the reader is referred to, for example, Misstear *et al.*, 2006, and other relevant text books, which summarise the main methods, limitations, how to conduct a test and how to analyse and interpret the data.

Test pumping ('pumping out test' or 'pumping test') is used to determine well efficiency, yield, drawdown, the shape and rate of expansion of the cone of depression and can be used to calculate the transmissivity and storage properties of the aquifer and likely orientation of fracture zones.

Test pumping is considered to test the borehole and the aquifer at a much larger length scale than permeability tests and packer tests – from hundreds of square metres up to several square kilometres in areal terms and generally up to 60–70 m below rock head in Ireland. Depending on the borehole construction and depth, the vertical response zone(s) could include all the pathways present or apparently present – subsoils, transition zone, shallow and deep groundwater.

Test pumping can consist of step tests and constant rate tests. A step test generally comprises testing a borehole at different pumping rates to establish the performance efficiency of the well and the rate at which a subsequent constant rate test is conducted. A constant rate test is the main test to assess the hydraulic and the storage properties of the aquifer. It generally involves pumping a well at a constant rate and measuring the drawdown response. Ideally, observation wells are available to monitor drawdown, as this allows for interpretation of the storage properties as well as a greater insight into the transmissivity of the aquifer, and orientation and development of the radius of influence.

There is a wide variety of techniques in the literature to allow the interpretation of pumping test data. Tests can be distinguished broadly into steady state and non-steady state methods, and they both assume certain conditions, some of which may be violated to greater or lesser extents. The deviation from idealised conditions needs to be considered to determine if a particular solution or method for estimating aquifer parameters is sufficiently robust. The general assumptions can include a fully penetrating well pumping at a constant rate, in a confined aquifer that is homogenous, isotropic and of infinite areal extent, and that groundwater flow is laminar. Solutions for unconfined aquifers, partially-penetrating wells, and leaky aquifers (for example) exist, but for any particular set of test data and analysis method chosen, the full set of applicable assumptions should be considered. Misstear *et al.* (2006) and Kruseman and De Ridder (1990) both describe and synthesise the main methods and assumptions employed in analysis of test pumping data.

- Hydraulic conductivity and transmissivity can be determined from steady state pumping tests for both confined (Theim equation) and unconfined aquifers (Theim, Dupuit equation).
- Non-steady state methods are adaptations of the fundamental equation put forward by Theis (1935) who developed a method to assess transmissivity and storativity by interpreting the time-drawdown data for a constant discharge rate for fully penetrating well in a horizontal, homogeneous, isotropic, areally infinite and fully confined aquifer. These assumptions are rarely met in practice but the method is generally robust enough to withstand the deviations to differing degrees depending on the specific conditions. In addition to calculations of transmissivity and permeability, storativity can be calculated in non-steady state methods, provided an observation well is present.

One of the most widely used methods of interpreting test pumping data comprises a powerful adaptation of the Theis method known as the Cooper–Jacob Straight line method. It is considered to be relatively robust, fast to do and also provides strong visual evidence on the behaviour of the aquifer and the presence of boundaries, either barrier or recharge boundaries. It provides a good first pass assessment of the aquifer behaviour and parameters, but careful interpretation is nonetheless required in order to select the appropriate parts of the curve.

Diagnostic drawdown derivative plots

Spane *et al.* (1993) illustrate the benefits of diagnostic plots and derivative analyses in assessing and interpreting hydraulic test data, particularly constant rate tests and slug tests. Reynard *et al.* (2009) outline why diagnostic plots are a useful and an important, but generally rarely used technique, to assessing and interpreting test pumping data. The focus is on plotting drawdown and the log derivative of drawdown against time, and comparing the graphical plot against a catalogue of typical model curves. Van Tonder *et al.* (2002) and Samani *et al.* (2006) present examples to test pumping data from hard rock fractured aquifers. Generic popular modelling

packages offer derivative analyses and diagnostic plots amongst the solutions to assess test pumping data. Worked examples are given in [Section 4.4.4](#).

4.2.5 Tracer tests

Tracer tests can be used to estimate travel times. Tracer tests are generally deployed in karst environments. The GSI have conducted many dye tracer tests and maintain a karst tracing database which includes established travel times. Tracer tests can also be undertaken in other aquifer type systems (i.e. fissure or intergranular permeability), but monitoring may have to be longer-term than for karst systems because higher porosities and lower permeabilities reduce travel times. The reader is referred to the GSI for obtaining information and advice on tracer tests.

4.2.6 Analytical approach

If it is considered at a site that fracture flow is significantly important for contaminant transport, but site data do not exist or are inconclusive, estimation of fracture permeability can be undertaken using analytical approaches (e.g. Misstear *et al.*, 2006; Banks *et al.*, 2010; Van Tonder *et al.*, 2002). There are many assumptions underlying this approach, including planar fracture geometry, smooth fracture planes, laminar groundwater flow, known fracture aperture, etc. A key underlying assumption if this approach were to be used is that the fracture is extensive relative to the distance between the contaminant point and the receptor/compliance point (i.e., the heterogeneity length scale is greater than the scale of interest at the site). However, although this approach has many assumptions, it may be a useful method to determine conservatively the first arrival times for contaminants.

4.3 LIMITATIONS ASSOCIATED WITH EXISTING DATA AND WITH IRISH GROUNDWATER FLOW SYSTEM CONDITIONS

4.3.1 General

Limitations on deriving aquifer parameters from existing data can occur due to the data themselves and to what the data relate, in terms of the geological framework (pathway), and the purpose for which they were taken. The main limitations can be related to the test pumping set-up, borehole construction and the hydrogeological assumptions and are discussed briefly as follows.

4.3.2 Test type, purpose and length

In Ireland, the principal purpose of a pumping test was (and is) to establish the borehole yield which in turn was (and is) used to estimate the ‘sustainable’ pumping rate for a development. The pumping test length is generally short, often less than 72 hours, with an inadequate log, no observation well (sometimes just a final unreliable drawdown value in the pumping well is reported), and a declining or variable pumping rate throughout the test due to submersible pumps being the main type used in Ireland.

4.3.3 Borehole construction and associated ‘leaky’ conditions

‘Traditional’ borehole construction in bedrock aquifers in Ireland typically comprises steel casing seated or collared into competent rock with no grout around the annulus. Therefore, contributions from the transition zone and/or overlying gravels, if present, can disguise the main bedrock aquifer hydraulic properties, and can lead to an overestimate of the estimated sustainable yield. Short duration pumping tests exacerbate this. It should be noted that ‘modern’ water well construction should follow the IGI (2007) and EPA (2013) guidelines, with grouted casing-out of the shallow groundwater. However, even with a grouted annulus, long-term

pumping tests or operational pumping of a fractured bedrock aquifer may draw water in from overlying gravels within the cone of depression, if present.

4.3.4 Hydrogeological assumptions

Irish aquifers are generally heterogeneous, anisotropic, not areally infinite, and the boreholes generally do not fully penetrate the aquifer. Assessment is further complicated as the bedrock aquifers are generally fractured and it is difficult to assess if confining conditions or not are present. Thus Irish aquifers often deviate from standard assumptions underpinning hydraulic testing. Sometimes a borehole may intersect a very large fracture which simply delivers all the water to a borehole to such a degree that the drawdown rapidly accelerates to the fracture zone, remains there until the fracture is depleted, upon which the drawdown rapidly accelerates again to the pump intake.

Recharge may be occurring as many Irish groundwater systems are unconfined. Bias from a particular fracture may skew the data suggesting a highly transmissive aquifer whereas, in fact, outside the fracture it is very weakly transmissive. This may not be evident during a standard short-term pumping test, but only become apparent during operational pumping.

Therefore the limitations of typical Irish pumping tests are associated with:

- relatively short tests;
- declining or variable pumping rates;
- unknown geology/ construction details;
- the lack of, or inadequate, observation well data;
- multiple straight-line segments on a semi-log versus time plot due to throttling of different fractures;
- bias towards one single large fracture;
- assumptions that cannot be met.

These factors can inhibit a reliable estimate of transmissivity and/or an estimate of storativity and permeability. Where there are no observation well data, storativity cannot be estimated. Further, it also limits the assessment of transmissivity, particularly in thin gravel deposits, as the continually reducing saturated thickness around the pumping well directly suggests a reducing transmissivity.

In many reports involving the type of tests above, the yield and the specific capacity are all that is reported.

4.3.5 Data sources and sample bias

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

4.4 APPROPRIATE PARAMETER ESTIMATION FOR IRISH AQUIFERS

4.4.1 General

There are advantages and limitations to the different types of hydraulic tests, but for broad bulk bedrock aquifer characterisation, transmissivity is considered to be the most useful and practical hydraulic property. Often hydraulic conductivity values can represent the extremes of highly permeable fractures or the low permeability rock mass enveloping the fractures. To characterise transmissivity, test pumping is the most appropriate method to capture a 'Representative Elementary Volume' of aquifer. The smaller scale tests (e.g. packer) tend to be biased toward the upper weathered broken horizon at the top of the competent rock, or to the part of isolated fractures connected directly to the borehole.

Combining different strands of hydraulic testing where different portions of the aquifer need to be characterised is the ideal approach. For example, a combination of small-scale permeability tests on advancing boreholes followed by a more extensive field test of a deep borehole. This approach was recently applied to the EPAs Groundwater Works Programme where pumping tests and rising head tests were deployed to characterise the subsoils, upper weathered broken rock zone (transition zone), the shallow bedrock zone and the deep bedrock zone (Moe *et al.*, 2010).

Care needs to be taken with test pumping gravel aquifers as the majority are unconfined and transmissivity may be underestimated around the pumping well due to the reducing saturated thickness. In this case a combination of hydraulic tests may be more appropriate.

4.4.2 Analysis methods for fractured aquifers

It is widely accepted that analysing test data in hard rock aquifers is difficult, as many of the assumptions underpinning standard approaches may not be wholly satisfied. Banks *et al.* (2005) point to the “*fractured, discontinuous, and extremely heterogeneous, nature of such aquifers*” and Misstear *et al.*, 2006, emphasise that:

- fractured rock aquifers are neither homogenous nor isotropic;
- groundwater flow is channelized in the fractures (non-Darcyan);
- well bore storage is not negligible in low yielding boreholes; and,
- pumping rates often decline from an initial discharge rate particularly in low yielding wells – quite rapidly if set too high.

As can be seen in **Figure 1** and **Figure 2** Ireland is dominated by fractured rock and karstified aquifers. Comte *et al.* (2012) synthesise issues and approaches in characterising hard rock aquifers, and report on an integrated approach applied in several catchments in Ireland. This integrated approach deployed geophysical, hydrogeological and geological techniques. Of the hydraulic tests conducted, the resultant test pumping data was analysed using standard non-steady solutions (single porosity and double porosity models) using standard off the shelf groundwater software. Moe *et al.* (2010) attempted to test pump low yielding terrains in several catchments some of which overlap with those catchments in the investigations undertaken by Comte *et al.* (2012). According to Moe *et al.* (2010), test pumping the low yielding boreholes was difficult, and they recommend setting the pump as deep as possible to enable pumping for longer at lower rates.

It is widely accepted that borehole yield and drawdown are generally considered to be extremely useful data to estimate the transmissivity (Misstear *et al.*, 2006, Banks *et al.*, 2005 and Banks

(1992b), as specific capacity is proportional to apparent transmissivity. Misstear *et al.* (2006) provide a range of constants collated by various authors for hard rock aquifers. The most typical constants reported are in the range of 0.82 to 0.9. The Logan approximation outlined by Misstear (1998) is reported as 0.82 (1/1.22).

Misstear *et al.* (2006) describe and synthesise approaches to interpretation of test data in hard rock aquifers, covering both high and low yielding scenarios. For high yielding situations, test data are generally analysed using standard methods for steady and non-steady states. Misstear *et al.* (2006) outline a technique by De Lange and Van Tonder (2000), and Van Tonder *et al.* (2002), which allows for characterisation of the flow in the fracture network around the borehole. Van Tonder *et al.* (2002) emphasise the use of diagnostic drawdown derivative plots to characterise flow regimes. These plots are useful to indicate the preferred model to determine aquifer parameters. The observed curves can be used to identify well bore storage effects, if the test pumping is sufficiently long, boundary effects, and are also useful to indicate distinct fractures where present, signalled by an approximate sinusoidal wave form in the plots, which represents dewatering of successive fractures.

Characterising low yielding hard rocks is difficult as demonstrated by Moe *et al.* (2010) and Comte *et al.* (2012). A combination of small-scale permeability tests on advancing boreholes followed by a more extensive field test of a deep borehole could also be deployed. Constant drawdown tests or recovery tests or low flow pumps can help to overcome this difficulty (Misstear *et al.*, 2006).

4.4.3 Approach to assessing test pumping data

The general focus is on larger-scale tests, as these are the most commonly undertaken and most readily available data. These data also better inform the broad characteristics and hydraulic behaviour rather than small scale tests. Black (2010) suggests small scale tests quite often yield unreliable results owing to leakage around the interval being tested and the test procedures in BS5930 (1999).

Given the limitations outlined in [Section 4.3.4](#), straight line adaptations of Theis such as the Cooper–Jacob Straight line method remain one of the most commonly and widely used methods to assess pumping test data. This method – despite the ‘noise’ associated with recharge particularly as most Irish aquifers are unconfined, variable pumping rates, apparent changing transmissivity in response to interaction with different fracture zones, and relatively short tests – is a useful method to interpret the majority of test pumping data in Ireland. However, the test data require careful consideration given that the fractured rock environment generates a variety of potential responses. Misstear *et al.* (2006) illustrate and discuss deviations from the ideal response in a Cooper-Jacob plot.

Misstear (2001) highlights the usefulness of the ‘Logan’ equilibrium approximation of transmissivity for situations when only limited data are available for the test well (and there are no observation wells). The Logan (and similar) methods relates well specific capacity to aquifer transmissivity. This relationship is based on equilibrium between the pumping rate and a stable final drawdown, i.e., if drawdown is declining then the resultant transmissivity value may be an overestimate, whereas if well losses are significant, then transmissivity will be underestimated.

It is recommended that a simple method such as the ‘Logan’ method is used in conjunction with more sophisticated methods to cross-check results, and where the data cannot be analysed using the likes of Cooper–Jacob or where sufficient data do not exist from the pumping test.

Wright (2002) discusses the evaluation of pumping tests in the context of Irish hydrogeology and offers 'tips' on how to consider some of the issues that arise which have been taken into account in the assessments for the current database to date. The full article is given in Appendix 3 whilst some of main points are given in **Box 4.1**.

Two further rules of thumb can be applied:

- In hydrogeological terms it is only if there are marked differences, say an order of magnitude, between results from different methods that give rise to concern and force the user to recheck assumptions, the data and the logs. Generally a difference of no more than 50% would generally be agreeable.
- Provided equilibrium conditions have been reached then a transmissivity value obtained from Cooper–Jacob or another such method should not be less than specific capacity.

Test pumping data give 'bulk' aquifer estimates for transmissivity and thereby permeability over a relatively large scale and are a useful approximation for the groundwater environment for an area constituted by a known aquifer and rock unit group. However, for groundwater velocity calculations, permeability can vary greatly over small distances. Thus, there may be zones and/or fractures that may have a significantly higher permeability than that calculated from the bulk transmissivity value.

Generally, permeability decreases with depth. Thus the transition zone will tend to comprise higher permeability values than the shallow or deep bedrock zones. The pathways also offer different opportunities for attenuation and dispersivity. The transition zone, depending on bedrock type can offer greater opportunity for chemical and physical weathering, particularly in shaley units. It is likely that dispersivity will be greater in the transition zone due to greater surface area, i.e., greater tortuosity. Where the bedrock tends to be more extensively fractured thereby greater connectivity dispersivity may be higher, for instance in the Lm aquifers.

4.4.4 Worked examples

Worked examples are presented in Boxes 4.2 to 4.7.

- Box 4.2 provides an example of estimating transmissivity in a situation where a borehole intersects a single productive fracture at depth.
- Box 4.3 demonstrates an insufficiently long pumping test with log-derivative diagnostic plot.
- Box 4.4 demonstrates a leaky/recharge boundary with log-derivative diagnostic plot.
- Box 4.5 a diagnostic log-derivative plot for a long pumping test in a fractured aquifer, illustrating the leaky/recharge and double porosity model.
- Box 4.6 illustrates an example using log-derivative and semi log plots and a combination of methods to derive a robust transmissivity value.
- Box. 4.7 illustrates an example for storativity.

Box 4.1 Tips on pumping tests (Wright, 2002)

1. Analysis

It remains the case that the main methods used by most people remain the 'Straight-Line' methods, using semi-log graphs of time-drawdown and recovery data. For a reliable T value, measurements in a suitably located and constructed observation well are almost essential. ONLY use later time data for Jacob analyses, and work out the 'u' value threshold for your particular test.

For recovery analysis, the pumping rate over the entire period of the test should be averaged. This should be done on a time basis, i.e., calculate the total volume of water pumped and divide it by the total time.

For any other analyses, don't attempt to average the pumping rate over the test. Look for periods of relatively constant pumping rate, e.g. estimate a Jacob straight-line gradient over a single period when the rate was constant. In deriving a specific capacity, use the discharge rate and drawdown at the end of a period where the rate was relatively constant.

2. Storativity (S)

Classical pumping test analysis includes formulae for deriving 'S' values, using observation well data only. In practice, this is much more difficult than deriving reasonable 'T' values, particularly because 'S' is much more sensitive to deviations from ideal conditions. Storativity values from pumping tests need to be regarded sceptically.

3. Permeability (k)

In theory, a value for permeability or hydraulic conductivity ('k') can be derived by dividing the 'T' value by the aquifer thickness (D). In practice, however, the permeability can vary hugely with depth, and it is likely that the permeability of the most critical layers (e.g. in estimating a maximum groundwater velocity) will be significantly higher than the value derived from $T = k.D$.

4. Specific Capacity (SC)

SC is a very useful parameter, particularly because it can be derived from a test even when the lack of a constant pumping rate precludes deriving any reliable T or S data. And from a decent SC value you can derive an approximate T value via the Logan approximation (Logan, 1964; Misstear, 2001). It can also be used to derive 'Productivity' categories (Wright, 2000). However, remember that:

- SC is supposed to represent the well at equilibrium, i.e. when drawdown has stabilised.
- If you have a relatively smooth drawdown curve (which should fit a Jacob straight line) you can extrapolate it (to a reasonable degree) to, say, 10,000 minutes (about one week) and estimate the likely drawdown at that time.
- However, if drawdown is showing signs of continuously increasing, then any such extrapolation is best avoided. This situation is quite common in Irish aquifers.
- In unconfined aquifers (which include the great majority of Irish aquifers) the specific capacity will vary seasonally, being highest in winter/spring when the water table is high and the saturated zone at its maximum, and lowest in summer/autumn, when the opposite is true. This difference will vary most where the water table fluctuates most.
- SC will also vary with the pumping rate. However, in confined aquifers the gradient is much less (theoretically there should be no gradient at all, but well losses complicate the picture).

Box 4.2 Estimating transmissivity for a well intersecting a significant fracture zone.

The pumping rate is 418 m³/d and there is no observation well and the well diameter is 0.2 m. The borehole depth is 46 m and the depth to bedrock is 14 m. A fracture is inferred between 19 and 22 m below the top of the casing. A semi-log plot of drawdown and time is given in [Figure 14](#).

The drawdown is initially very steep and dramatically flattens out over the course of a few minutes and is in equilibrium at that rate.

The Logan equilibrium method yields a transmissivity of approximately 23 m²/day, which gives a permeability of 0.7 m/day, assuming an aquifer thickness of 32 m (46m-14m).

A Cooper-Jacob solution yields a transmissivity of approximately 30 m²/day, suggesting a permeability of approximately 1 m/day.

The De Lange & Van Tonder (2000) method gives a transmissivity of 20 m²/day.

The permeability value calculated is an average permeability over the total depth of the assumed aquifer thickness and represents the average permeability. The fracture permeability is much greater but the thickness of the fracture is unknown.

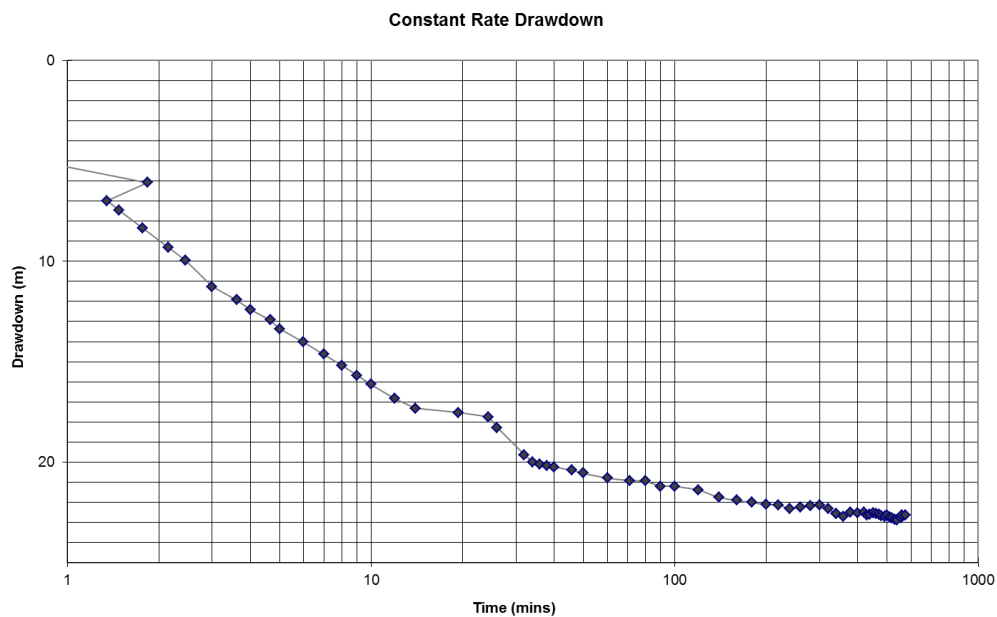


Figure 14 Semi-log plot of constant rate test data.

Box 4.3 Diagnostic plot (log-derivative) suggesting that test is not long enough

The log-derivative is given in [Figure 14](#). Ideally the log-derivative should be constant over 1 to 1.5 log cycles. The log derivative despite the scatter is still increasing, i.e., drawdown has not stabilised and suggests that that the test is not long enough to adequately satisfy the use of different interpretative techniques.

Nonetheless, an assessment using a Cooper-Jacob solution yields a transmissivity estimate of approximately $250 \text{ m}^2/\text{d}$, and using the Logan equilibrium estimate, transmissivity is $250 \text{ m}^2/\text{d}$. However, as drawdown has not stabilised, the estimates are treated with caution.

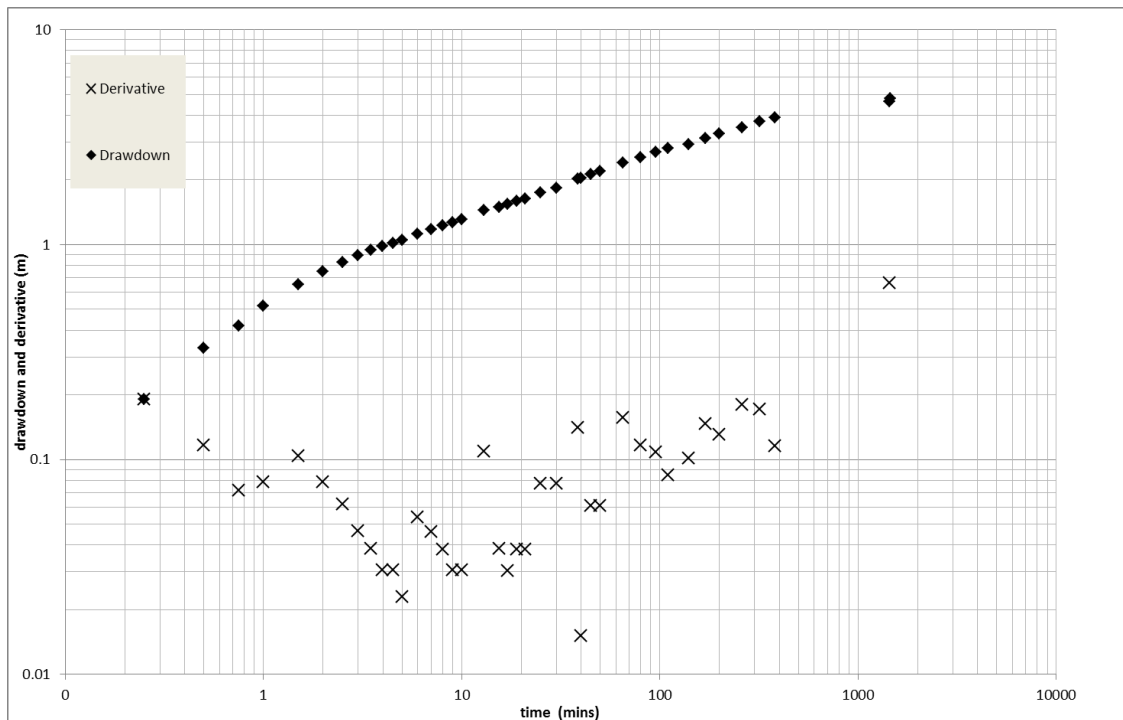


Figure 15 Diagnostic plot of drawdown and the logarithmic derivative.

Box 4.4 Diagnostic plot for a well in gravels adjacent to a stream

The diagnostic plot (**Figure 16**) is most like the leaky or recharge boundary model. A Cooper-Jacob solution yielded a transmissivity in the order of 60-90 m²/d which compared favourably to a Logan estimate of approximately 50 m²/d.

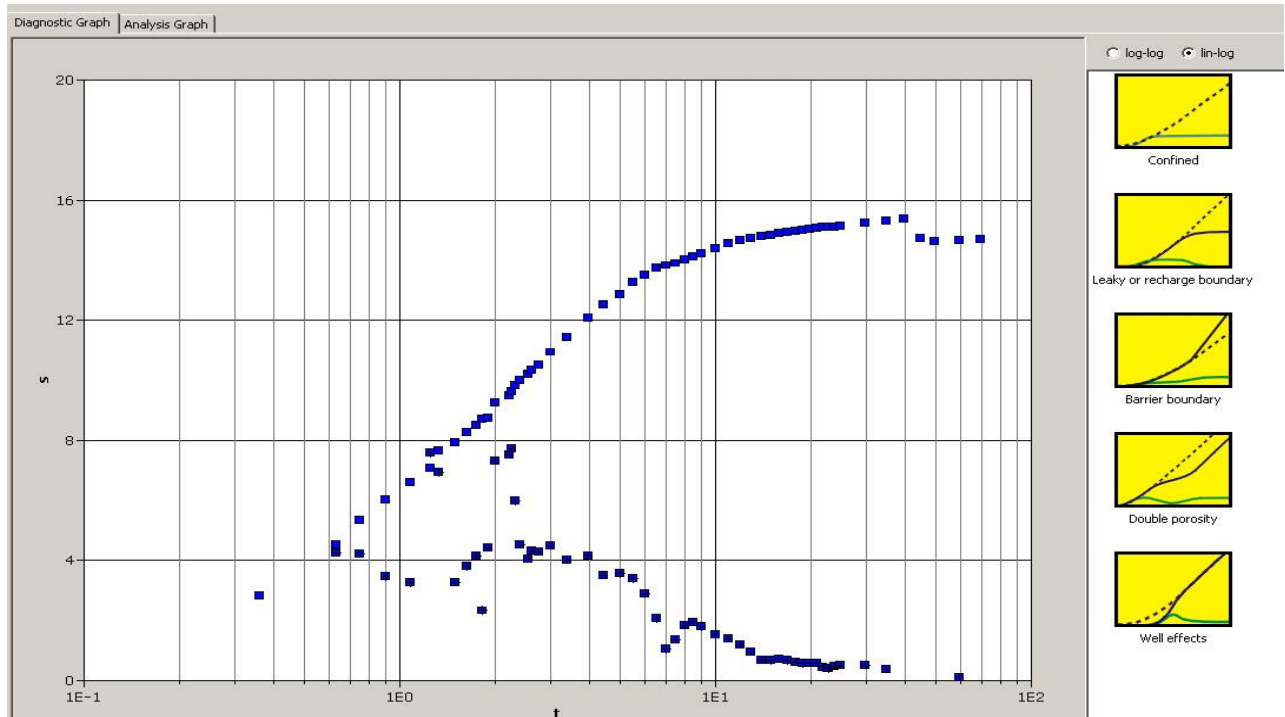


Figure 16 Diagnostic plot of drawdown and the logarithmic derivative for a public supply borehole situated in gravels close to a stream.

Box 4.5 Diagnostic plot for a long pumping test in a fractured aquifer

The log derivative plot (**Figure 17**) provides some insight into the flow characteristics. The pattern suggests a double porosity and a recharge boundary model. In addition, the slopes show a sinusoidal wave form pattern that points to successive fracture dewatering. A Logan equilibrium estimate of transmissivity is $287 \text{ m}^2/\text{d}$ and estimated transmissivity is $200 \text{ m}^2/\text{d}$ using a non-steady state solution.

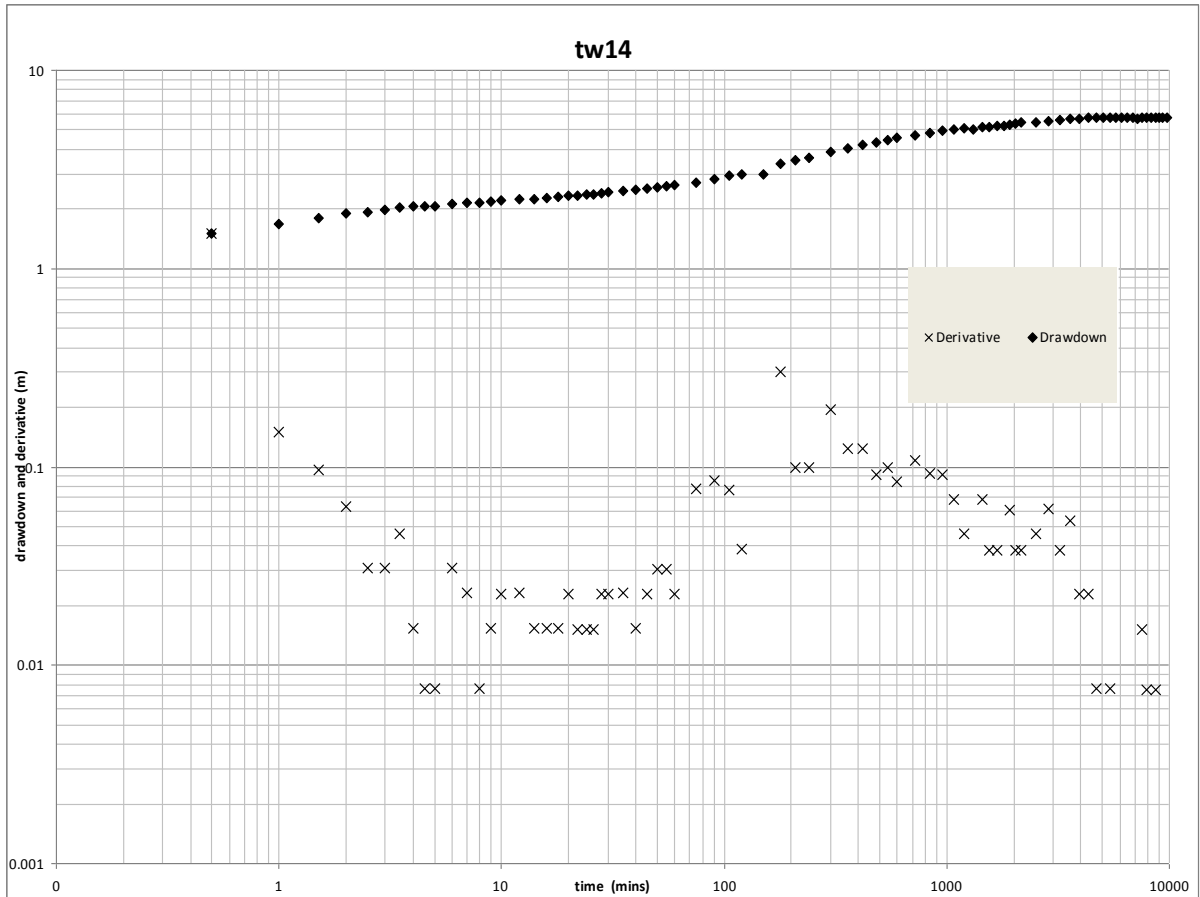


Figure 17 Diagnostic derivative plot

Box 4.6 Example estimating specific capacity, transmissivity from a pumping well in bedrock

A borehole was tested with a step test and two constant rate tests (24hr, 7 days). It is known from the log that the transition zone and shallow and deep bedrock zones contribute to the borehole and that there are significant fractures at 29 m to 32 m bgl. Even though this is relatively good data there are still typical aspects that often occur with 'Irish' data, for instance the discharge declines from 1800 m³/d to 1420 m³/d over the test.

As can be seen in the table, specific capacity reduces with increasing stress. Each step was finished before stabilisation of drawdown. Steps 1-3 are not considered reliable for estimating transmissivity. Specific capacity is estimated using the final discharge rate and final drawdown rate for the step tests and the constant rate tests, and the preferred value is 70 m³/d/m, taken from the 7-day day test.

Complicating the interpretation is drawdown; whilst it is reducing toward the end of the 7 day test, giving what is commonly termed 'pseudo-steady state', it is still declining though the abstraction rate is reducing also. The water level is about 27 m bgl, which is just above the main inflow zone.

Test	Specific Capacity (m ³ /d/m)	Transmissivity (m ² /d) Logan	Transmissivity (m ² /d) Cooper- Jacob
Step 1	141	172	
Step 2	122	149	
Step 3	115	140	
Step 4 (24hr)	105	128	
7 day Constant Rate	70	85	75 (early) 45 (late)

A diagnostic plot is given in [Figure 18](#) of drawdown and the log derivative of drawdown against time on a log-log plot. The log derivative appears scattered due to the 'noisy' pattern of the log derivative data. However, this plot compared to ideal model plots suggests that either a confined or a leaky/recharge boundary solution may be applied. In addition, there is an approximately sinusoidal form to the curve which may also suggest successive fractures being dewatered (Van Tonder *et al.*, 2002).

Transmissivity in this example is assessed using the Cooper-Jacob and the Logan method, and the semi-log plot of drawdown against time is shown in [Figure 19](#). The values range from approximately 45-80 m²/day depending on which portion of the graph is used, and so it becomes difficult to choose what is representative as the changing apparent transmissivity may correspond to dewatering of upper shallow more connected permeable zones and as the cone of depression intersects and draws down different fractures at depth. The 'Logan' method suggests transmissivity in the order of 85 m²/day.

The preferred estimate in this example is in the order of 70 to 90 m²/d. The lower Cooper-Jacob estimates are not reliable and are less than specific capacity. In addition, analysed data are from the pumping well and well losses are not considered in this example.

Box 4.6 continued.

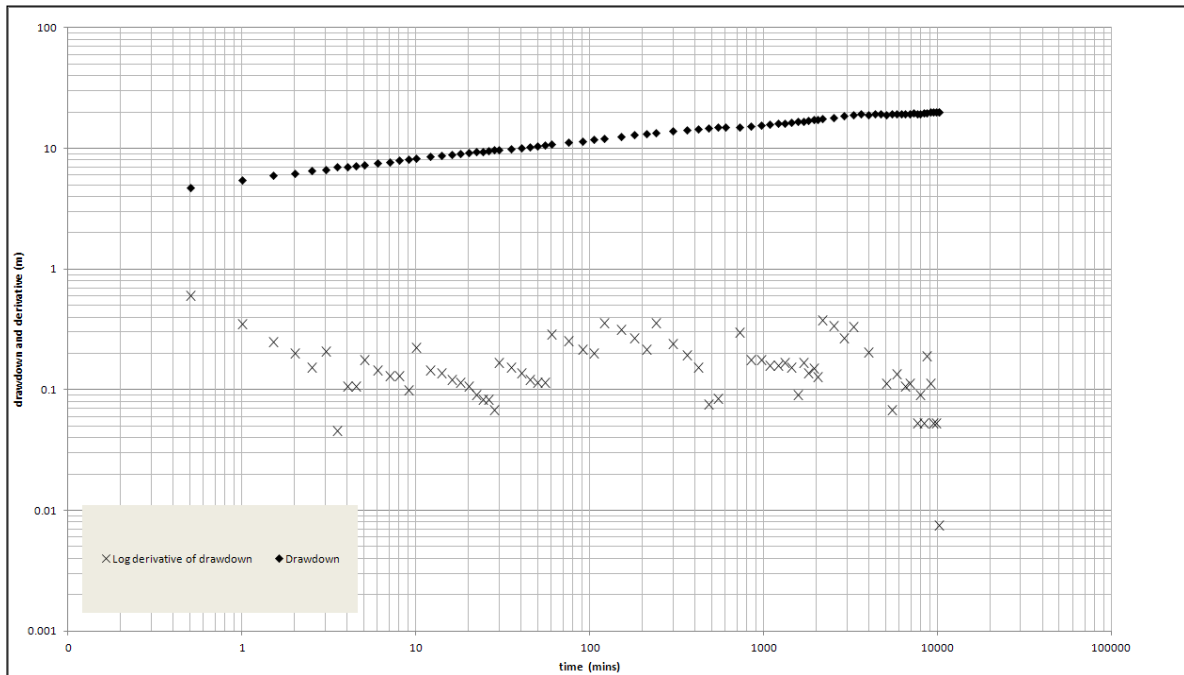


Figure 18 Diagnostic plot of drawdown and log derivative of drawdown against time. The log derivative data are noisy but suggest a confined or recharge boundary model.

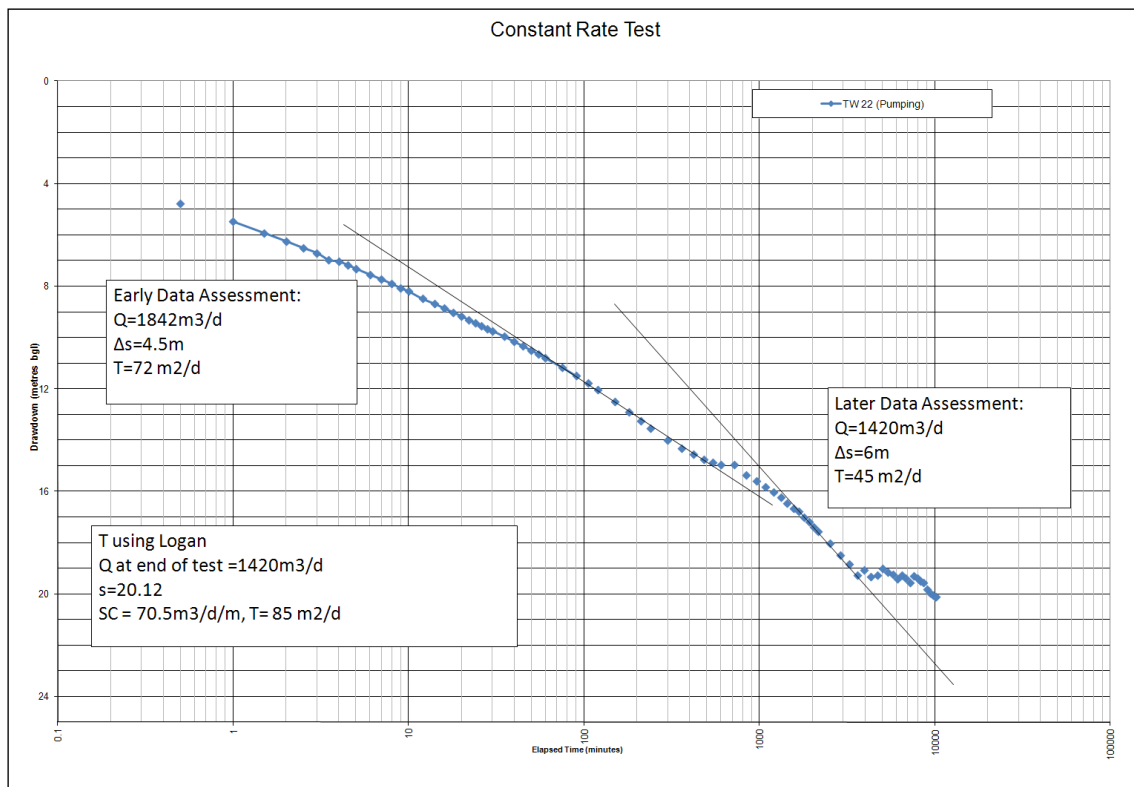


Figure 19 Semi-Log plot of drawdown against time for a constant rate test; note different apparent transmissivity for different parts of the data

Box 4.7 Estimating specific capacity, transmissivity and storativity

The fractured limestone aquifer is confined by 35 m of low permeability till. The pumping rate is $691\text{m}^3/\text{d}$ and the final drawdown in the pumping well is 31 m. The observation borehole is 30 m from the pumping well. A semi-log plot of drawdown against time is shown in

Figure 20.

Specific capacity is approximately $22\text{ m}^3/\text{d}/\text{m}$. Transmissivity using Cooper-Jacob is approximately $25\text{ m}^2/\text{d}$ for both the observation and pumping boreholes, using the data between 100 and 2000 minutes, and approximately $27\text{ m}^2/\text{d}$ based on the Logan equilibrium method.

The value for storativity is calculated to be 6.5×10^{-5} and is considered to be valid for time greater than 0.0117 days (20 minutes) according to the relevant criteria. The log and the water levels also suggest it is a confined aquifer.

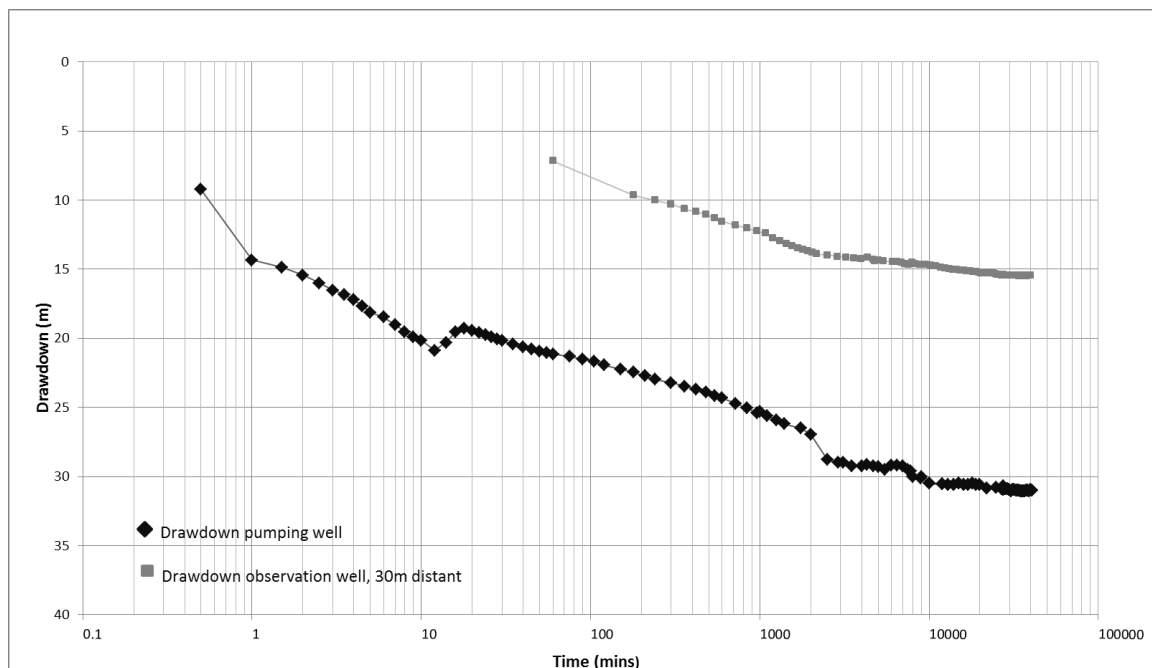


Figure 20 Semi-Log plot of drawdown against time for a constant rate test assessed for T and S using Cooper Jacob straight line method (data source KT Cullen, 2002 Johnstown Bridge)

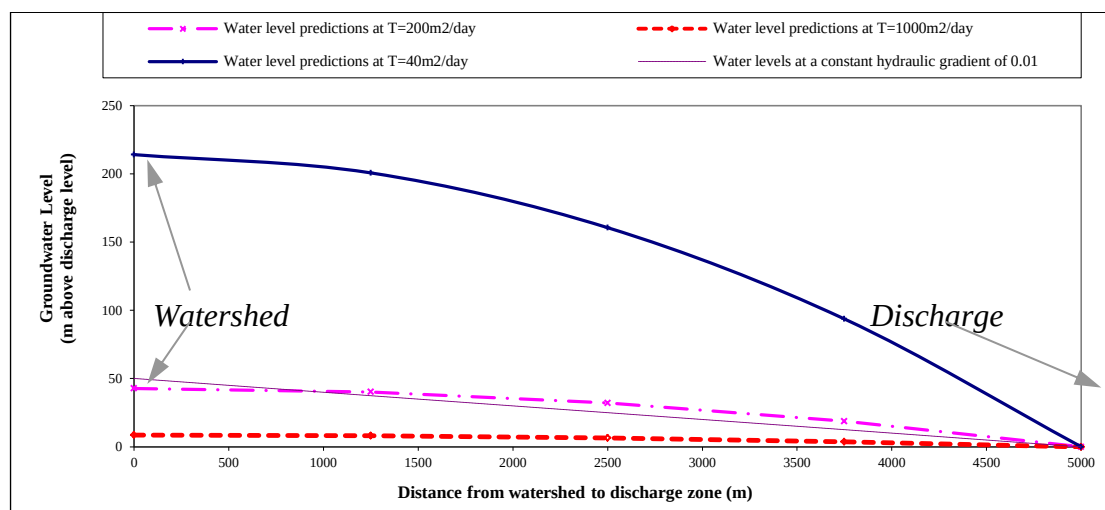
4.5 PARAMETER INTERDEPENDENCE

From Darcy's law and Dupuit's equation, it is clear that over a particular portion of aquifer that has broadly similar groundwater flow characteristics, the hydraulic parameters need to be consistent with each other due to their interdependence.

For example, for any groundwater system, transmissivity, hydraulic gradient, permeability needs to fit with recharge, and the topography and landscape of the area. The topographic gradient provides for a check against groundwater gradient. Generally, a moderate to high transmissivity suggests a relatively low hydraulic gradient even in areas of high relief.

The hydraulic gradient across an area is generally expected to be less than the topographic gradient. In Ireland, transmissivity and storage are generally low and potential recharge is high. For example, a relatively high transmissivity value, for instance, greater than $500 \text{ m}^2/\text{d}$, suggests a high groundwater throughflow, and accompanying gradients need to be appropriate. This is illustrated in the diagram in

Figure 21 (from Fitzsimons *et al.*, 2005) which shows that at low recharge levels the effects of successively lower transmissivity effectively ‘drowning’ the landscape for a given recharge, with the water table theoretically rising high above the ground surface as it cannot accept and transmit the amount of recharge being applied. This phenomenon is more fully described in Fitzsimons *et al.* (2005).



*Figure 21 Relationship between water level and transmissivity along a simulated groundwater flow line, 5 km long and 1m wide, receiving a constant recharge of 250 mm/year (after Fitzsimons *et al.*, 2005)*

The parameter interdependence should be borne in mind when selecting appropriate parameter values from the aquifer parameter database, and the parameters should be self-consistent and consistent with any site-specific information.

PART 2

5 AQUIFER PARAMETERS DATABASE STRUCTURE AND FIELD DEFINITION

5.1 DATABASE REQUIREMENTS

The primary database structure referenced is the Scottish Aquifer Properties project (Graham *et al.*, 2006. - SNIFFER WFD27, BGS CR06/073N: Scottish Aquifer Properties: 2006 Interim Report). This is a co-funded project by the Scottish Environment Protection Agency via SNIFFER and the British Geological Survey. This database is a relatively simple and easily interrogated database comprising fields that are appropriate to Ireland. This is largely due to the comparable hydrogeological framework as poorly productive aquifers dominate large tracts of both countries.

Banks (2010) indicated that a good database should be:

- *“Large: in order to provide a good degree of confidence in calculated mean, median or percentile yields*
- *Representative: there is a clear danger that ‘failed’ (i.e., poorly yielding) wells will tend to be under-reported to national databases, relative to successful wells that are eventually taken into production.*
- *Reliable: yield data, often of variable quality, should ideally be quality-filtered to secure reliable statistical analysis”.*

5.2 MAIN DATABASE STRUCTURE AND FIELDS

The database was built in EXCEL and be imported into a Geographical Information System, with easy overlay on both the Aquifer and Rock Unit Group maps.

The database comprises one main sheet comprising a single row per borehole and the fields are organised into logical groupings.

The first group consist of record identifiers as shown below and described briefly as follows.

RECORD IDENTIFIERS														
Database Identifier	Name (local identifier)	Licence No.	EPA identifier (EU code)	Drinking water code	GSI name	Townland	Area	Post Code	County	Six inch	Type	Easting	Northing	Accuracy (m)

Database Identifier: this is a unique index number.

Name (local identifier): this is the name of the borehole on the source reference, e.g. “TW1” which may be useful if required to examine the source reference and is considered a useful means of further identification/cross reference.

There are a number of identifiers to facilitate cross-referencing with other datasets. These are self-explanatory and are:

License No.: - borehole records that are captured in an EPA licence report.

EPA identifier (EU code): a borehole record that may be included in the EPA monitoring network.

Drinking water code: Local Authority identifiers for water supply boreholes.

GSI name: boreholes within the GSI ‘in-house’ database (Geodata) are indexed with unique identifiers.

Post Code: included for future identification should post codes be deployed in Ireland.

Townland, County and Six inch are self-explanatory and included for identification and filtering and searching purposes.

Easting and Northings are reported as 12 figure Irish Grid Coordinates.

Area: the purpose of this field is to give the reader/practioner a broader regional indication of where a record pertains to, e.g., the townland of Ballycunningham, County Cork is given a regional area identifier of Dripsey, and the townland of Clomantagh Lower is given an area identifier of Nuenna, Freshford. Not every record is populated with this field.

Accuracy (m): is included to indicate the precision of the location and also allow for filtering and quality indexing of entries.

Type: indicates if the borehole record is for a trial well, production borehole, a monitoring borehole or an abstraction borehole.

The next set of fields are basic record information fields as shown below and described briefly as follows.

BASIC RECORD INFORMATION												
Elevation (mOD) (ground level)	Borehole Depth (m)	Depth to bedrock (m)	Summary Log	Water Strikes / inflows (mbgl)	Subsoil mapped Code	Groundwater Vulnerability mapped code	Confined	Pathway	Local Bedrock Description	Bedrock Formation	Rock Unit Group	Aquifer Category

Elevation (mOD) (ground level): Ground level at the borehole given in metres above Ordnance Datum, which is fixed as Mean Sea Level, at Malin Head, County Donegal, which was adopted as the national datum in 1970. Earlier maps used the low water mark at Poolbeg Lighthouse, Dublin. Malin Head datum is approximately 2.7 m above the Poolbeg Lighthouse datum.

Borehole Depth (m): depth of the borehole in metres.

Depth to bedrock (m): depth to top of the rock in metres.

Summary Log: this is a text field entry describing the basic geology, e.g. 15 m of till overlies pure limestone.

Water Strikes/inflows (m bgl): records of the reported inflow zone in metres below ground level (m bgl).

Subsoil mapped code: record of the main subsoil type according to the main subsoils dataset (Teagasc subsoils as given on the GSI and EPA websites).

Groundwater vulnerability mapped code: record of the mapped groundwater vulnerability as per the GSI website.

Confined: a simple text description of whether or not the main aquifer is confined or not and is recorded as Yes or No or Uncertain. It can be difficult to assess the conditions present around the borehole.

Pathway: recorded as per

Figure 7 to indicate what pathway the borehole record is referencing, and if the hydraulic data entered are for a specific pathway or combination of pathways, e.g., shallow bedrock.

Local Bedrock description: this field is designed for entering the bedrock reported on the log if available which may be different to the mapped geology for the area.

Bedrock Formation: this field may be useful for future analysis of Rock Unit Groups (RUGs) ([Section 3.3](#)).

Rock Unit Group: one of the 27 GSI RUGs is chosen and entered. RUGs are the generalised groupings for the many bedrock formations mapped across the country ([Section 3.3](#)).

Aquifer Category: the recorded aquifer category as per the GSI Aquifer map is reported.

The next set of fields are fields on construction details as shown below and described briefly as follows.

CONSTRUCTION DETAILS								
Construction details	Upper Casing Diameter (mm)	Upper Casing Bottom Depth (mbgl)	Lower Casing Diameter (mm)	Lower Casing Bottom Depth (mbgl)	Screen / Open Hole Diameter (mm)	Screened / Open Interval (mbgl)	Screen Length (m)	Grouted

Construction details: a simple text description of how the borehole was drilled and constructed.

Upper and Lower Casing Diameter and Depths: this is useful to cross reference with the pathway, RUG and aquifer category and then to the hydraulic information reported and entered.

Screen details: diameter and the interval depths, e.g., 150 mm from 50 m bgl to 65 m bgl, which is then used to populate the **Screen Length (m)**, which in turn is used in the parameter estimation of hydraulic conductivity. This field allows for indicating whether or not the borehole is simply open hole; as most boreholes in Ireland are open hole in the bedrock.

Grouted: this is populated with yes or no or uncertain, and is useful as it allows for an assessment if one particular pathway, say the deep bedrock is the only contributor of groundwater or if the all the pathways are contributing. This is important to determine if the hydraulic response relates to one or more pathways.

The next set of fields are the main 'property' fields, shown below and are described as follows.

Hydraulic Test Type	Test Interval	Test Duration (hours)	Yield (m3/d)	Test Pumping Discharge Rate (m3/d)	Pumping test drawdown (m)	Steady / Non Steady State	Long Term / Current Abstraction rate (m3/d)	Longterm Drawdown (m)
---------------------	---------------	-----------------------	--------------	------------------------------------	---------------------------	---------------------------	---	-----------------------

Specific Capacity Range (m3/d/m)	Specific Capacity Pumping Test	Specific Capacity Current abstraction	Specific Capacity PV	Specific Capacity comment	Productivity Class
----------------------------------	--------------------------------	---------------------------------------	----------------------	---------------------------	--------------------

Parameter_Estimation_methodology	Transmissivity (estimated from SC)	Transmissivity_Preferred (m2/d)	Transmissivity_constant_rate_test (m2/d)	Transmissivity_recovery (m2/d)	Transmissivity_steptest (m2/d)	Transmissivity comment	Transmissivity_Quality
----------------------------------	------------------------------------	---------------------------------	--	--------------------------------	--------------------------------	------------------------	------------------------

Lugeon	Rock Permeability Range (m/d)	Rock Permeability (m/s)	Rock Permeability mean (m/s)	Rock Permeability mean (m/s)	Rock Permeability mean (m/s)
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Storativity	Specific Yield	Porosity	Site Gradient	Gradient comment	Static Water level mbgl	Static water level (mAOD)	Pumping Water level (mOD)
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File Source

Hydraulic Test Type: composition of testing, i.e., a step test, constant rate test, falling head/ rising head / packer test.

Test Interval: originally included to allow for recording of specific or successive depths tested in falling/rising head or packer tests.

Test Duration (hours): record of the number of hours the test lasted.

Yield (m³/d): the reported yield. This may be the same as the test pumping discharge but in many cases, particularly private boreholes, it relates to a drillers estimate.

Test Pumping Discharge (m³/d): this could be the range of rates from the start to the end of the test, and/or the average over the course of the test and/or the final rate at the end of the test. This allows cross referencing of the specific capacity and the transmissivity values for either the constant rate tests or the recovery tests.

Pumping Test Drawdown (m): Generally the drawdown at the end of the test.

Steady / Non steady state: an assessment of the drawdown data indicates where equilibrium conditions have been reached or not which is in turn important for an inspection of the transmissivity values obtained.

Long term / current drawdown (m) & Long term / current abstraction rate (m³/d): this is important if the borehole was drilled several years ago and a comparison of the original test pumping data with the current pumping regime can be made; useful to see if specific capacity has changed.

Specific Capacity (SC) Range ($\text{m}^3/\text{d}/\text{m}$): a summary of the specific capacities obtained from the tests and the current pumping if available.

Specific Capacity Pumping Test ($\text{m}^3/\text{d}/\text{m}$): based on the final discharge rate and drawdown for the test.

Specific Capacity Current Abstraction ($\text{m}^3/\text{d}/\text{m}$): based on the current daily abstraction rate and drawdown.

Specific Capacity Preferred Value ($\text{m}^3/\text{d}/\text{m}$): The preferred value is based on the judgement of preferred values for pumping and drawdown, explained in the '**Specific Capacity Comment**' field.

Specific Capacity Comment: Generally used to explain the preferred value or other relevant information on yield and drawdown.

Productivity Class: It is based on log-log plots of specific capacity against pumping rate. This plot is shown in [Figure 3](#)

Parameter_Estimation_Methodology: The method/solution used to estimate transmissivity is given.

Transmissivity (T) [units m^2/d]: (estimated from Specific Capacity) (SC)) An estimate of transmissivity is given by multiplying the preferred specific capacity value by 1.22, which is multiplier used in the 'Logan' equilibrium approximation of transmissivity. This relationship is premised on equilibrium between the pumping rate and drawdown being reached (Misstear, 2001) and also assumes that well losses are not significant.

Transmissivity Constant, Recovery, Step Test: (T) [units m^2/d]: Estimates of transmissivity are given where a detailed assessment has been made.

Transmissivity Preferred (T) [units m^2/d]: This is the preferred value of transmissivity and is normally the estimate of highest quality and the rationale is given in the '**Transmissivity Comment Field**'. For example, it might be the value from an observation borehole. Transmissivity values are reported in the one record for both the observation and pumping well.

Transmissivity Reliability: The identifiers A, B, C are given to denote quality of the value, which normally relates to uncertainty in construction details or the basic record information. Additional criteria include test length, estimation methodology. Normally, constant rate test data is given an A. If the record only contains a yield and drawdown for a standard 72-hour test these are attributed with a B unless it is known or can be judged to be in equilibrium.

Lugeon: A Lugeon can be converted into permeability; 1 Lugeon is approximately 1.1×10^{-7} m/s.

5.3 SUMMARY TABLES

Summary Tables:

- The purpose of a summary transmissivity table is to give sensible values for aquifer parameters to those can be referred to and used for predictive modelling. It comprises a matrix of transmissivity values for RUGs according to aquifer category.
- The summary table is an expression of the bulk property for the aquifer as a whole. This is because transmissivity is the most practical and important aquifer parameter. It is more reliable when compared with hydraulic conductivity where data from tests may represent values between extremes represented by a high permeability fracture or the surrounding low permeability rock.
- The values include a best estimate (geometric mean) and credible upper and lower values for transmissivity, as well as other basic stats. This is different to the 'preferred' value for each record.
- The main database is a standalone database; however, the summary table is supplemented by specific capacity data from the GSI's in-house database 'Geodata'.

Summary tables are included in **Appendix 1 and 2**.

6 DATA ANALYSIS

6.1 INTRODUCTION

Data have been analysed and summarised according to bedrock type and sand and gravel, using as many data as possible. Data with high confidence on the parameter value determined are summarised in the aquifer parameters database and are used as the primary data source. However, these data are insufficient to statistically characterise aquifer classes and the rock unit groups (RUGs). Therefore other data, such as the specific capacity data from the GSI's Geodata database, are used to augment and constrain characterisation of typical values.

6.1.1 *Data sources and data distribution*

Data are derived from a variety of sources and the data constitute information from permeability testing (falling/rising/constant head), packer tests and test pumping. Data from pumping tests comprise 55% of the main database records, while the remainder comprise data from permeability or packer tests. The data from permeability and packer tests is biased to data based in Dublin – data from the port tunnel and/or the underground rail connector. The GSI Geodata well database comprises over 2,300 records that report a specific capacity value, and these data have been used to augment the analyses, but are not included in the primary database.

6.1.2 *Bedrock aquifer parameter database*

The main bedrock aquifer parameter database currently comprises over 600 records from a variety of data sources, from different hydraulic tests representing different scale-lengths within the different pathways and in different hydrogeological settings distributed across the country.

6.1.3 *Sand and gravel aquifer parameter database*

The gravel database consists of over 30 records, predominantly public supply boreholes (trial wells and production wells), distributed across the country, and mainly from defined sand and gravel aquifers (Lg or Rg). The test intervals are generally less than 10 m of saturated material and the wells have relatively high yields.

6.2 DATA DISTRIBUTION

As can be seen from **Table 1** and **Table 2**, there is an uneven distribution of records both in terms of aquifer category and RUG. This is mainly due to the differences in area occupied by the various aquifer categories and individual rock units, as indicated in **Table 1** and

Figure 22. Generally, the aquifers and RUGs which are more spatially extensive are better represented. The poorly productive aquifers (Pu, PI, LI) occupy about 70% of the land surface (**Table 1**).

Table 1 Proportion of land surface underlain by the bedrock aquifer categories and the number of records per aquifer category (count only from main database)

Flow Regime	Aquifer Category	area (km ²)	% area	Count
Poorly Productive	Locally Important Bedrock Aquifer which is moderately productive only in local zones (LI)	29044	41.9%	322
	Poor Bedrock Aquifer which is generally unproductive except for local zones (PI)	20019	28.9%	112
	Poor Bedrock Aquifer which is generally unproductive (Pu)	1761	2.5%	7
Productive Fissured	Locally Important Bedrock Aquifer which is generally moderately productive (Lm)	2884	4.2%	67
	Regionally Important Fissured (Rf)	1706	2.5%	27
Karstic	Regionally Important Karstified (Rk)	713	1%	13
	Regionally Important Karstified (Rk ^c)	8122	11.7%	14
	Regionally Important Karstified (Rk ^d)	4558	6.6%	101
	Locally Important Karstified (Lk)	548	0.8%	1
Total (excludes lakes)		69374		664

Table 2 List of Rock Unit Groups, abbreviated nomenclature, number of records per RUG (not including the supplementary data from Geodata)

Rock Unit Groups		count
Basalts & other Volcanic rocks	BV	1
Permo-Triassic Sandstones	PTS	1
Permo-Triassic Mudstones and Gypsum	PTMG	0
Westphalian Sandstones	WSA	6
Westphalian Shales	WSH	0
Namurian Shales	NSH	0
Namurian Sandstones	NSA	0
Namurian Undifferentiated	NU	18
Dinantian Shales and Limestones	DSL	6
Dinantian Mixed Sandstones, Shales and Limestones	DMSSL	2
Dinantian Sandstones	DS	3
Dinantian Pure Bedded Limestones	DPBL	83
Dinantian Upper Impure Limestones	DUIL	269
Dinantian Dolomitised Limestones	DDL	37
Dinantian Pure Unbedded Limestones	DPUL	16
Dinantian Lower Impure Limestones	DLIL	22
Dinantian (early) Sandstones, Shales and Limestones	DESSL	15
Dinantian Mudstones and Sandstones (Cork Group)	DMSC	4
Granites & other Igneous Intrusive rocks	G II	13
Devonian Kiltorcan-type Sandstones	DKS	6
Devonian Old Red Sandstones	DORS	29
Silurian Metasediments and Volcanics	SMV	26
Ordovician Metasediments	OM	10
Ordovician Volcanics	OV	17
Cambrian Metasediments	CM	2
Precambrian Quartzites, Gneisses & Schists	PQGS	71
Precambrian Marbles	PM	10
Total		664

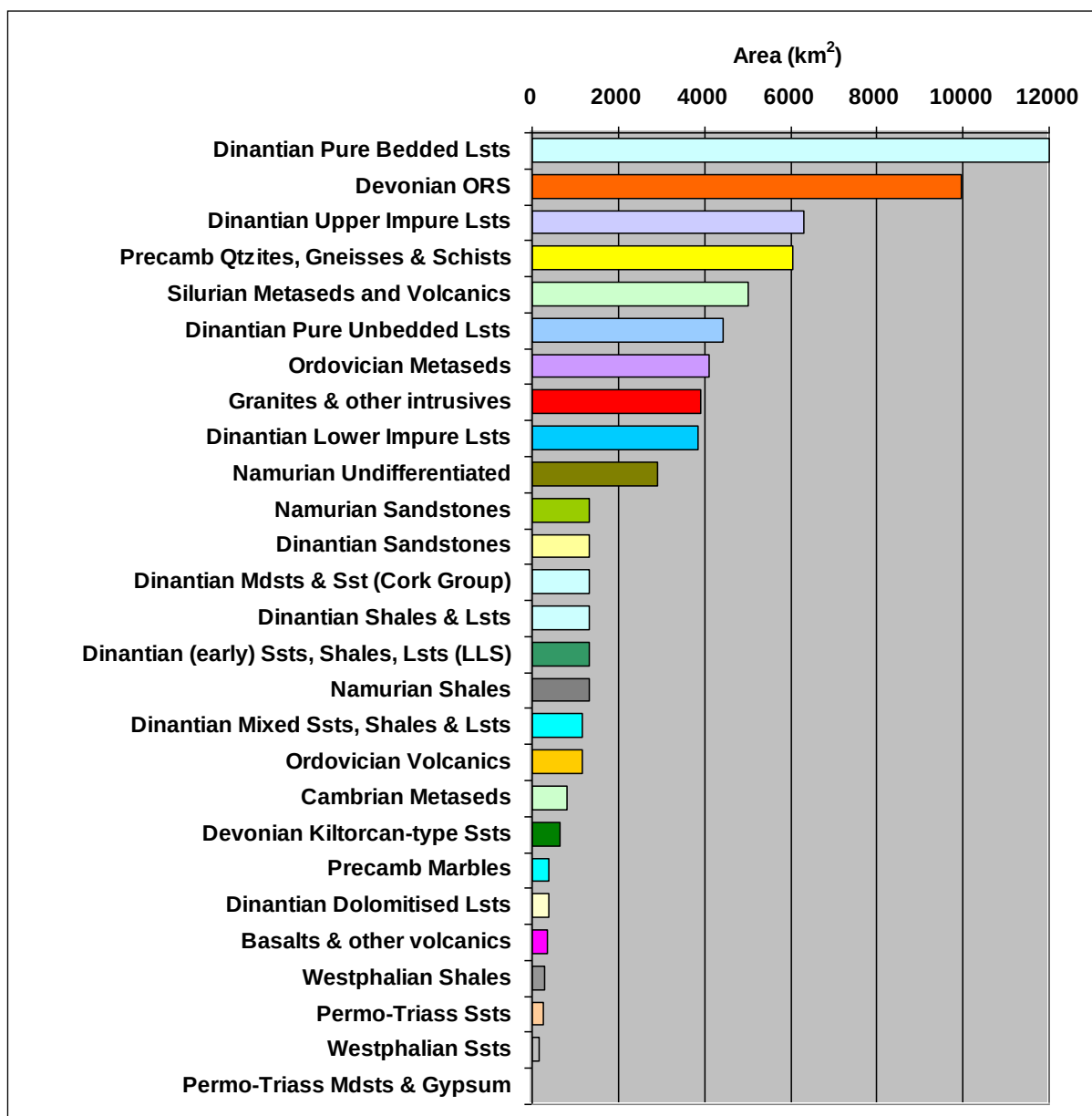


Figure 22 Rock Unit Group by area

6.3 STATISTICAL APPROACH

The analysis is undertaken on a combination of the high confidence data contained in the main database, and transmissivities derived from the more numerous, but lesser quality, specific capacity data in the GSI “Geodata” database using the Logan equilibrium approximation formula.

One of the principle objectives of the project is to provide information on the typical or representative values for a given RUG or aquifer. It was considered that **Best, Upper** and **Lower Estimate** values be determined, using a statistical characterisation based on summary descriptive statistics and graphical plots/distributions.

In general, for groundwater flow parallel to geological structures (bedding or fissures), the arithmetic average of hydraulic conductivity is the most appropriate mean. For correlated random fields (log normally distributed), the geometric mean best represents the hydraulic conductivity. For flow across geological structures (e.g. across layers in sand and gravel deposits), the harmonic mean is appropriate.

Mature karst systems are highly organised systems where flow become concentrated in fewer conduits, and conduits/fissures are localised on pre-existing geological structures (oriented fractures/veins/beds). Consequently, it is suggested that the arithmetic average of transmissivity best represents bulk transmissivity for flow parallel to the general conduit orientation. Similarly, the harmonic mean is suggested for flow perpendicular to the general conduit orientation. Bulk *permeability* estimates are not considered useful in conduit karst, in which travel times derived from tracer tests are more appropriate.

There is a large amount of work done in the areas of geostatistics and numerical modelling in considering the appropriate statistical mean in natural hydrogeological and geological data. Banks *et al.*, 2005, advocate the use of non-parametric statistics to characterise fractured hard-rock aquifers, and that this gives a good first-order assessment of the data. The statistical distributions of hydraulic conductivity and transmissivity data, and borehole yields have been widely observed to be approximately log-normal, in common with other natural data. For example, Banks (1998, 2005, *et al.*, 1994, *et al.*, 2010) show that the distribution of borehole yield in crystalline rocks in Norway is approximately log-normally distributed. This log-normal distribution is due to the log-normal distribution of fracture aperture and length (Banks *et al.*, 2010). Verbovšek (2008) demonstrates hydraulic data to be log-normally distributed in dolomite rocks in Slovenia. Prudic (1991) demonstrates a log-normal distribution for hydraulic conductivity values in sand and gravel aquifers.

A visual inspection of the graphical plots presented in

Figure 23 and **Figure 24** demonstrate an approximate log-normal distribution for the transmissivity data. For instance, the probability plot in **Figure 24** yields a straight line through the majority of the data which is diagnostic of an approximate log-normal distribution. Under a Kolmogorov-Smirnov test the maximum deviation does not satisfy a hypothesis of log-normality, however, the main deviations occur at the extremes of the distribution, similar to observations in data presented by Banks *et al.*, 2010, and importantly, the key aspect is the good fit of the majority of the central portion of the data.

Banks (2010; *et al.*, 2005) indicate that the geometric mean and the standard deviation characterise log-normal distributions, and that the bulk transmissivity is best represented by the geometric mean or median (approximately equal for log-normal distributions). Moe *et al.*, 2010, uses the geometric mean to report on hydraulic conductivities obtained from the EPA Groundwater Works Programme. Comte *et al.*, 2012, used the geometric mean of the hydraulic parameters obtained from the hydraulic tests deployed for their characterisation of the catchments investigated for some uncertain test results. The British Geological Survey (Jones *et al.*, 2000, and Allen *et al.*, 1997) uses the geometric mean value for transmissivity in the minor and major aquifer reports.

Thus a 'Best' estimate for transmissivity is derived for the fractured bedrock aquifers, using the geometric mean. In addition, to describe the range and the central portion of the data, an 'Upper' and 'Lower' estimate is provided that correspond with the 90th and 95th percentiles, and the 5th and 10th percentiles respectively.

Permeability is a more difficult parameter to provide a bulk value or best estimate for. Banks *et al.*, 2010, point out the limitations of using bulk transmissivity to estimate hydraulic conductivity due to scale dependency and the depth dependence (Comte *et al.*, 2012) and limitations within the data. Misstear *et al.*, 2006, indicate that the scale dependency of a calculated hydraulic conductivity can be reduced by increasing the representative elementary volume or interval. Rovey *et al.*, 1995, examine the scale dependency of hydraulic conductivity measurements in varying karstic systems, and observe an increase in hydraulic conductivity with scale; however, they suggest that for 'mature' karst systems that a regional conductivity estimate may not be appropriate.

Arithmetic and harmonic averages are provided for karst aquifers where conduit flow dominates. The GSI karst data base provides travel times (velocities).

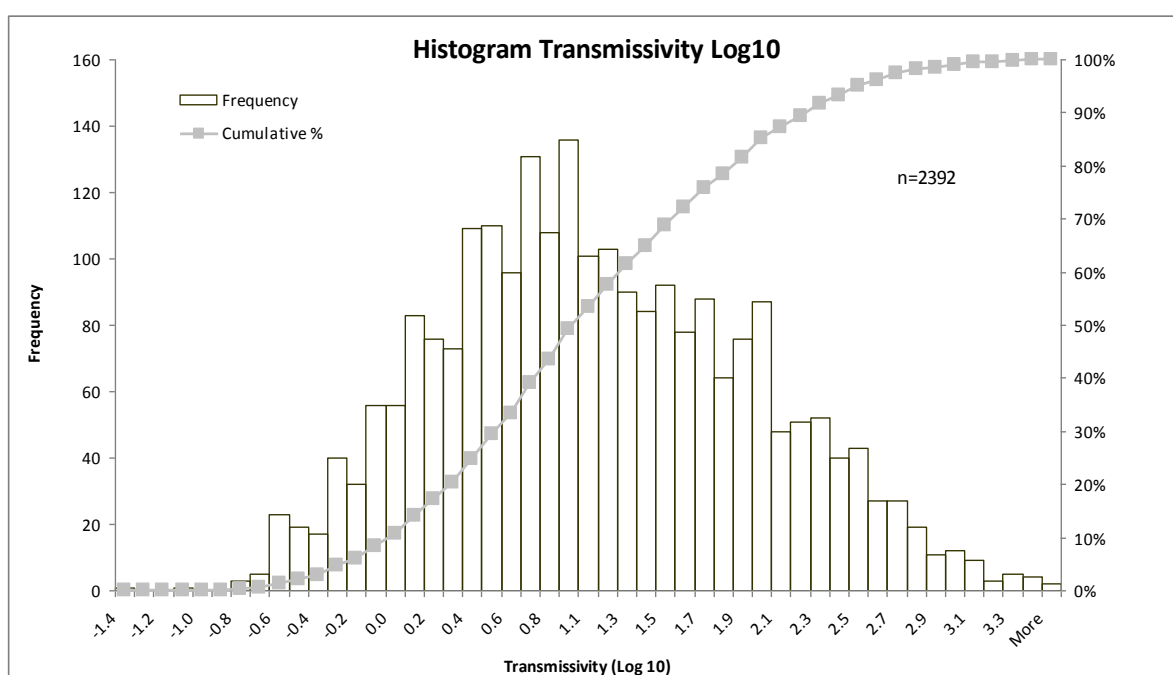


Figure 23 Histogram of transmissivity (Log₁₀) using the available bedrock geodata records with a specific capacity

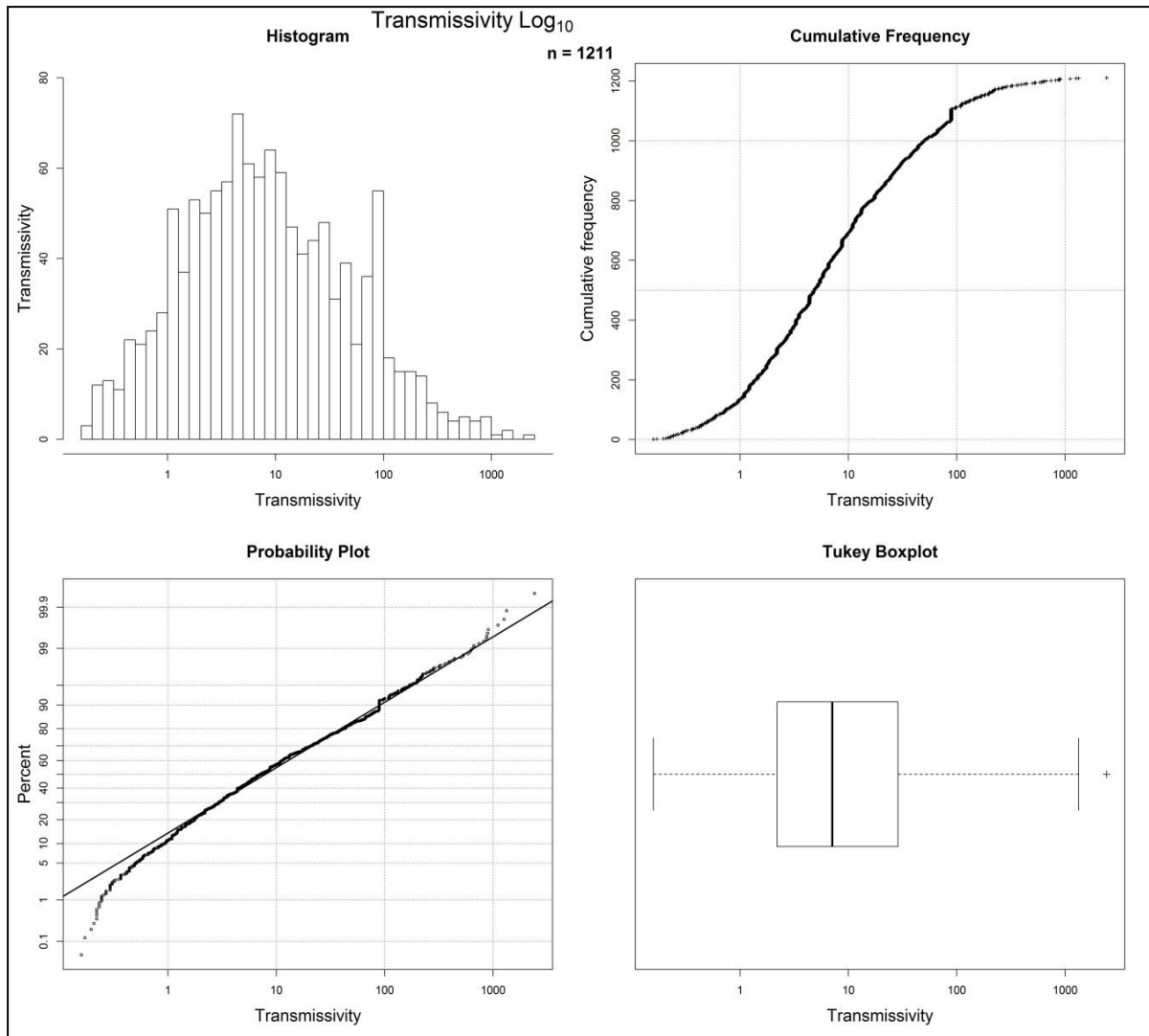


Figure 24 Graphical plots for transmissivity data for aquifer category (LI)

6.4 TRANSMISSIVITY

6.4.1 Assessment of transmissivity

Transmissivity data are analysed for two classification schemes: aquifer category and RUG.

6.4.2 Transmissivity as a function of aquifer category

Transmissivity summary statistics for each aquifer category are presented in [Appendix 1](#) and [2](#), [Table 4](#) and [Figure 26](#) and [Figure 27](#). Individual histograms for each aquifer category are provided in [Appendix 4](#).

Best Estimate

[Figure 26](#) and [Figure 27](#) show the 'Best' estimate for each of the bedrock aquifer categories graphically. The figures and tabulated data show that the 'Best' estimates for:

- Poorly Productive Aquifers (Pu, Pl and LI categories) are less than 10 m²/d.
- Productive Fissured Aquifers (Lm and Rf categories) range from 20 – 30 m²/d.
- Karstic Aquifers (Lk, Rk and Rk^d categories) range from 20 – 70 m²/d. The arithmetic mean bulk transmissivity for Rk^c aquifers is greater than 500 m²/d.
- Sand and Gravel Aquifers (Rg and Lg categories) are approximately 350 m²/d.

As a first approximation, an attempt to correlate the QSC Productivity Indices and the 'best' estimates was done by selecting a realistic discharge for each productivity index and a nominal drawdown of 5 m that would approximately demark the boundaries between the indices, shown in **Figure 25** values of discharge to classify transmissivity magnitude. Thus, by using a Logan approximation a range for transmissivity can be made for the productivity categories shown in **Table 3**. This range is broadly in line with the best estimates for each of the category types.

Table 3 Expected range of transmissivity from QSC chart and the derived best estimates

Productivity	Discharge (m ³ /d)	Drawdown (m)	Specific capacity (m ³ /d/m)	Transmissivity (Logan) (m ² /d)	Expected Range (m ² /d)	Aquifer	Best Estimate (m ² /d)
I	500	5	100	122	>120	Rg	400
II	500	5	100	122	50-120	Rk	70
III	200	5	40	49	20-50	Rf, Lm, Ll, Rk	20-70
IV	70	5	14	17	5.0-17.0	Ll, Pu, Pl	4.0-7.0
V	20	5	4	5	<5	Pu, Pl	4

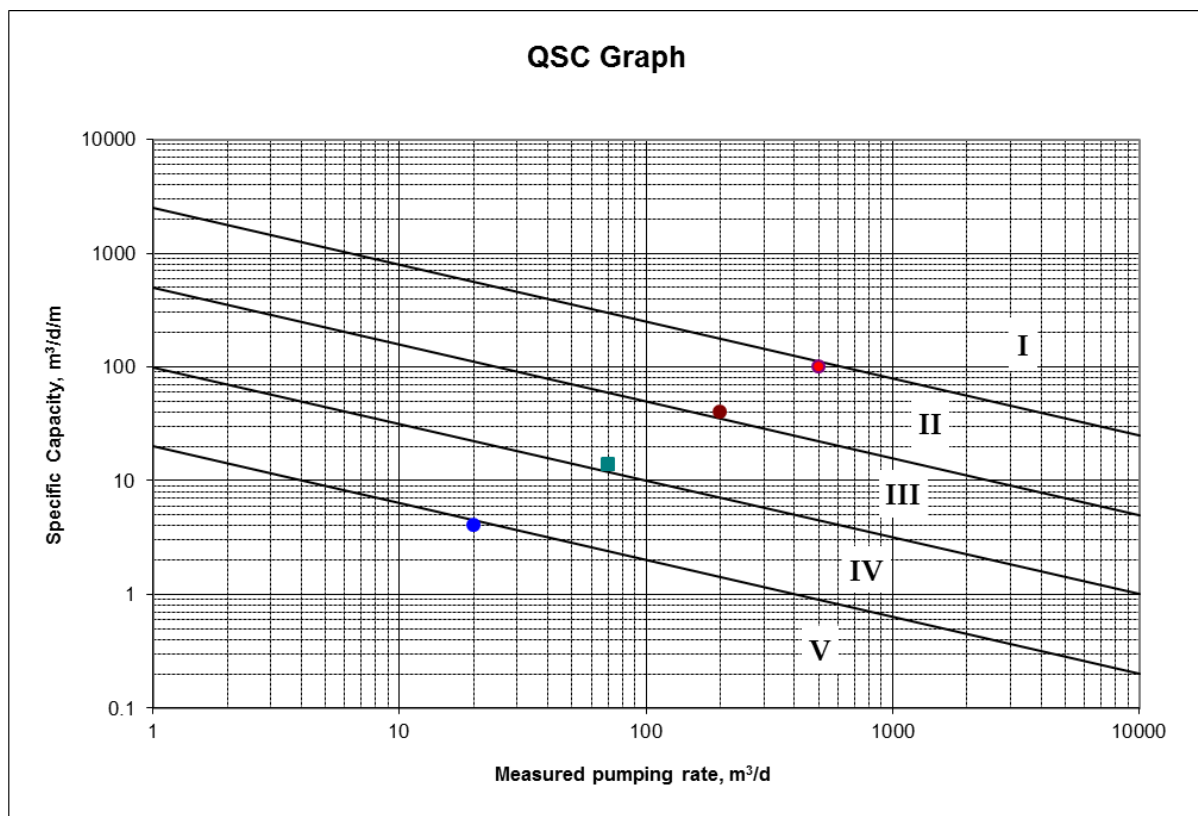


Figure 25 QSC plot of data from Table 3.

Lower and Upper Estimates and data variability

Figure 27 shows the 'Lower' and 'Upper' estimates for each of the bedrock aquifer categories graphically. The figures and tabulated data show that:

- Poorly Productive Aquifers (Pu, Pl and Ll categories) range from 0.4 – 165 m²/d.
- Productive Fissured Aquifers (Lm and Rf categories) range from 1 – 310 m²/d.
- Karstic Aquifers (Lk, Rk, Rk^c and Rk^d categories) range from 0.7 – 1110 m²/d.

- Sand and Gravel Aquifers (Rg and Lg categories, not shown on graph) range from 44 – 2650 m²/d.

General points:

- In general, there is a decrease in the 'Best' estimate of the Regionally Important Aquifers through to the Poor Aquifers with the apparent exception of the karst sub-type – Rkc.
- The 'box and whisker' plots in [Figure 27](#) illustrate the variability across each aquifer category and demonstrate the overlap across the categories. The interquartile range (25th percentile to 75th percentile) indicates the variability of the data about the central portion of the data spread, which is generally greater in the Regionally Important Aquifers.
- The standard variation and the coefficient of variation (CV) of the logarithm of the data decrease from the Regionally Important Aquifers to the Poor aquifers.
- The 95th percentile is far greater in the karstified aquifers than the poor aquifers.

Locally Important Karst Aquifers (Lk): are karstified limestone aquifers which are generally too small to be classified as 'Regionally important', and are not subdivided into karst sub-types (diffuse, conduit). The small discontinuous areas classified as Lk comprise different Rock Units that, elsewhere, are classed as one of the Regional Karst sub-types – Rk^d, Rk^c or Rk, and therefore Lk is not a different Aquifer category *per se*, and consequently there are no appropriate values for the Best Estimates or Upper/Lower Estimates for the Lk category. In order to look up a value for Lk, it is necessary to check for the Rock Unit Group and then to check the aquifer category for a larger area of that Rock Unit nearby. There are three main geographic areas in which this occurs:

- Small isolated areas of Lk in the south of the country are generally Pure Unbedded Limestones (Waulsortian) or Pure Bedded Limestones (Ballyadams Formation) which for the larger contiguous areas in the south are classified as Regionally Important Karst Aquifers (Rk^d) of the diffuse karst sub-type.
- Small isolated areas of Pure Bedded Limestones (Oakport, Dartry Limestones) in the north and west of the country generally classified as Regionally Important Aquifers (Rk^c) of the conduit karst sub-type.
- The Dinantian Upper Impure Limestones of Westmeath (specifically, the Derravarragh Cherts) are currently considered to be equivalent to the conduit karst sub-type (Rk^c).

Regionally Important Karst Aquifers:

Rk: From [Figure 26](#) and [Figure 27](#) and [Table 4](#) and the histograms in [Appendix 1](#) it appears that Rk is significantly more transmissive than the other karst aquifers. The available data are predominantly from Monaghan, and specifically from the Ballyshannon Limestones in the north of the county and the Milverton Group in the south of the county – both considered Dinantian Pure Bedded Limestones. As most of the data are clustered in Monaghan and the given general lack of data it is recommended that the Best Estimate given in [Table 4](#) is representative of these limestones in Monaghan only, and that for other areas of Rk, that the representative values are taken from the Rk^d category, because from a visual inspection, despite the lack of data, the distribution is more similar to the Rk^d data. In particular, the lower estimates are almost certainly an overestimate and it is recommended that the lower estimates are taken from the Rk^d group.

Rk^d and Rk^c histograms are interesting; the main difference being that the central tendency of the Rk^d group is greater. The geometric mean for Rk^c is 20 m²/d, and is 50 m²/d for Rk^d. The difference is due to the greater number of poor yielding boreholes. The data do not account for the large karst springs; although at the top end of the >1000 m²/d bin range there are a number boreholes that have extremely high transmissivity values – essentially where the borehole has

intersected a submerged cavern. The results indicate that the geometric mean is not necessarily appropriate for Rk^c . The Rk^c category denotes karst aquifers where the groundwater flow is dominated by karst conduits. Groundwater flows through an organised, dynamic hierarchical network of larger and large conduits approaching the spring. At regional scale the focus to a spring is directional. The arithmetic and harmonic means are included in [Table 4](#). Consideration of a best estimate transmissivity needs to take into account the GSI Karst database which includes travel times for tracing studies carried out in the karst aquifers.

Table 4 Summary statistics, including Best, Upper and Lower Estimate values

Aquifer category	# of data	T m ² /d Best Estimate	Derivation of Best Estimate	T m ² /d Upper Estimates		T m ² /d Interquartile range (spread about the mean) See Figure 18			T m ² /d Lower Estimates		T m ² /d			
				95 th %ile	90 th %ile	75 th %ile	25 th %ile	IQR	10 th %ile	5 th %ile	Arithmetic Average [log ₁₀]	Standard deviation [log ₁₀]	Coeff Variation log ₁₀ T	IQR/Best Estimate
Rk	23	70 100 5	Geomean Arithmetic Harmonic	360	166	125	48	77	35	30	2	2	4	1.1
Rk ^c	211	20 535 3	Geometric Arithmetic Harmonic	672	380	89	3.7	85	1.2	0.7	2.73	3.58	7.16	4
Rk ^d	202	47 600 6	Geomean Arithmetic Harmonic	1118	441	196	12	184	3.3	1.2	2.78	3.76	7.5	3.9
Rf	160	30	geomean	312	245	85	8	78	4	3	1.96	2.26	4.5	2.7
Lm	132	20	geomean	200	168	54	6	47	2	1.3	1.79	2.08	4.15	2.5
LI	1163	7	geomean	152	74	24	2	22	.88	0.5	1.56	2.03	4.07	2.94
PI	364	4.2	geomean	70	38	12	1.3	10	0.6	0.4	1.25	1.73	3.47	2.47
Pu	25	4.5	geomean	19	18	11	2.3	8.7	1.3	0.71	1.5	1.73	3.46	1.8
Rg/Lg	31	350	geomean	2650	2150	900	155	745	70	44	2.9	3.13	6.26	2.1

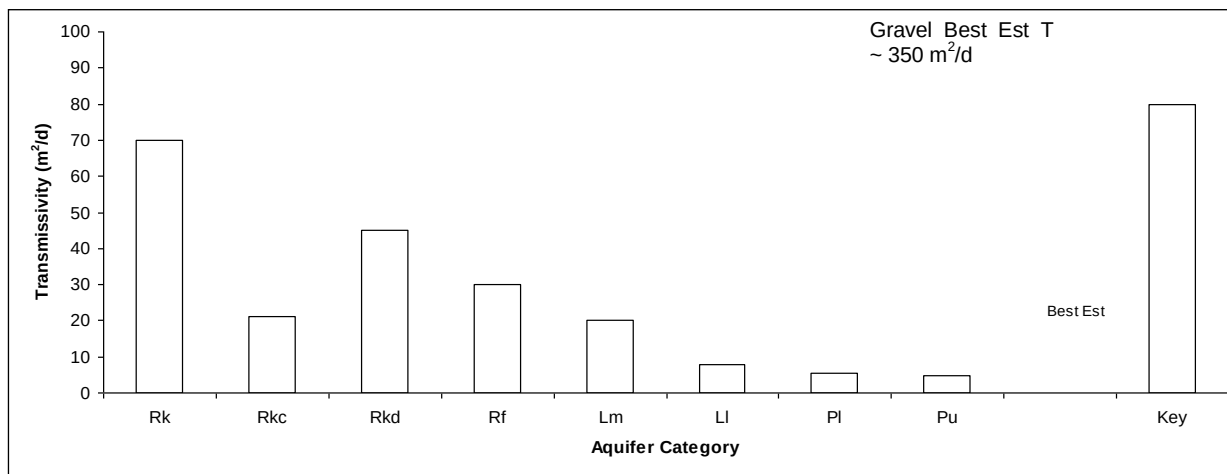


Figure 26 Best Estimate Transmissivity values (m²/d) for different Bedrock Aquifer categories (note geometric means shown for all categories – see tables and discussion for other estimates).

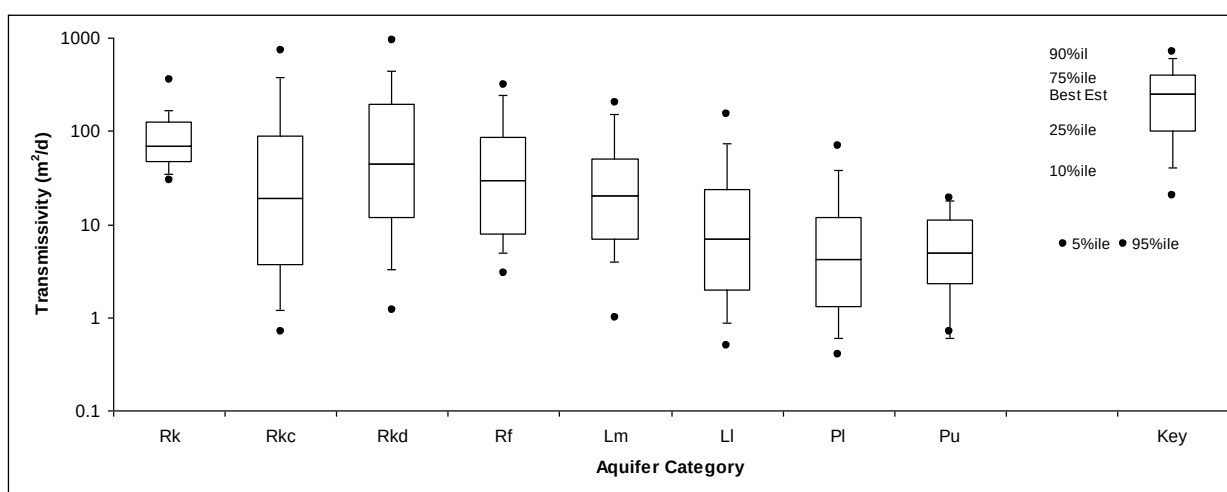
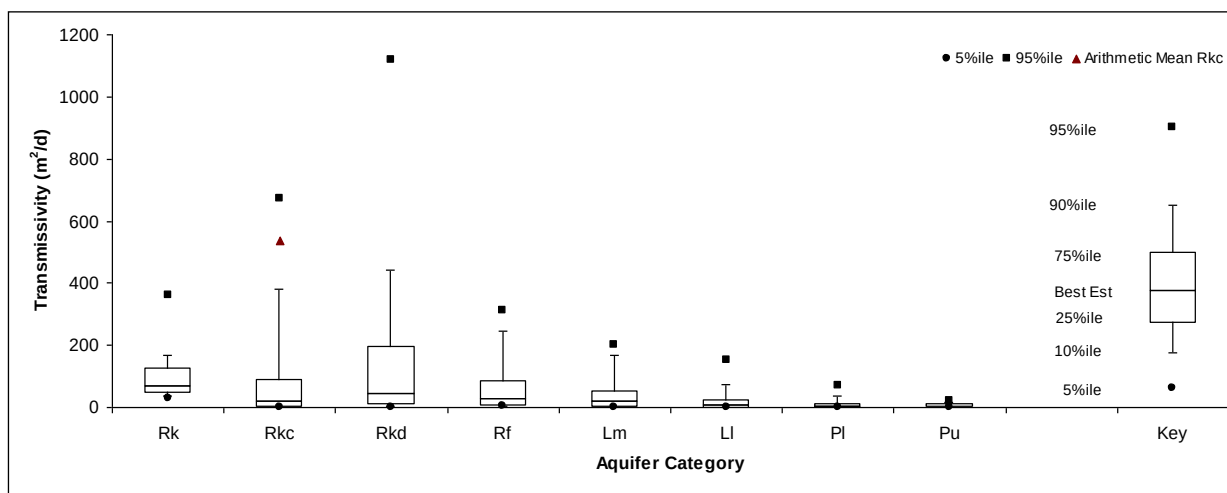


Figure 27 Distribution of Transmissivity values (m²/d) for different Bedrock Aquifer categories shown on a 'box and whisker' style graph. Upper graph arithmetic scale, Lower graph logarithmic scale

6.4.3 *Transmissivity as a function of Rock Unit Groups*

Transmissivity summary statistics for rock unit group category are presented in, [Appendix 1, Table 5](#) and box whisker plots are given in [Figure 28](#) and individual histograms for each are presented in [Appendix 5](#).

The remainder of the section focuses on salient aspects of the data and relevant geographic differences.

Insufficient data

One of the main limitations in assessing the rock unit group data is the lack of data for some of the units under their different aquifer categories, which means that the ‘best’ estimate is taken from the appropriate aquifer category. [Appendix 1](#) has colour coded those units and respective aquifer categories as orange.

There are 4 RUGs that rely entirely on the parent aquifer category: the Basalts, Westphalian Shales, Permo-Triassic Mudstones and Gypsum, and the Permo-Triassic Sandstones.

The following units have subsets of different aquifer categories that have insufficient data and rely on the aquifer category data: Ordovician Volcanics, Silurian Metasediments and Volcanics, Dinantian Upper Impure Limestones, Dinantian Sandstones, Dinantian Mixed Sandstones and Shales, Dinantian Shales and Limestones, Namurian Undifferentiated, Namurian Shales. [Appendix 1](#) indicates which subsets have insufficient data.

Regional differences in groundwater flow properties owing to greater/lesser geological deformation (folding/faulting/jointing) within the same rock type is well known and captured as part of the national aquifer classification (e.g. Waulsortion in the south is Rk^d, and in the midlands is LI). These regional differences can be seen in [Table 5](#) and also histograms in [Appendix 5](#). Where the aquifer classification does not currently fully capture the variations, these are discussed below. Note the implications for the choice of aquifer parameter values and the associated conceptual model depending on lithology (RUG) and also aquifer category.

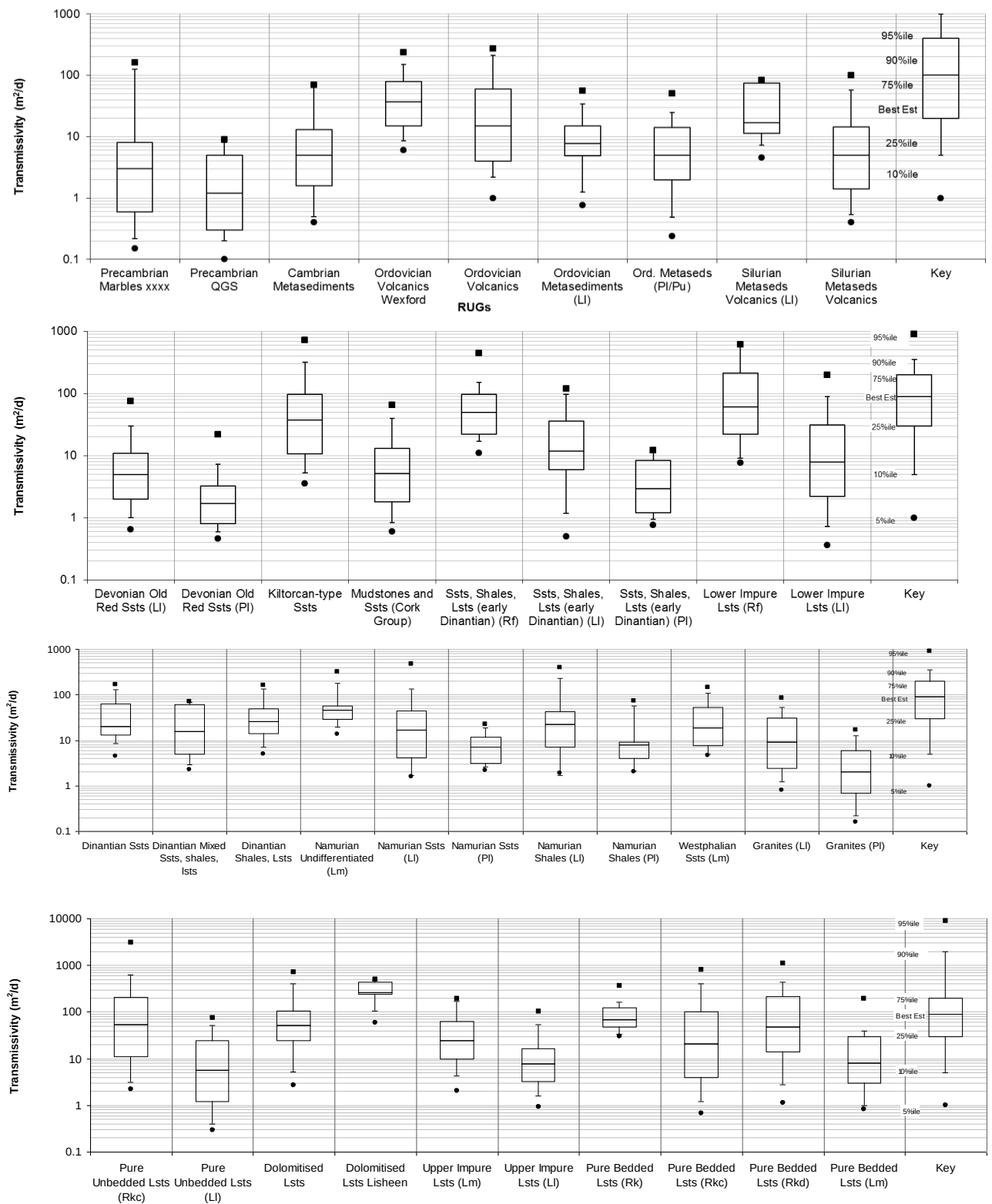


Figure 28 Log log whisker plots of RUGs Transmissivities

Table 5 Summary statistics, Best, Upper and Lower Estimate values for RUGs (see table 3 for abbreviated nomenclature). Note that an RUG can have more than one aquifer classification.

RUG (aquifer class)	# of data	T m ² /d Best Estimate	T m ² /d Upper Estimates		T m ² /d Interquartile range			T m ² /d Lower Estimates		T m ² /d			
			95 th %ile	90 th %ile	75 th %ile	25 th %ile	IQR	10 th %ile	5 th %ile	Arithmetic Average [log ₁₀]	Standard deviation [log ₁₀]	Coeff. Variation log ₁₀	IQR/Best Estimate
PM	16	3	160	125	8	0.6	7.4	0.22	0.15	1.5	1.7	3.5	2.5
PQGS	62	1.2	9	8	4	0.3	3.7	0.2	0.1	1.1	1.9	3.8	3
CM	27	5	70	70	13	1.6	11.4	0.5	0.4	1.5	1.8	3.6	2.3
OV (Wexford) (Rf)	60	37	235	151	79	15	64	8.6	6	1.8	1.9	3.7	1.7
OV, (Waterford, Kilkenny (Rf)	46	15	274	208	60	4	56	2.2	5	1.8	2.06	4.1	3.7
OM (LI)	93	8	56	34	15	5	10	1.24	1	1.6	1.8	3.7	1.3
OM (PI, Pu)	83	5	46	25	14	2	12	0.5	0.2	1.6	1.9	3.9	2.4
SMV (LI)	9	17	166	150	65	11	54	7	5	1.7	1.8	3.6	3.2
SMV (PI)	121	5	100	57	14	1.4	12.6	0.5	0.4	1.3	1.7	3.4	2.5
DORS (LI)	280	5	75	30	11	2	9	1	0.7	1.3	1.9	3.9	1.8
DORS (PI)	49	2	22	7	3	0.8	2	0.6	0.5	0.8	1.3	2.7	1
DKS	36	37	718	316	98	11	87	5	4	2.1	2.5	5	2.3
DMSC	81	5	65	40	13	1.8	11.2	0.8	0.6	1.2	1.5	3	2.2
DESSL (Rf)	12	50	450	151	97	22	75	17	11	2.3	2.4	4.8	1.5
DESSL (LI)	31	12	126	96	36	6	30	1.2	0.5	1.7	1.9	4	2.5

RUG	# of data	T m ² /d Best Estimate	T m ² /d Upper Estimates		T m ² /d Interquartile range			T m ² /d Lower Estimates		T m ² /d			
			95 th %ile	90 th %ile	75 th %ile	25 th %ile	IQR	10 th %ile	5 th %ile	Arithmetic Average [log ₁₀]	Standard deviation [log ₁₀]	Coeff. of Variation log ₁₀	IQR/Best Estimate
DESSL (PI)	15	3	12	11	8	1.2	7.8	0.9	0.8	0.7	0.7	1	2.6
DLIL (Rf)	12	60	600	500	213	22	191	9	8	2.2	2.3	4.7	3
DLIL (LI)	182	8	200	90	30	2	28	0.7	0.4	1.5	1.9	3.8	3.5
DPUL (RK _c)	47	55	3000	630	200	11	189	3	2	3	4	8	3.4
DPUL (LI)	115	6	74	50	24	1.2	22.8	0.4	0.3	1.5	2	4	4
DDL	32	50	700	400	100	24	76	5	3	2.1	2.3	4.7	1.5
DDL (Lisheen)	29	260	500	470	436	240	196	100	60	2.5	2.1	4.3	0.8
DUIL (Lm)	50	25	195	170	65	10	55	4	2	1.7	1.8	3.6	2.2
DUIL (LI)	98	8	100	54	17	3	14	1.4	0.9	1.3	1.5	3	1.8
DPBL (Rk)	23	70	360	170	125	50	75	34	30	2	2	4	1
DPBL (RK ^c)	195	20	771	400	100	4	96	1	0.7	2.8	3.6	7	4.5
DPBL (RK ^d)	142	50	1100	440	215	14	201	3	1	2.5	2.9	6	4
DPBL (Lm)	23	8	200	40	20	3	17	1	0.8	1.7	2.2	4.5	2
DS	8	20	170	130	64	13	51	9	5	1.7	1.8	3.7	2.5
DMSSL	8	16	70	68	60	5	55	3	2	1.4	1.5	3	3.4
DSL	16	26	160	135	50	14	36	7	5	1.7	1.7	3.4	1.4
NU (Lm)	8	45	320	180	55	30	14	20	14	1.6	2	4	0.3
NSA (LI)	32	17	465	134	44	4	40	1.7	1.6	2.2	2.4	5	2.3

RUG	# of data	T m ² /d Best Estimate	T m ² /d Upper Estimates		T m ² /d Interquartile range			T m ² /d Lower Estimates		T m ² /d			
			95 th %ile	90 th %ile	75 th %ile	25 th %ile	IQR	10 th %ile	5 th %ile	Arithmetic Average [log ₁₀]	Standard deviation [log ₁₀]	Coeff. of Variation log ₁₀	IQR/Best Estimate
NSA (PI)	8	7	22	18	12	3	9	2.6	2.2	1	1	2	1.2
NSH (LI)	8	22	400	227	43	7	36	1.9	1.7	1	1	2	1.6
NSH (PI)	5	8	72	56	9	4	5	2.1	2	1	1	2	0.65
WSA (Lm)		20	150	110	52	8	44	5	5	1.6	1.8	3	2.2
GII (LI)	60	9	85	52	31	2	29	1.2	0.8	1.4	1.6	3	3.2
GII (PI)	61	2	17	13	6	0.7	5	0.22	0.16	0.74	1	2	2.5

Regional differences

Ordovician Metasediments RUG (OM)

A mixed geological unit present in a number of regions across the country. Classed as a Regionally Important Fissured Aquifer (Rf) in County Waterford, and a Locally Important Aquifer that is Moderately Productive only in Local Zones (LI) in Wicklow and Wexford.

Majority of the transmissivity data are Logan estimates of transmissivity from specific capacity values. Data for Waterford OM (classed as Rf) suggest that, despite lack of data, the distribution is across the lower ranges, and that the OM data for Waterford is more typical of LI rather than Rf. This is consistent with fact that the Ordovician Volcanics (discussed below) are less transmissive generally in Waterford than in Wexford.

Ordovician Volcanics RUG (OV)

The OV RUG is classed as a Regionally Important Fissured Aquifer (Rf) in counties Wexford and Waterford where it occupies a significant areal extent. This RUG occurs as relatively small extents in other counties and mainly classed as poorly productive, excepting an area in north County Dublin where it is classed as a Locally Important Aquifer that is Moderately Productive (Lm).

This unit comprises mainly rhyolitic volcanics of the Campile Formation in County Wexford and a mixture of volcanics and slates in County Waterford. This difference is reflected in the transmissivity as shown in the histogram in Appendix 5, with the data from Waterford, Kilkenny, Dublin and Meath stacked in the lower bin ranges.

Dinantian Dolomitised Limestone Aquifers (DDL)

This Rock Unit Group essentially comprises dolomitised limestones, generally in the southeast of the country and generally from purer portions of Waulsortian and Ballysteen Limestones. They are classed as Regionally Important Karst Aquifers (Rk^d). The transmissivity values range from 1–1000 m²/d, with a central tendency from 10–100 m²/d. Inspection of the histogram indicates that the distribution is bimodal due to the data from the Lisheen mine site. The geometric mean excluding the Lisheen data is 52 m²/d. The Lisheen transmissivity data have a geometric mean of 260 m²/d. The presence of cavities, infilled paleo-karst features, and a transmissive north-south fracture network are the likely reasons for the higher transmissivities at Lisheen (SRK, 1995).

Dinantian Upper Impure Limestones (DUIL)

This Rock Unit Group comprises impure, dark grey to black, well-bedded, fine to coarse-grained limestones, and is widely distributed across the country, and informally, is often referred to as the 'Calp'. Due to the considerable variation in lithology, structural influences and influences from karstification and dolomitisation, the aquifer classification ranges across PI, LI, Lm and Lk, though they are predominantly classed as a Locally Important Aquifer that is Moderately Productive only in local zones (LI).

The portion of DUIL classed as Lk is specifically the Derravaragh Cherts, mapped in county Westmeath. The limited data available for the Derravaragh Cherts suggest a central tendency and a range similar to the DUIL (LI) group. However, studies including dye tracing indicate a strongly karstic component to a regional groundwater flow regime (Quinlan, 2010; GSI Newsletter No.48). Currently therefore, the best estimates are those for the Rk^c Aquifer category.

The portion classed as Lm is mapped across an area of north Kildare, north Dublin and south Meath.

There are small areas in county Dublin of DUIL classed as PI, which consist of the Tober Colleen Formation. There are insufficient data for analysis where DUIL is classed as PI, therefore the best estimates are taken from the overall PI aquifer category group.

Dinantian Mixed Sandstones, Shales and Limestones (DMSSL)

This Rock Unit Group consists mainly of the Boyle Sandstone and the Meenymore Formations, and other less extensive units of similar lithologies. There are very few data available for these rocks which are mainly classed as LI, with the exception of undifferentiated DMSSL in County Louth, classed as Lm. Therefore the best estimates are represented by the overall LI Aquifer group, with some exceptions, namely the Meenymore Formation in County Monaghan and the Boyle Sandstones. Refer to the LI Aquifer Group for the best estimates.

The Meenymore Formation in North County Monaghan forms a relatively productive zone in association with the underlying and adjoining Dartry Formation (DPBL), from which the Tydavnet Group Water Scheme abstracts water. This combination is sometimes referred to as the 'Knockatallon Aquifer' (Cullen, 1985, 1997; Kelly, 2001; Misstear *et al.*, 2008)), as hydrogeologically, both units seem to be in hydraulic connection and the available geological logs indicate the rocks to be quite similar. In the vicinity of the main abstraction boreholes the Best Estimate for transmissivity is in the order of 60-70 m²/d. Further out, away from the main productive zone, the transmissivity appears to decrease and as reported in Misstear *et al.*, 2008, this fault bounded block appears to be isolated hydraulically from adjacent rocks.

The Boyle Sandstone occurs mainly in Roscommon, Sligo, Mayo and North Galway. Transmissivity values range from 4 – 26 m²/d, (Ibbotson, 2001), and the Best Estimate for transmissivity is 10 m²/d.

The area of undifferentiated DMSSL in County Louth has very few data and the estimates are derived from the overall Lm aquifer category, thus the Best Estimate for transmissivity is 20 m²/d.

6.4.4 Sands and Gravels

Sands and Gravels classed as Locally Important Sands and Gravels (Lg) or Regionally Important Sands and Gravels (Rg) are considered together as they are regarded to be lithologically and hydraulically equivalent and there are relatively few data to assess them separately. There are 33 transmissivity data based on good pumping test data, most of which reached steady state. A visual inspection of the graphical plot presented in

Figure 29 demonstrates an approximate log-normal distribution for the transmissivity data. There are a few extremely high values which may be related to the location alongside rivers or lakes. The Best estimate is 350 m²/d with an upper range of 900 m²/d (75th percentile) to 2650 m²/d (95th percentile) and a lower range of 44 (5th percentile) to 150 m²/d (25th percentile).

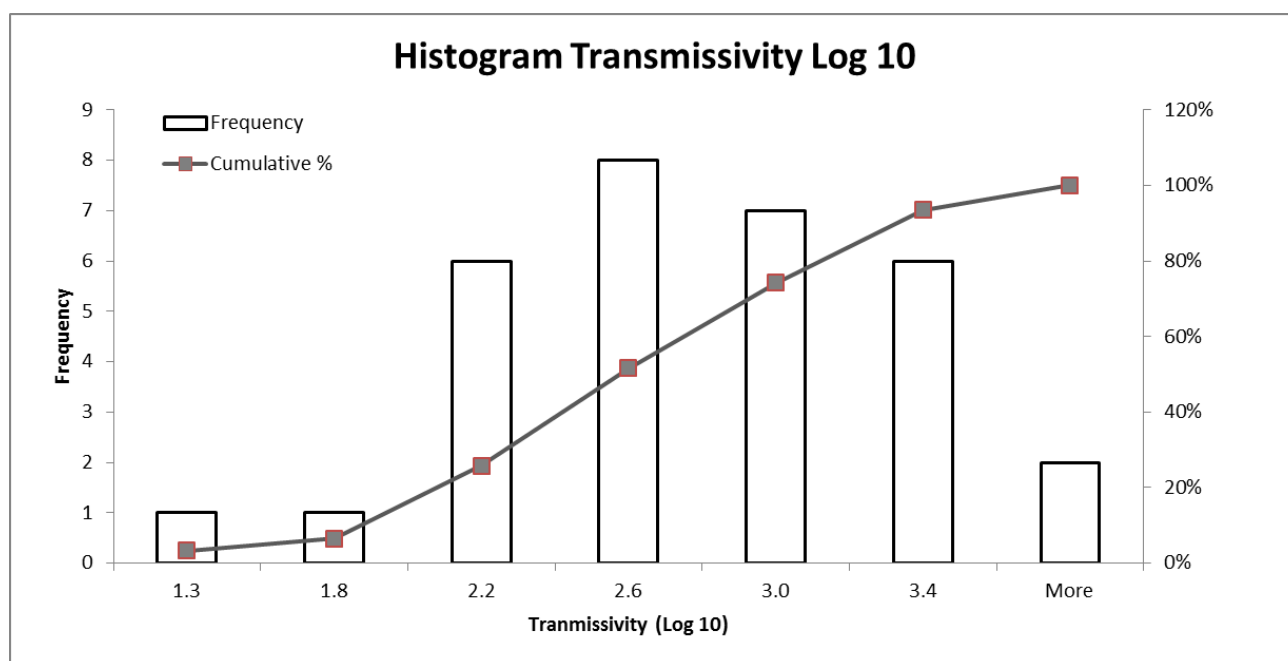


Figure 29 Histogram of Transmissivity for Sands and Gravels (Lg and Rg)

6.5 PERMEABILITY

6.5.1 Bedrock

There are few good data readily available for direct measurements of permeability for any of the Rock Unit Groups and Aquifer Categories for all of the pathways. In general these data represent relatively small length scales, where the typical 'screen length' or 'test length' is 1 to 2 m occurring across the Transition Zone and Shallow Bedrock zones. The bulk of the available data are clustered around the Dublin area obtained from the major infrastructural developments such as the Metro, Dart underground and Port Tunnel and Interconnector and therefore may not represent permeability nationally.

Figure 30 and **Figure 31** illustrate that bulk permeability decreases with depth and tends to decrease as a function of aquifer classification – though are insufficient data to fully examine this element. Note also that individual or clusters of fractures in the shallow and deep bedrock zones may have high hydraulic conductivities, but that this is averaged out by considering their contribution to the borehole flows along the entire depth of the zone.

As a crude proxy to test the available data, the specific capacity data from Geodata was used to estimate K, by taking the total depth of the borehole and subtracting the depth to bedrock from it; this value was then used when dividing the Logan estimate of transmissivity to obtain an average permeability value.

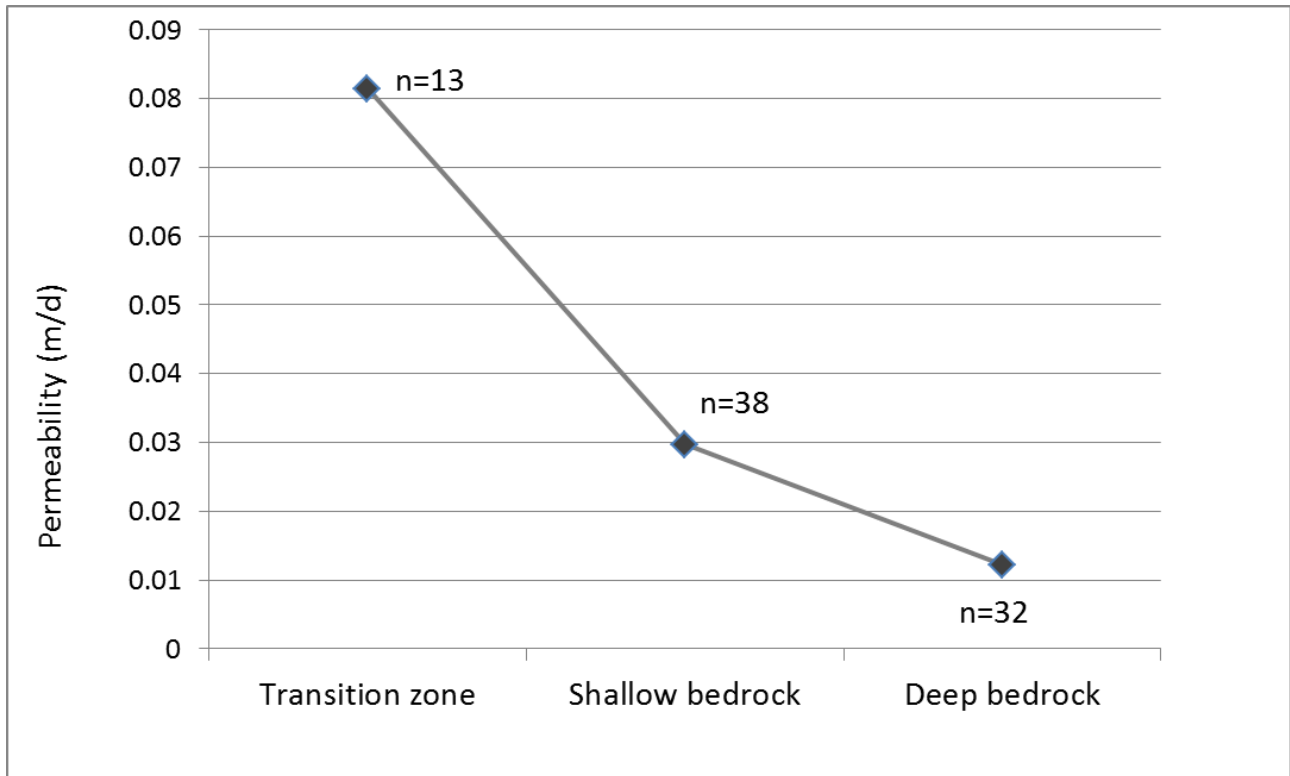


Figure 30 Bulk permeability (m/d) for Transition Zone (TZ), Shallow Bedrock (SB), Deep Bedrock (DB)

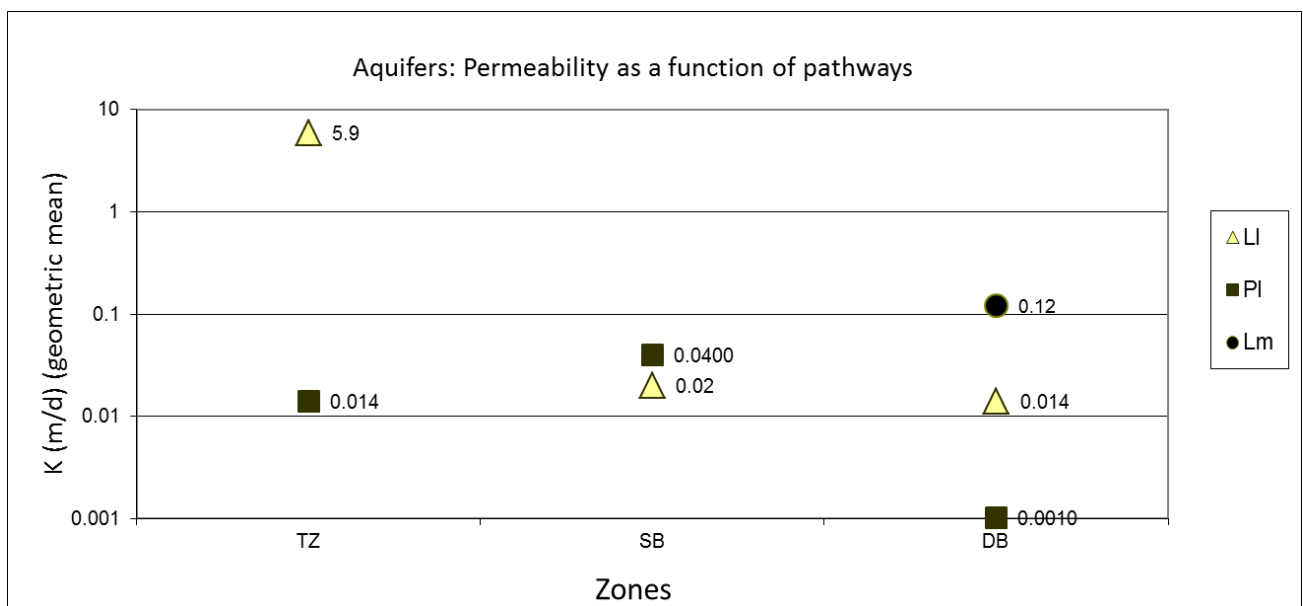


Figure 31 Permeability (m/d) for Transition Zone (TZ), Shallow Bedrock and Deep Bedrock, Shallow Bedrock (SB), Deep Bedrock (DB) across available aquifer categories

Some observations:

- The values for permeability appear to increase with increasing aquifer productivity, and there appears to be a relatively strong correlation between the available data from the aquifer parameters database and the proxy data from Geodata as shown in
- **Figure 32.**
- The estimates from the aquifer parameters database are less than those from Geodata. This may be as expected as those derived from geodata are from transmissivity values and thus are capturing the average permeability for the entire borehole length.
-
- **Figure 30** and **Figure 31** shows the estimates for the different flow pathways across the aquifer categories for which there are a few data, and there is an expected decrease in permeability with depth. Comte *et al.*, 2012, indicate that the geometric mean permeability for the transition zone in a PI aquifer is 0.09 m/d, shallow bedrock is 0.016 m/d, and deep bedrock is 0.0012 m/d. Note that the estimates shown in **Table 6** include the raw data in Comte *et al.* (2012). The difference between the aquifer parameter database and 'geodata' parameter estimates is thought to arise due to the reasons discussed in Section 4.3.5.

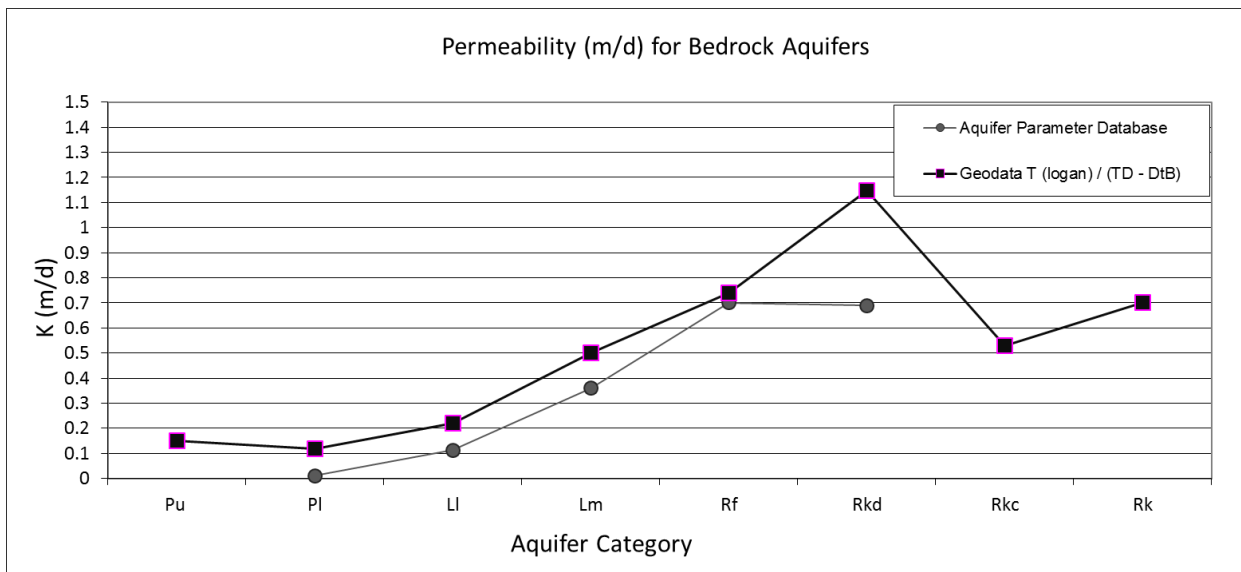


Figure 32 Permeability (m/d) for the bedrock aquifers categories from the aquifer parameters database and Geodata, suggesting a reasonable correlation between the permeability values, also showing that the average permeability calculated from T is higher as might expected. This does not appear to hold for the karst aquifers.

Table 6 Estimates of bulk hydraulic conductivity (m/d) for the aquifer categories from the databases

Aquifer	Parameters database	Geodata
Pu		0.15
PI	0.011	0.12
LI	0.113	0.22
Lm	0.360	0.5
Rf	0.700	0.74
RK ^d	0.690	1.148
RK ^c		0.53

Rk		0.7
Lk		0.48
Rk		1.14

6.5.2 Sand and Gravel Aquifers

The permeability estimates for the sands and gravel aquifers are based mainly on the best estimate transmissivity values divided by screen length. A brief analysis of the drawdown data and the position of the screens indicate that the final drawdown is largely above the screen or close to the top, thus it is assumed that the transmissivity estimate is not overly influenced by the cone of depression and that the estimate of permeability is reasonable. The Best Estimate is 38-40 m/d with an upper range 60, 200, 395 m/d for the 75th, 90th and 95th percentile respectively. The lower estimates range from 8 to 16 m/d for the 5th and 25th percentiles.

6.5.3 Subsoils (tills)

Till is the dominant subsoil deposit in Ireland, covering much of the bedrock in Ireland, particularly the non-mountainous areas (Hunter-Williams *et al.*, in press; Fitzsimons and Misstear, 2006). Other deposits include peat, lacustrine silts and clays and glaciofluvial sand and gravels. The extensive till deposits that cover large parts of the landscape influence recharge and groundwater vulnerability (Fitzsimons and Misstear, 2006). The tills are generally unsorted, heterogeneous comprising a wide range in particle sizes, and primary porosity is significant. The subsoil distribution has been mapped (Teagasc, 2006) and is currently being updated by GSI and is available on both the GSI and EPA websites.

Swartz *et al.*, 2003 observed a correlation between standard textural descriptions (BS 5930) and particle size data, and also observed that field and laboratory measurements yielded a wide range of permeability values; *in-situ* values ranging from 10^{-6} m/s to 10^{-10} m/s for tills, while the laboratory measurements and permeability values are of the order of 10^{-10} m/s to 10^{-11} m/s. Subsoil permeability values indicate permeability at a local scale – permeability measurements are highly scale dependent. Laboratory results can be orders of magnitude lower than *in-situ* tests. There is a general lack of high quality data relating definitive subsoil textures to values. It is also recognized that factors such as density/compactness and preferential flow paths can influence permeability at a site (Swartz *et al.*, 2003). In addition Black (2010) indicates that there are common practical problems with obtaining reliable data, associated with the BS 5930 methodology for conducting piezometer tests, and that the largest errors tend to be with leakage around the borehole.

Though subsoil permeability varies greatly over short horizontal and vertical distances, there are broad patterns (Meehan and Lee, 2012). The Geological Survey of Ireland define and map regional subsoil permeability maps, using an integrated holistic approach that utilises textural descriptions, particle size data, hydraulic measurements, drainage and vegetative indicators, topsoil maps, bedrock maps, digital elevation models, and ice flow models (Swartz, 1999; Lee, 1999, Fitzsimons *et al.*, 2003; and GSI County Groundwater Protection Scheme reports).

There are three broad permeability categories defined: ‘high’, ‘moderate’ and ‘low’. Most tills in Ireland are considered to have a ‘moderate’ or ‘low’ permeability, as described in Swartz *et al.*, 2003. The boundary between ‘moderate’ and ‘low’ permeability is approximately 10^{-8} - 10^{-9} m/s (Swartz, 1999, Fitzsimons *et al.*, 2003), and the boundary with high is approximately 10^{-4} m/s to 10^{-5} m/s (O’Suilleabháin, 2000; Misstear *et al.*, 2009).

‘Moderate’ permeability subsoils generally have less than 14% clay and low permeability subsoils have greater than 12% clay (Fitzsimons, *et al.*, 2003). ‘Low’ permeability subsoils tend to have more than

50% fines and ‘moderate’ permeability subsoils tend to have less than 35% fines. ‘High’ permeability sands and gravels tend to be sorted and have less than 7% fines (O’Sulleabháin, 2000).

‘Low’ permeability tills are generally defined by the textural classes ‘CLAY’ and/or ‘SILT/CLAY’. ‘Moderate’ permeability tills generally comprise ‘SILTS’ and/or ‘SANDS’. Note that silty SAND in this context refers to the tills rather than glaciofluvial deposits.

Of the data reviewed there are few reliable textural descriptions, and they are also from a few sites. Of the available data, the finer grained sediments, described as either boulder clays, tills or glaciomarine clays, silts and sands, permeability is in the order of 10^{-6} m/s to 10^{-9} m/s. The permeability is in the order of 10^{-5} m/s for the coarser grained sediments (though it is not clear if they are from tills or not). These values appear low in comparison to the 10^{-4} m/s as reported by O’Suilleabháin (2000) and to **Table 7**, and this may be due significant fines and only represent a local specific site.

EPA Guidance document on Authorisation of Discharges to Groundwater tabulates the ranges of permeability as a function of textural definition using BS5930 in **Table 7**.

Table 7 Estimated permeability ranges for subsoil textures (Taken from EPAs Guidance Document on Authorisation of Discharges to Groundwater)

Texture (BS5930)	m/d	m/s
GRAVEL/SAND	>5	5×10^{-5}
SILT	1×10^{-2} to 5	1×10^{-7} to 5×10^{-5}
SILT/CLAY	5×10^{-3} to 5×10^{-1}	5×10^{-8} to 5×10^{-6}
CLAY	$< 5 \times 10^{-3}$	$< 5 \times 10^{-8}$

6.6 TRAVEL TIMES/VELOCITY

In certain situations, velocities can be estimated based on Darcy’s Law and estimates of permeability, hydraulic gradient and porosity. This equation is generally appropriate for the gravel aquifers. Velocities, though variable, will generally be quite low (less than, say, 1 m/day), due to the high porosity in most gravels and the low hydraulic gradients which occur in the larger, higher transmissivity gravels.

Velocities are much more variable in the bedrock aquifers, but are generally high by international standards. This is due to the low porosity which is typical of most bedrock aquifers.

Highest rates are found in the karstic aquifers, where velocities of tens or even hundreds of metres per hour have been identified by a number of tracer test experiments across the country.

Section 4.5 outlined the consistency required between parameters for any particular site.

6.7 STORAGE

6.7.1 Bedrock

There are 86 records available for confined storage coefficient and unconfined specific yield and these are distributed across all the aquifer types with the exception of Rk^c for which there are no data.

Figure 33 shows the number of records available and the geometric mean for each of the aquifer types. The number of records per aquifer category is insufficient; only Rk^d , Lm, Lk, LL, and PI have some degree of representation. Despite this, as can be seen in

Figure 33, there are enough data to indicate the expected values for unconfined and confined conditions and that these are broadly equivalent across the aquifer categories.

It can be seen that the specific yield is low, in the order of 0.01 (1×10^{-2}) and confined storage coefficient is in the order of 0.0001 (1×10^{-4}).

The overall geometric mean for confined storage coefficient using the 39 records in the database ignoring aquifer category or RUG is 0.00011 (1.1×10^{-4}) and similarly the overall geometric mean using the 35 records in the database of specific yield is 0.01 (1×10^{-2}).

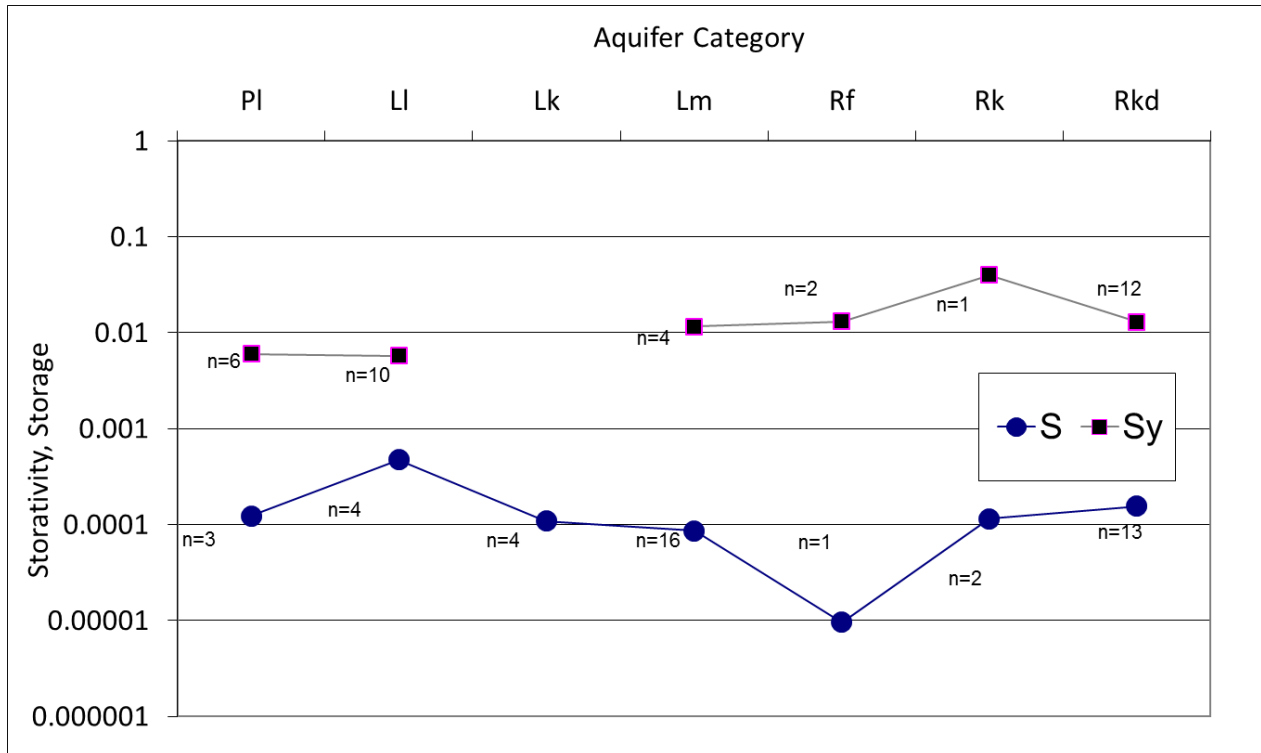


Figure 33 Geometric mean for confined storage coefficient and specific yield across the aquifer categories represented

Analysing the data as a function of RUG is limited as most RUGs do not have any records. **Table 8** summarises the storage coefficient as a function of the generic flow regime grouping of bedrock aquifers as described in Section 3.4.

The values compare well with ranges for specific yield reported in Tedd *et al.*, 2012 for bedrock aquifers in the Southeastern River Basin District as follows:

- Rk^d : 0.01 to 0.06,
- Ll: 0.03 to 0.04.

Tedd *et al.*, 2012 calculated specific yield values from annual average groundwater level variations.

Table 8 Storage coefficients (geometric means) per flow regime grouping

Flow Regime	Storativity (confined)	Specific Yield (unconfined)
Karstic (Rk , Lk , Rk^c , Rk^d)	1.1×10^{-4} (0.00011)	1.4×10^{-2} (0.014)
Productive fissured bedrock (Rf , Lm)	1.6×10^{-4} (0.00016)	1.1×10^{-2} (0.011)
Poorly productive bedrock (Ll , Pl , Pu)	2.6×10^{-4} (0.00026)	1.7×10^{-2} (0.017)

6.7.2 Sands and Gravels

There are few data available for sands and gravels.

Tedd *et al.*, 2012, report a range of 0.13–0.19, for specific yield for sand and gravel in the southeastern river basin district analysing groundwater level hydrographs. These are consistent with specific yield estimates by Daly (1994).

Misstear *et al.*, 2009, suggest a specific yield for the Curragh sand and gravel aquifer in Kildare of 0.19.

Specific yield of 0.1 is reported for a sand and gravel aquifer in ArdTullybeg, Co. Louth (An Foras Forbatha/GSI, 1982).

Gravels in Arklow, Co. Wicklow and Robertstown in Co. Kildare, were both test pumped by White Young Green (2009) and K.T. Cullen² (2001). The gravels at Robertstown are confined whilst they are unconfined at Arklow. The data suggest that specific yield for the gravels at Arklow ranges from 0.04 to 0.08 – though this is considered to be lower than expected. The confined storage coefficient for the gravels in Robertstown is estimated to range from 0.0003 (3×10^{-4}) to 0.003 (3×10^{-3}).

6.7.3 Subsoils

There are few storage coefficients or porosity data available. In a study conducted by Kilfeather (2008) on tills in County Laois, the porosity ranged from 1% to 19%. It is highly difficult to predict subsoil porosities and according to Kilfeather (2008) detailed site investigations are required and deriving porosity estimates from particle size analyses is unreliable. Misstear and Brown, 2002, and Misstear *et al.*, 2008, assume a porosity of 40% for a low permeability till in County Monaghan. Specific yield for clay rich tills is reported in the literature as being in the order of 2% to 6%, and in the order of 6% to 16% for silty/sandy tills (Morris and Johnson, 1967; Heath, 1983). GSI (Aquifer report in prep) suggest estimated values in **Table 9**.

Table 9 Estimated values of porosity, specific yield and specific retention (GSI Aquifer report in prep)

Material	Porosity (%)	Specific Yield (%)	Specific Retention (%)
Sand & gravel	15	14	1
Clay	50	2	48
Peat	90	15	65

6.7.4 Effective porosity

Specific yield (Sy), also known as the drainable porosity, is a ratio, less than or equal to the effective porosity, indicating the volumetric fraction of the bulk aquifer volume that a given aquifer will yield when all the water is allowed to drain out of it under the forces of gravity.

Specific yield can be close to effective porosity, but there are several subtle things which make this value more complicated than it seems. Some water always remains in the formation, even after drainage; it clings to the grains of sand and clay in the formation. Also, the value of specific yield may not be fully realized until very large times, due to complications caused by unsaturated flow.

- In fractured rocks, effective porosity is approximately equal to specific yield (**Table 9**).

² White Young Green acquired K.T. Cullen in 2001, but some reports around 2002 are under K.T. Cullen

- In sediments, effective porosity is greater than specific yield, for example in poorly sorted sand and gravel ([Table 9](#)).

7 SUMMARY AND CONCLUSIONS

Hydraulic data have been summarised for bedrock units and sand/gravel aquifers as a function of aquifer category and Rock Unit Group (RUGs). Realistic transmissivity values are provided for each of the aquifer categories and the RUGs. For a number of RUGs, there are insufficient data to either populate the RUG or an aquifer subset of the RUG. Specific capacity data from GSI Geodata provided a more robust statistical basis for the selection of the 'Best' estimates and the 'Upper' and 'Lower' ranges. Summary tables are provided for both bedrock and sand and gravel aquifers. Relevant information on the subsoils is limited to summarising the key permeability boundaries and ranges for the main textural classes.

In general, there is a decrease in the 'Best' estimate for transmissivity of the Regionally Important Aquifers through to the Poor Aquifers with the apparent exception of the karst sub-type – Rkc. The 'Best' estimates are as follows for the general flow types:

- Poorly Productive Aquifers (Pu, Pl and Ll categories) are less than 10 m²/d.
- Productive Fissured Aquifers (Lm and Rf categories) range from 20 – 30 m²/d.
- Karstic Aquifers (Lk, Rk and Rk^d categories) range from 20 – 70 m²/d. The arithmetic mean bulk transmissivity for Rk^c aquifers is greater than 500 m²/d.
- Sand and Gravel Aquifers (Rg and Lg categories) are approximately 350 m²/d.

There are insufficient specific in-situ permeability data to fully characterise the aquifer and rock unit classifications. Bulk hydraulic conductivity estimates are derived from transmissivity data from the aquifer parameters database. (Available proxy transmissivity estimates from specific capacity data correlate reasonably well, though generally higher). Bulk permeability decreases with depth in the bedrock aquifers as expected. Individual fracture permeabilities are likely to be significantly higher than bulk permeability estimates, particularly as the borehole interval assessed increases.

It is important to point out for the karstified aquifers that, when estimating a velocity in the context of a time of travel, it is important to consult with the GSI Karst tracing database to collate information on travel times from conducted tracer studies.

Due to the nature of the available data, storage and effective porosity data are very limited. This study collected 39 data, and the remainder of the data derive from groundwater supply source assessments in sand/gravel aquifers, and from a study by Tedd *et al.* (2012).

- Specific yield across all bedrock aquifer categories is low, in the order of 0.01 (1x10⁻²) and the confined storage coefficient is in the order of 0.0001 (1x10⁻⁴). There seems to be a weak dependency on aquifer type, but there are insufficient data to derive a statistically significant relationship.
- Specific yields in sand/gravel deposits range from around 0.1 to 0.19. A single storage coefficient value for confined sands/gravels is 0.003 (1x10⁻³).

It is responsibility of user to assess best value for their site based on site specific considerations and also the nature and requirements of the study (e.g. bulk transport or first arrival times). Also, when undertaking site investigations, to choose most appropriate methods to determine appropriate parameters of interest. Over a particular portion of aquifer that has broadly similar groundwater flow characteristics, the hydraulic parameters need to be consistent with each other due to their interdependence. Parameter interdependence should be borne in mind when selecting appropriate parameter values from the aquifer parameter database, and the parameters should be self-consistent and consistent with any site-specific information. The general approach to parameter estimation as given by Wright (2002), and techniques and methods given in Misstear *et al.* (2006), is appropriate for

Irish conditions and the type of test data collected. An integrated approach using cross checks is suggested with the additional use of diagnostic plots. Diagnostic plots provide an additional technique to assessing test pumping data, and can offer a useful insight into the data. High resolution data from a data logger is required to reduce the scatter in the data.

8 FUTURE WORK AND IMPROVEMENTS

Additional work on obtaining high quality hydraulic information is required both on the bedrock and the subsoils. Further potential data sources are listed as follows:

Consultants: One of the main difficulties is getting consultants to provide data due to their time constraints. Some consultants provided data for the current project which has been invaluable, and it is known that there are other data with other consultants. It is suggested that each of them is called to discuss the data needs and if required conduct visits to acquire the relevant data. It could be assumed that hydrogeological data collected for the national aquifer delineation project means that the data trawl is post 2004 or thereabouts to concentrate on recent and possibly higher quality data.

Drillers and pumping test providers: It may be beneficial to contact some of the main pumping test providers and drillers to ask about recent or current major drilling projects. It would be useful to liaise with the likes of the local authorities, Irish Water and the National Federation of Group Water Schemes.

Site investigation data: There are site investigation data acquired for the Groundwater Vulnerability mapping project and the focus of that was collecting depth to bedrock – there may be additional hydraulic conductivity data from the site investigation data. This will chiefly be in related to the shallower pathways and a priority on this will have to be discussed.

Source Protection Zone reports: Recently completed reports and on-going reports need to be checked for data and acquired for the database if of high enough quality.

Mineral Exploration and Aggregates Work: Currently there are exploration programmes in County Limerick on-going and it is likely that there are data which may be made available to the GSI or EMD. It may be confidential at this stage but contacts should be made. EMD should be approached to find out if there are other known exploration programmes being conducted. Similarly the Irish Quarry and Mining Society and the Irish Concrete Federation may be able to assist with information gathering.

Another data capture approach is to build a smart phone 'App' that could allow a driller or consultant to input a digital well record that could be uploaded to a database. This could function similar to the current EPA "See it? Say it!" application allowing people to make an environmental complaint.

9 REFERENCES

- Allen, D. J., Brewerton, L. J., Coleby, L. M., Gibbs, B. R., Lewis, M. A., MacDonald, A. M., Wagstaff, S. J., and Williams, A. T. 1997. The physical properties of major aquifers in England and Wales. British Geological Survey Technical Report WD/97/34. 312 pp. Environment Agency R&D Publication 8.
- An Foras Forbatha and Geological Survey of Ireland. Groundwater Resources in the N.E. (R.D.O). Region. March 1982. Volumes 1 to 3.
- Aziz, C.E., Newell, C.J., Gonzales, J.R., Haas, P., Clement, T.P., Sun, Y., 2000. BIOCHLOR—Natural attenuation decision support system v1.0. User's Manual, U.S. EPA Report, EPA 600/R-00/008.
- Banks, D., Gundersen, P., Gustafson, G., Mäkelä, J., and G. Morland, 2010. Regional similarities in the distributions of well yield from crystalline rocks in Fennoscandia.
- Banks, D., Morland, G., Frengstad, B. 2005. Use of non-parametric statistics as a tool for the hydraulic and hydrogeochemical characterization of hard rock aquifers.
- Banks, D., 1998. Predicting the Probability Distribution of Yield from multiple boreholes in Crystalline Rock. Groundwater, Volume 36 No. 2.
- Banks, D., E.R. Torps, Skarphagen, H. 1994. Groundwater Resources in Hard Rock; Experiences from the Hvaler Study, Southeastern Norway. Applied Hydrogeology 2/94.
- Bear, J. 1972. Dynamics of fluids in porous media. American Elsevier, New York.
- Black, J. 2010. The practical reasons why slug tests (including falling and rising head tests) often yield the wrong value of hydraulic conductivity Quarterly Journal of Engineering Geology and Hydrogeology 2010; v. 43; p. 345-358.
- Blake, S., Jones, A.G., Muller, M., Henry, T., Allen, A. 2013. IRETherm: Multi-disciplinary investigation of Irish warm springs and their potential for geothermal energy provision. Geothermal Association of Ireland Annual Conference, Kilkenny, 2013.
- British Standards Institution. 1999. Code of Practice for Site Investigations. BS 5930.
- British Standards Institution 2003. Hydrometric determinations - Pumping tests for water wells. Considerations and guidelines for design, performance and use. BS ISO 14686.
- Brown, D. L., Narasimhan, T. N. 1995. An evaluation of the Bouwer And Rice method of slug test analysis. Water Resour. Res. Vol. 31 (5) pp 1239-1246.
- Butler, J.J., Jr. 1998. The Design, Performance, and Analysis of Slug Tests. Lewis Publishers. ISBN 1-56670-230-5
- Butler, J.J., Jr., et al. 1994. The use of slug tests to describe vertical variations in hydraulic conductivity. J. Hydrol. 56: pp 137-162.
- Bower, H., and R.C. Rice. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. Water Resources Research 12, no. 3: 423-428.
- Comte, J.C., Cassidy, R., Nitsche, J., Offerdinger, U., Pilatova, K., and R. Flynn. 2012. The typology of Irish hard-rock aquifers based on an integrated hydrogeological and geophysical approach. Hydrogeology Journal.

- Cullen, K. T. 2002. Environmental Report for Groundwater Abstraction from Calp Aquifer at Johnstown Bridge, Co. Kildare. Report for Kildare County Council.
- Cullen, K. T. 2001. EIS for Groundwater abstraction from North Kildare Aquifer, Robertstown, Co. Kildare. Report for Kildare County Council.
- Cullen, K. T. 1985. Report on the Drilling and Testing of Trial Wells in North County Monaghan.
- Cullen, K. T. 1997. Monaghan Town Water Supply Augmentation. Groundwater Resources Report. Report for Monaghan County Council.
- Daly, E.P. 1994. Groundwater Resources of the Nore River Basin. Geological Survey of Ireland Report Series (Groundwater), RS 94/1.
- Daly, E.P. 1995. The principal characteristics of the flow regime in Irish aquifers. In Proceedings of the 15th Annual IAH (Irish Group) Seminar: The Role of Groundwater in Sustainable Development.
- Deakin, J., Misstear, B.D., Murphy, A., Dowling, M. and Flynn, R. (2010) Investigating water flow and contaminant pathways to rivers using chemical hydrograph separation, National Hydrology Conference, Athlone, 11 November 2010, 2010, pp1-11
- De Lange, SS and van Tonder, GJ. 2000. Delineation of borehole protection zones in fractured rock aquifers. Proceedings of the XXX IAH Congress on Groundwater: Past Achievements and Future Challenges (Ed Sililo, O), Cape Town, South Africa. 26 November-1 December 2000. Balkema, Rotterdam.
- Dunphy, R. 2004. The role of fracture systems in controlling groundwater yields in the post-Silurian rocks of Ireland. Final report to the GSI, 141 pp. Based on MSc Thesis, TCD.
- EPA, 2011. Guidance on the Authorisation of Discharges to Groundwater. ISBN 978-1-84095-413-5.
- EPA, 2013. Guidance on the Management of Contaminated Land and Groundwater at EPA Licensed Sites. ISBN: 978-1-84095-511-8.
- EPA, 2013. EPA DRINKING WATER ADVICE NOTE Advice Note No. 14: Borehole Construction and Wellhead Protection. EPA, Johnstown Castle, Ireland.
http://www.epa.ie/pubs/advice/drinkingwater/EPA_DrinkingWater_AdviceNoteNo14b_web.pdf
- Fitzsimons, V. P., and Misstear, B. D., 2006. Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland. *Hydrogeology Journal*, 14, 548-561.
- Fitzsimons, V., Daly, D., Wright, G., and T. Hunter-Williams. 2005. Rock type versus Fractures – Current understanding of Irish Aquifers. IAH (Irish Group) Conference Proceedings. Tullamore.
- ³Ford Consulting Group, 2011. Review of a contaminated land and groundwater assessment framework & tools for Ireland. Report for EPA.
- Gelhar, L.W., Welty, C., Rehfeldt, K.R. 1992. A Critical Review of Data on Field-Scale Dispersion in Aquifers. *Water Resources Research*, Vol., 28, No. 7, pp 1955-1974.
- Groundwater Working Group (2003) Guidance Document No. GW 2. *Water Framework Directive (WFD) River Basin District Management Systems: Approach to Delineation of Groundwater Bodies*, 16pp.
- Graham, M T, Ball, Ó Dochartaigh, D., Irving, K, and E. Simpson. 2006. Scottish Aquifer Properties, 2006 interim report, British Geological Survey report CR/06/073N.

³ Geosyntec Consultants acquired Forde Consulting Group in 2012.

GSI, 2006. Criteria used in aquifer classification. Available from:
<http://www.gsi.ie/Programmes/Groundwater/Aquifer+Classification.htm>

GSI. In Prep. Aquifer Classifications in the Republic of Ireland.

Hickey, C. 2010. The Use of Multiple Techniques for Conceptualisation of Lowland Karst, a case study from County Roscommon, Ireland. *Acta Carsologica* 39/2, 331-346, Special Edition: Research Frontiers and Practical Challenges in Karst Hydrogeology. Postojna.

Hickey, C. 2008. Landforms and Hydrology of the Lowland Karst of County Roscommon, Ireland. Phd Thesis. Trinity College Dublin.

Hunter Williams, N., Misstear, B.D., Daly, D., and M. Lee (2013). Development of a national groundwater recharge map for the Republic of Ireland. *Quaternary Journal for Engineering Geology and Hydrogeology*.

Hvorslev, M.J. 1951. Time lag and soil permeability in groundwater observations. Bulletin no. 36. Waterways Experiment Station, Corps of Engineers, U.S. Army.

IGI (2007) Guidelines for Drilling Wells for Private Water Supplies.
<http://www.igi.ie/assets/files/Water%20Well%20Guidelines/Guidelines.pdf>

Jones, H. K., Morris, B L., Cheney, C. S., Brewerton, L. J., Merrin, P D., Lewis, M. A., MacDonald, A. M., Coleby, L M., Talbot, J. C., McKenzie, A. A., Bird, M. J., Cunningham, J., and Robinson, V. K. 2000. The physical properties of minor aquifers in England and Wales. British Geological Survey Technical Report WD/00/04. 234 pp. Environment Agency R&D Publication 68.

Kelly, R. 2001. An investigation into groundwater resources in the Knockatallon area of north-west Monaghan. MSc dissertation, Queen's University Belfast.

Krásný, J. 1993. Classification of transmissivity magnitude and variation. - *Ground Water*, 31, 2, 230-236. Dublin, Ohio.

Krešić N., and A. Mikszewski. 2013. Hydrogeological Conceptual Site Models: Data Analysis and Visualization. Taylor & Francis Group. ISBN 978-1-4398-5222-1.

Kruseman, G.P., N.A. de Ridder and J.M. Verwij. 1990 (2nd edition, 2000). Analysis and Evaluation of Pumping Test Data. International Institute for Land Reclamation and Improvement, Wageningen, Netherlands.

Lee, M. (1999). Surface indicators and land use as secondary indicators of groundwater recharge and vulnerability. Unpublished (Research) MSc thesis. Department of Civil, Structural and Environmental Engineering, Trinity College Dublin.

Meehan, R., and Lee, M. 2012. Subsoils across the Irish Landscape; their textural and bulk density characteristics, and resultant variations in permeability. EPA Conference 2012.

Misstear, B. 2012. Some key issues in the design of water wells in unconsolidated and fractured rock aquifers. *Italian Journal of Groundwater*.

Misstear, B. D. R., Brown, L., and P. M. Johnston. 2009b. Estimation of groundwater recharge in a major sand and gravel aquifer in Ireland using multiple approaches. *Hydrogeology Journal*, 17, 693-706.

Misstear, B. D., Banks, D., and L. Clark. 2006. Water Wells and Boreholes. Wiley & Sons Ltd. ISBN-13: 978-0-470-87989-7.

- Missteart, B. D., Brown, L., and N., Hunter-Williams. 2008. Groundwater recharge to a fractured limestone aquifer in County Monaghan, Ireland. *Quarterly Journal of Engineering Geology and Hydrogeology*, 41, 465–476.
- Missteart, B. D., and L. Brown. 2002. Recharge and Groundwater Vulnerability. STRIVE report series No. 6. (2002-W-MS-16). Available for download on <http://erc.epa.ie/safer/reports>.
- Missteart, B.D., 2001. Editors' Message. The value of simple equilibrium approximations for analysing pumping test data. *Hydrogeology Journal* (2001) 9:125–126.
- Missteart, B.D., 1998. The Logan Method for analysing pumping test data. GSI Groundwater Newsletter No. 34. Geological Survey of Ireland.
- Moe, H, Craig, M, and D. Daly, 2010. Poorly Productive Aquifers – Monitoring Installations and Conceptual Understanding.
- Neuman SP (1995) On advective dispersion in fractal velocity and permeability fields. *Water Resources Research* 31(6):1455–1460.
- Neuman S. P. 2005. Trends, prospects and challenges in quantifying flow and transport through fractured rocks. *Hydrogeol. J.* 13(1): 124–47.
- O'Brien, R.J., Missteart, B.D., Gill, L.W., Deakin, J.L. and Flynn, R. (2012) Developing an integrated hydrograph separation and lumped modelling approach to quantifying hydrological pathways in Irish river catchments. *J. Hydrol.*, 486, 259–270.
- O'Suilleabháin C. (2000). Assessing the Boundary Between High and Moderately Permeable Subsoils. Unpublished MSc thesis. Department of Civil, Structural and Environmental Engineering, Trinity College Dublin.
- Swartz, M. (1999). Assessing the Permeability of Irish Subsoils. Unpublished (Research) MSc thesis. Department of Civil, Structural, and Environmental Engineering, Trinity College Dublin.
- Prudic, E. 1991. USGS Water Resources Investigations Report 90-4121. A contribution of the Regional Aquifer System Analysis Program.
- Quinlan, C., 2010. Karstification and Groundwater-surface water Interactions in the Meath-Westmeath Lakeland region. Phd Thesis Trinity College Dublin.
- Quinlan, C., 2010. Groundwater– lake interactions in the Meath-Westmeath lakeland region. *Groundwater Newsletter* ISSN 0790-7753. Issue 48. <http://www.gsi.ie/NR/rdonlyres/A7891647-3EE0-47E7-9BDD-BCF062F6269A/0/GWNewsletterNo48.pdf>
- Renard, P., Glenz, D., and M. Mejias, 2009. Understanding diagnostic plots for well-test interpretation. *Hydrogeology Journal* 17: 589–600.
- RPS Consultants 2008 (Glasgow, G., Jennings, S.). Further Characterisation Study. An integrated approach to quantifying groundwater and surface water contributions of stream flow. RPS Report for Southwestern River Basin District for Further Characterisation.
- Singal, B. B. S., and R. P. Gupta. 2010. *Applied Hydrogeology of Fractured Rocks*. 2nd Ed. Springer.
- Samani, N., Pasandi, M., and D. A. Barry, 2006. Characterizing a heterogeneous aquifer by derivative analysis of pumping and recovery test data.

Spane, F.A., Jr., and S.K. Wurstner, 1993. DERIV: A computer program for calculating pressure derivatives for use in hydraulic test analysis, *Ground Water*, vol. 31, no. 5, pp. 814-822.

SRK, 1995. Lisheen Zinc/Lead Project, Ireland Hydrogeology, Hydrology and Mine Dewatering Planning Report. Prepared for Minorco Lisheen Ltd/Ivernia West Plc Joint Venture.

Swartz, M., Misstear, B.D.R., Daly, D., and E.R. Farrell. 2003. Assessing subsoil permeability for groundwater vulnerability. *Quarterly Journal of Engineering Geology and Hydrogeology*. V. 36:173-184

Teagasc / EPA, 2006. Digital Subsoil map of Ireland. Prepared as part of the EPA Soils and Subsoil Mapping Project, Teagasc, Kinsealy. Dublin. [the digital maps are available on both the EPA and GSI websites]

Van Tonder, G., Bardenhagen, I., Riemann, K., van Bosch, J., Dzanga, P., and Xu Yongxin. 2002. Manual on Pumping Test Analysis in Fractured-Rock Aquifers. Institute for Groundwater Studies. Water Research Commission.

Verbovšek, T. 2008. Estimation of Transmissivity and Hydraulic Conductivity from Specific Capacity and Specific Capacity Index in Dolomite Aquifers. *Journal of Hydraulic Engineering*, Vol. 13, No. 9.

White Young Green. 2009. Drilling and Testing Report. Arklow Water Supply. Report for Wicklow County Council.

Wright, G. 2000. QSC graphs: an aid to classification of data-poor aquifers in Ireland. In Robins, N.S & Misstear, B.D.R. (eds) *Groundwater in the Celtic Regions: Studies in Hard Rock and Quaternary Hydrogeology*. Geological Society, London, Special Publications, 182, 169-177.

Wright, G., 2002. Tips on tests. *Geological Survey of Ireland Groundwater Newsletter*, Issue Newsletter No. 40.

WRIGHT, G. 1997. QSC graphs – a tool to assist in aquifer classification. *Geological Survey of Ireland Groundwater Newsletter*, Issue No. 32.

APPENDIX 2 SUMMARY TABLE SANDS / GRAVELS T, K

Lg/Rg			Lg/Rg		
T m2/d Upper Estimates (75, 90, 95 percentile)	T m2/d Lower Estimates (5, 25 percentile)	T m2/d Best Estimate Geomean	K m/d Upper Estimates (75, 90, 95 percentile)	K m/d Lower Estimates (5, 25 percentile)	K m2/d Best Estimate Geomean
1055 (75), 2565 (90%), 2650 (95%)	44 (5%), 160 (25%)	350 (geomean)	60 (75%), 260 (90%), 620 (95%)	8(5%), 14(25%)	36 (geomean)

APPENDIX 3 'TIPS ON TESTS' (WRIGHT, 2002)

This appendix is taken from Wright, G., 2002. Tips on tests. Geological Survey of Ireland Groundwater Newsletter, Issue Newsletter No. 40.

What they didn't tell you about Pumping Tests on the MSc Course.....

This note was written in response to reading many pumping test analyses/evaluations in several countries over the past thirty-odd years.

Pumping test evaluation is covered (sometimes to excess) on taught Hydrogeology courses. It may or may not be covered on other taught courses, and if you obtained a postgraduate degree by research you may have missed out completely. In any case, coursework and textbook examples almost only deal with ideal situations, where the numerous conditions required by the various formulae (isotropy, homogeneity, horizontal flow, near-infinite aquifer, constant discharge rate, etc., etc.) apply.

The real world of Irish hydrogeology is a long way from fulfilling most of these conditions. In fact, the temptation is often to throw in the towel and assume that pumping tests cannot be analysed at all. However, despair is not the only option (though sometimes it may be the best!).

The objectives of pumping tests normally comprise some or all of the following:

- to estimate the sustainable yield of a well;
- to estimate aquifer properties including T and S and identify the presence of lateral or vertical boundaries to the aquifer system;
- to estimate any interference effects with other wells, springs or surface water bodies;
- to detect short-term variations in water quality during testing and to provide water samples for analysis;
- to investigate any changes in well performance over time due to, e.g., silting up, clogging of well screen, or reductions in regional or local water levels.

The tips below deal with some of the commonest problems in evaluating pumping tests (particularly in Ireland) as well as some of the commonest mistakes made.

1. Uses of Pumping Tests

Keep in mind that pumping tests are not only used (and useful) for estimating aquifer properties (T & S, etc.). In fact, values for T & S are not often required, or are required only as approximations. In Ireland, pumping test results are more often needed for estimating the sustainable pumping rate of a well or group of wells.

The principal hydrogeological use of pumping test data is, in fact, to assist in understanding the behaviour of the well and the aquifer. Before you dive into the procedures for deriving aquifer parameters, look at the graphs to try to understand what is going on in the well. It can often be helpful to have a graphical log of the well (strata and construction) alongside the drawdown curve (at the same scale).

2. Transmissivity (T)

There are now many more equations and methods available for estimating T and S than when I first learned Hydrogeology in the mid-sixties, when we were basically limited to the methods of Thieme, Theis, Jacob, Walton and Boulton. However, it remains the case that the main methods used by most people remain the 'Straight-Line' methods, using semi-log graphs of time-drawdown and recovery data. The reason is easy to see – they are simple and they seem to work. However, in their very simplicity lies their pitfall, and I have seen these methods abused wherever I have worked.

- For a reliable T value, measurements in a suitably located and constructed observation well are almost essential.

- The Jacob method is derived directly from the Theis formula, and there is a **vital** proviso: the value of the function 'u' MUST be small. Textbooks differ on how small it must be – Davis & De Wiest (1966), Krusemann & de Ridder (1970), Bouwer (1978) and Reeves (1986) say less than 0.01, while Driscoll (1986) and Fetter (1994) say less than 0.05. This happens when 't' is large and/or 'r' is small. For example, where 'r' is 20m, 'T' is 100m²/d and 'S' is 0.2, 't' must be about 12 hours or more. Although 'u' will almost always **appear** to be small enough in a pumping well (because 'r' is very small, 0.1m) in practice the early time data will usually be hugely influenced by well losses. Therefore, ONLY use later time data for Jacob analyses, and work out the 'u' value threshold for **your** particular test.
- Don't try to draw straight lines through all parts of the drawdown graph which appear to approach a straight line, often leading to multiple estimates of 'T'. Multiple gradients can only be justified where there are clear hydrogeological grounds – where boundary conditions (Barrier or Recharge) are suspected, or a clear horizontal variation, e.g. gravels above a poorer bedrock aquifer. In these conditions, be careful – the apparent 'T' value after a barrier has been reached will not be correct, while a gravel layer will probably have a different 'T' value from that of the underlying rock.
- Beware of jumping to the conclusion of a barrier boundary – sharp increases in the drawdown curve are much more likely to result from horizontal layering, or a gradual reduction in permeability with depth, than from vertical barriers.
- If different methods of analysis produce markedly different 'T' values, don't just attempt to average them. Think about why you are getting different values. What assumptions are being made? Where errors are most likely to be introduced? Why might one or another method be inappropriate?

3. Recharge

Irish aquifers are normally unconfined. This means that (a) extended pumping will tend to reduce the (saturated) aquifer thickness and thereby reduce the Transmissivity, and (b) many pumping tests are affected by recharge, especially if they take place in a wet period. Recharge is most likely to exhibit itself towards the end of the test, when the incremental drawdown is small compared with recharge rates. Look out for flattening or reversal of the drawdown curve, and for a recovery curve which extends back to a level above that of the initial static water level (before pumping). Recharge can be allowed for if you have water level monitoring data for a well in the same aquifer, outside the cone of depression, and the test drawdown data can be corrected. A possible alternative approach is to apply a linear correction for all drawdown data over the period of recharge, i.e. take the amount of 'excess recovery' and distribute the error over the recharge period. Recharge will particularly affect any estimates of aquifer properties derived from the recovery curve.

4. Pumping Rate (Q)

Classical pumping test analysis assumes that the pumping rate remains constant throughout a test. In practice, this rarely happens. Positive-displacement pumps (i.e. piston pumps or Mono-type pumps) can maintain a constant rate (and for this reason their pumping rate must be controlled through their engine speed and not through a gate valve on the outlet) but most tests in Ireland use a submersible pump. Submersibles operate on the suction principle and their pumping rates decrease as the head (i.e. drawdown) increases. Different pumps have different head-discharge relationships which can be examined in the manufacturer's literature. Fortunately, the reduction in pumping rate is normally small after the early part of the test.

In addition, many tests are carried out without hydrogeological supervision and the supervisor often 'plays around' with the pumping rate during the test, perhaps because it is clear that the initial rate is unsustainable, or alternatively because it becomes clear that the well can yield more than expected. Making hydrogeological sense of such a test may be difficult, but is often not impossible.

For Recovery analysis, the pumping rate over the entire period of the test should be averaged. This should be done on a time basis, i.e. calculate the total volume of water pumped and divide it by the total time.

For any other analyses, don't attempt to average the pumping rate over the test. Look for periods of relatively constant pumping rate, e.g. estimate a Jacob straight-line gradient over a single period when the rate was constant. In deriving a specific capacity, use the discharge rate and drawdown at the end of a period where the rate was relatively constant.

5. Storativity (S)

Classical pumping test analysis includes formulae for deriving 'S' values, using observation well data only. In practice, this is much more difficult than deriving reasonable 'T' values, particularly because 'S' is much more sensitive to deviations from ideal conditions. Storativity values from pumping tests need to be regarded sceptically.

6. Permeability (k)

In theory, a value for permeability or hydraulic conductivity ('k') can be derived by dividing the 'T' value by the aquifer thickness (D). In practice, however, the permeability can vary hugely with depth, and it is likely that the permeability of the most critical layers (e.g. in estimating a maximum groundwater velocity) will be significantly higher than the value derived from $T = k.D$.

7. Specific Capacity (SC)

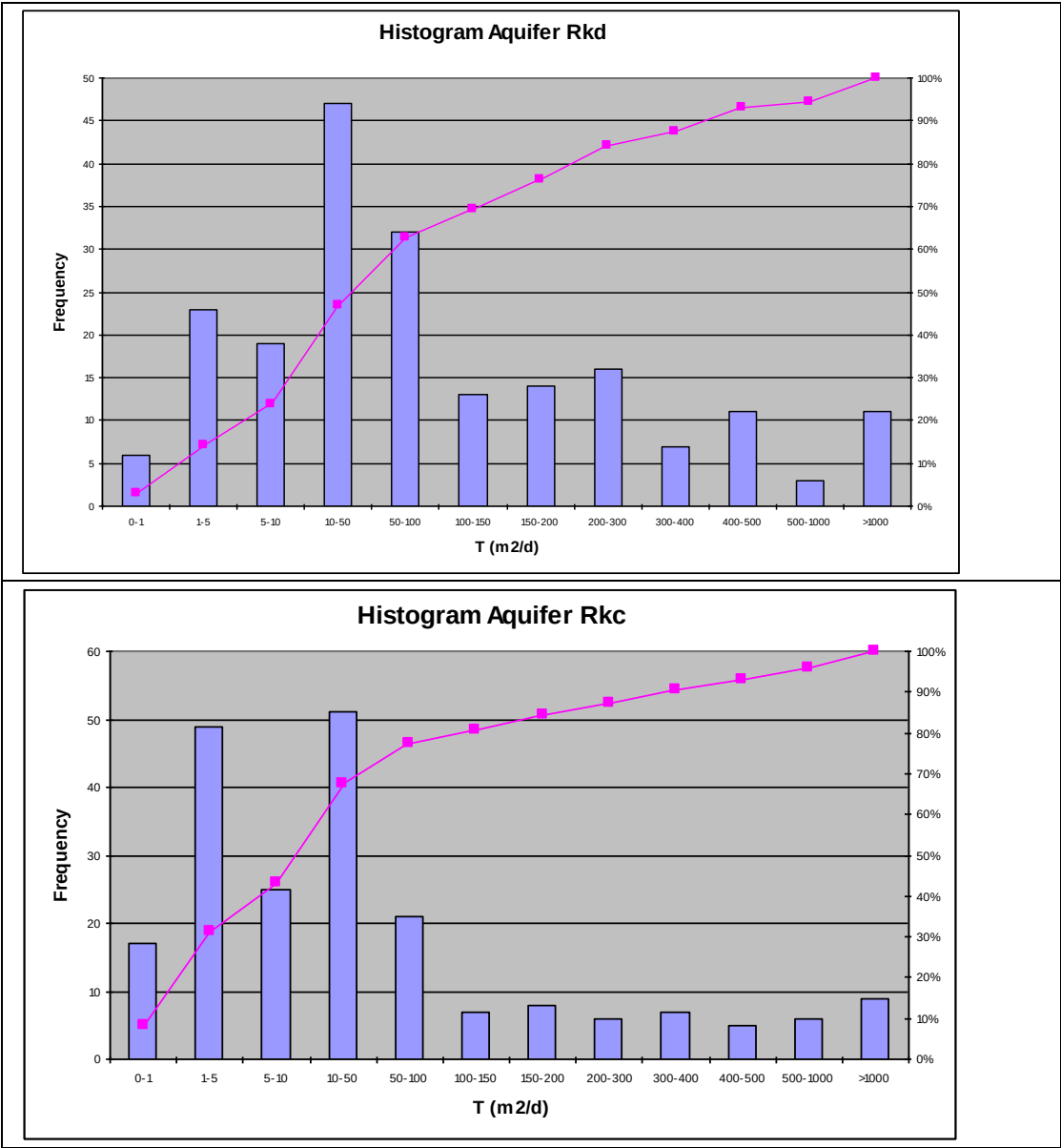
SC is a very useful parameter, particularly because it can be derived from a test even when the lack of a constant pumping rate precludes deriving any reliable T or S data. And from a decent SC value you can derive an approximate T value via the Logan approximation (Logan, 1964; Misstear, 2001). It can also be used to derive 'Productivity' categories (Wright, 2000). However, remember that:

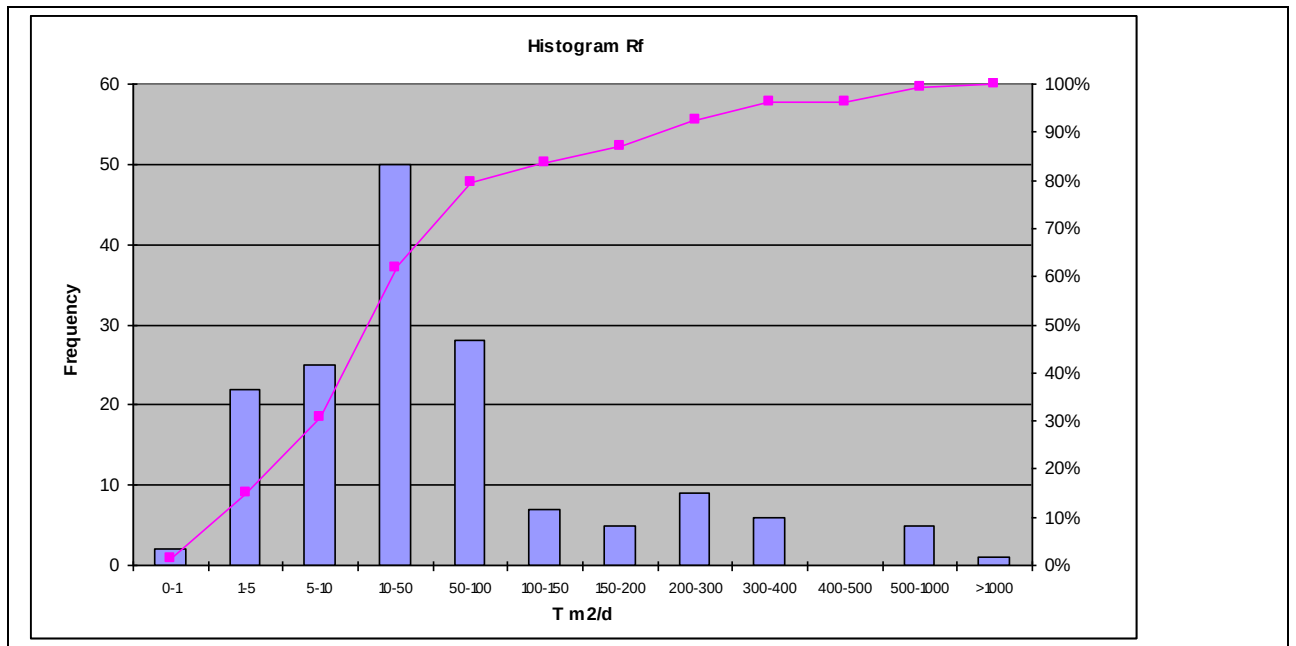
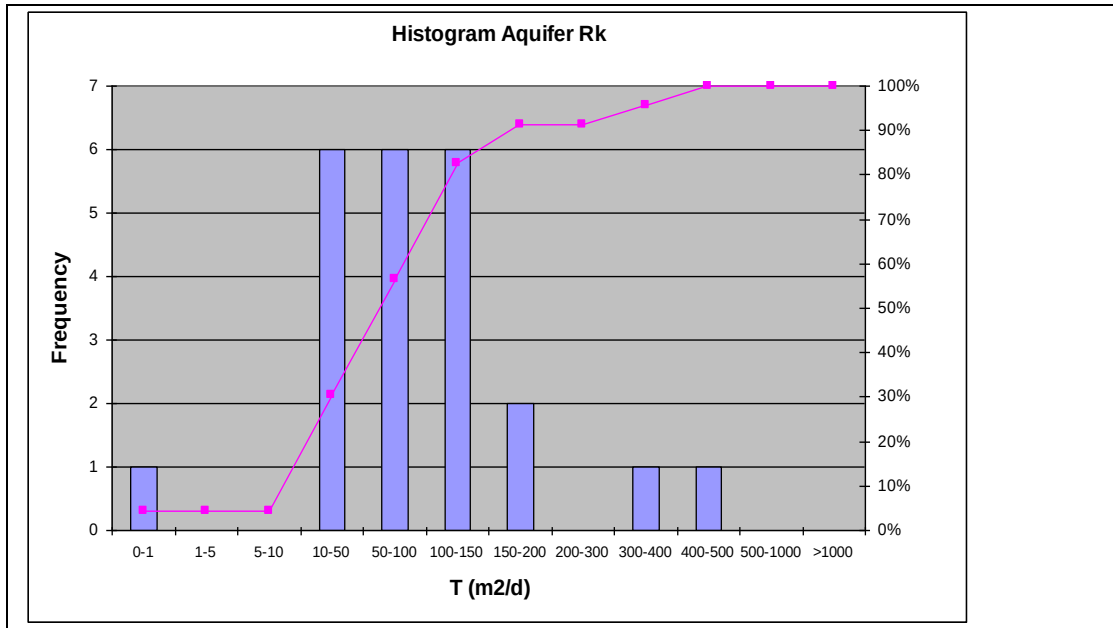
- SC is supposed to represent the well at equilibrium, i.e. when drawdown has stabilised.
- If you have a relatively smooth drawdown curve (which should fit a Jacob straight line) you can extrapolate it (to a reasonable degree) to, say, 10,000 minutes (about one week) and estimate the likely drawdown at that time.
- However, if drawdown is showing signs of continuously increasing, then any such extrapolation is best avoided. This situation is quite common in Irish aquifers.
- In unconfined aquifers (which includes the great majority of Irish aquifers) the specific capacity will vary seasonally, being highest in winter/spring when the water table is high and the saturated zone at its maximum, and lowest in summer/autumn, when the opposite is true. This difference will vary most where the water table fluctuates most.
- SC will also vary with the pumping rate. However, in confined aquifers the gradient is much less (theoretically there should be no gradient at all, but well losses complicate the picture).

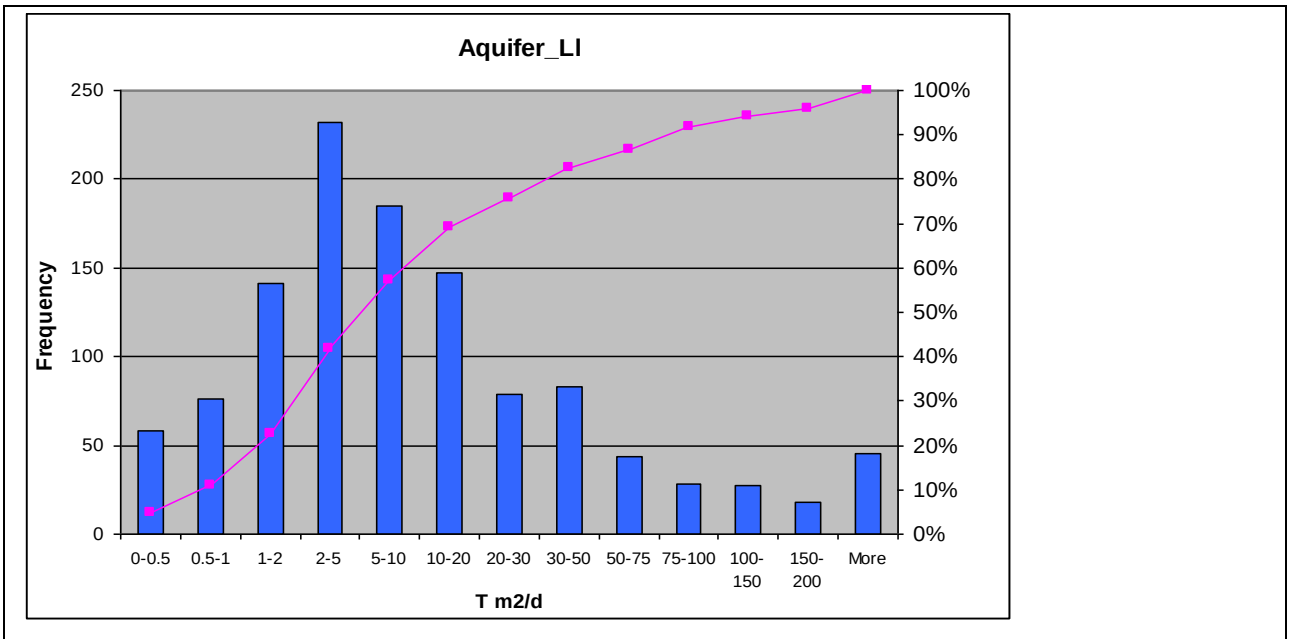
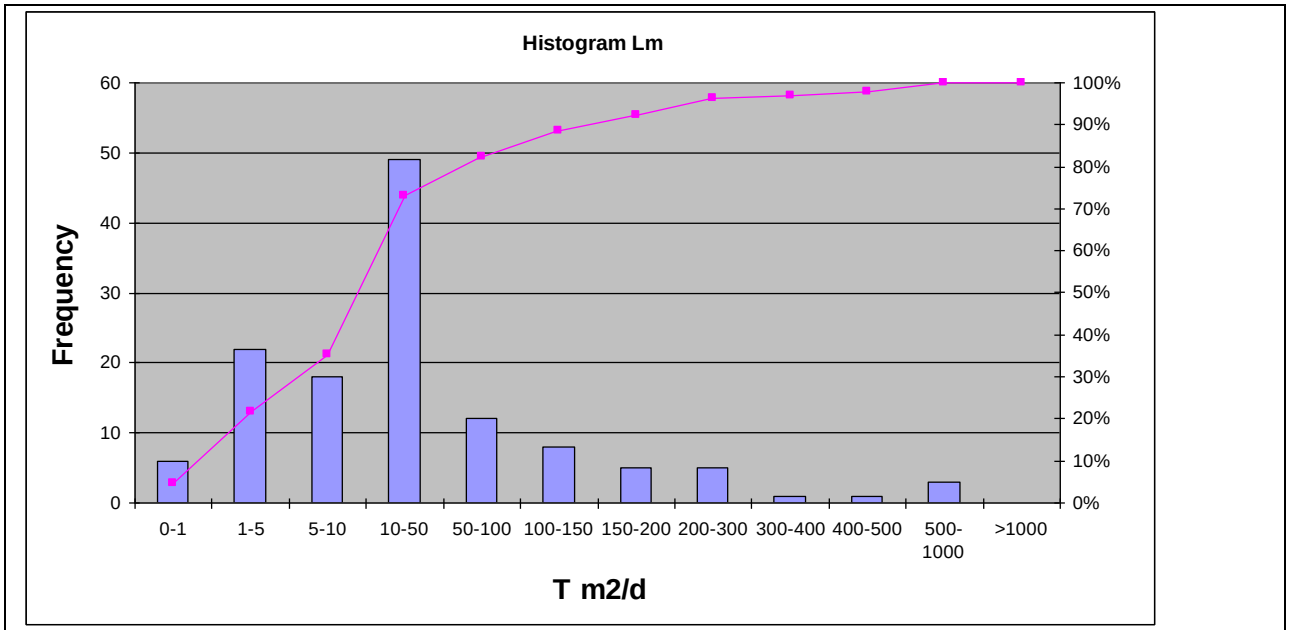
Finally, remember that a single pumping test, even with the benefit of observation wells, still represents only a relatively small part of an aquifer. If there is a choice to be made between carrying out an extensive test on one well or simpler tests on a number of wells, the latter will usually give you a more representative picture of the nature of the aquifer.

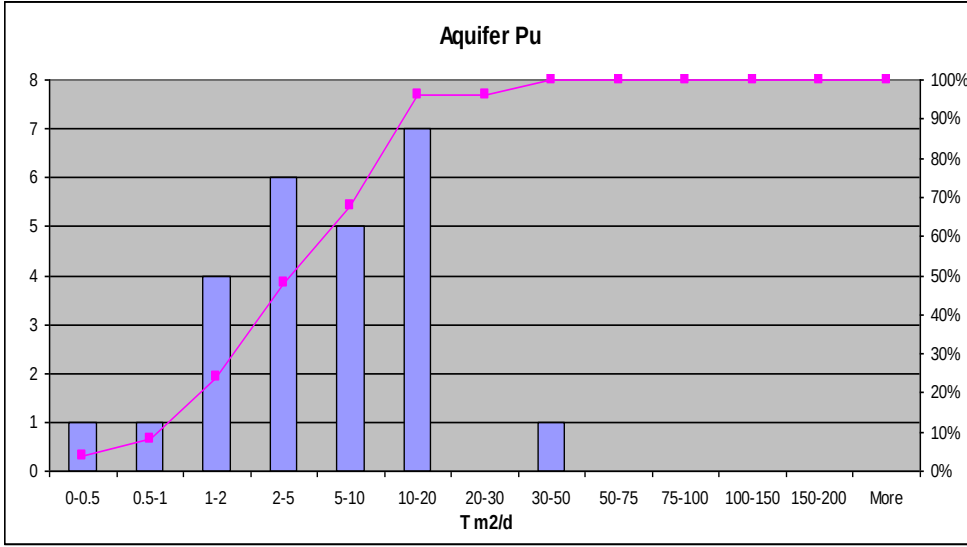
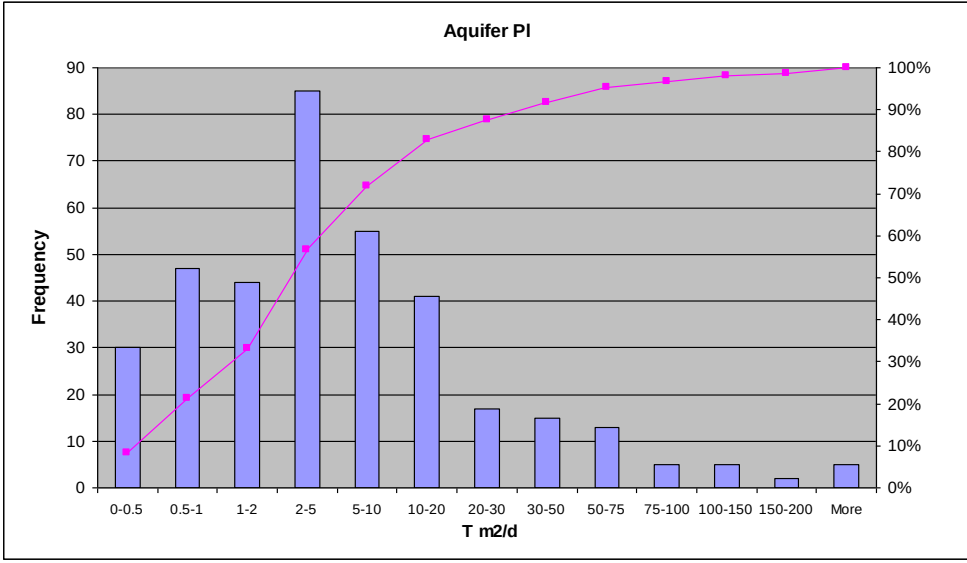
For more details of how pumping tests should be carried out you could do worse than read our GSI Information Circular (Wright, 1985).

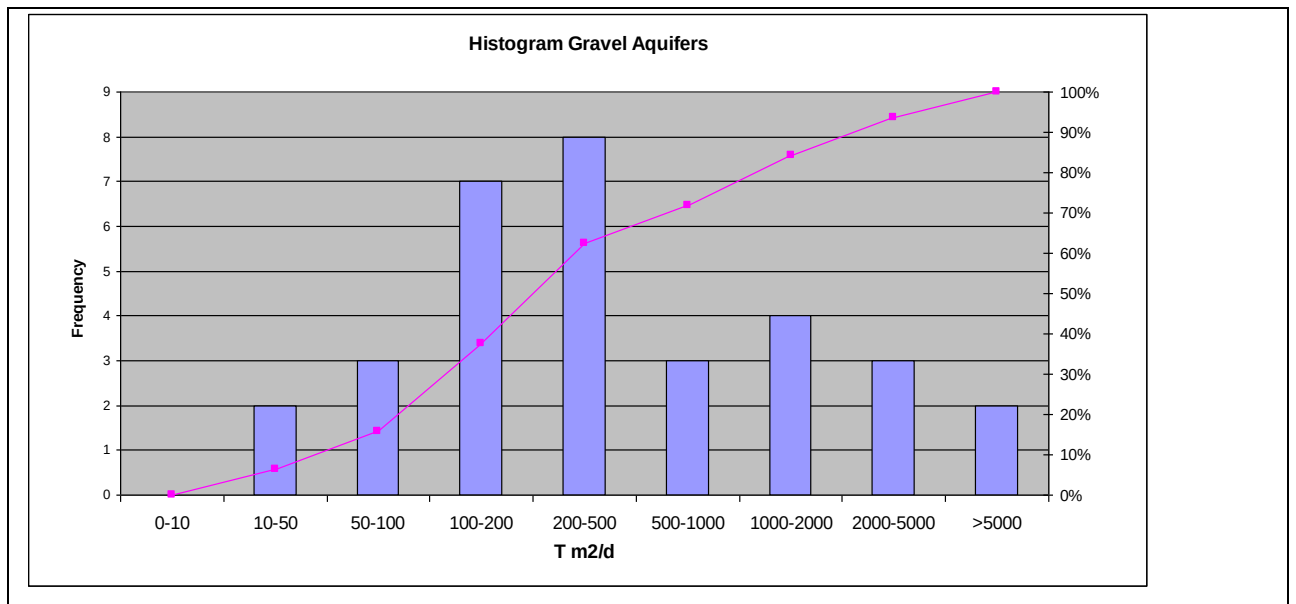
APPENDIX 4 AQUIFER HISTOGRAMS











Individual Histogram for the Gravel aquifers

APPENDIX 5 RUG HISTOGRAMS

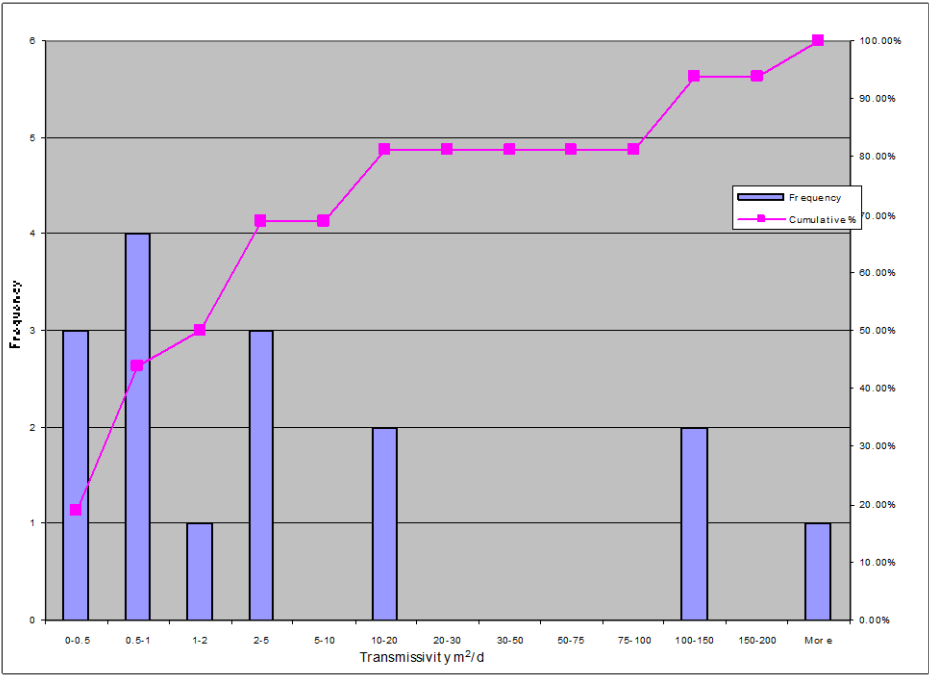


Figure 34 Transmissivity Histogram for the Precambrian Marbles

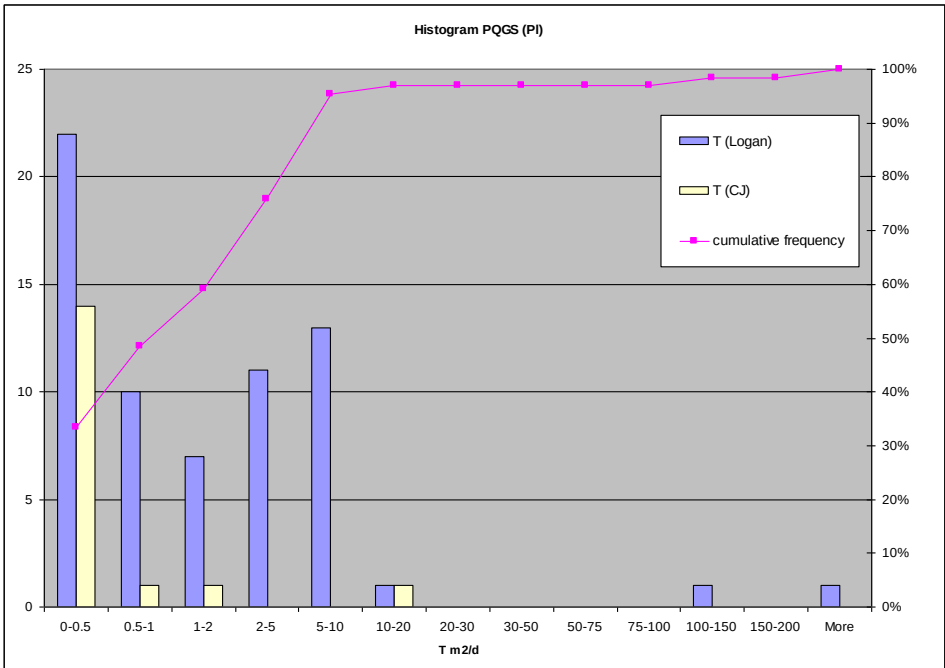


Figure 35 Transmissivity Histogram for the Precambrian Quartzites, Gneisses and Schists

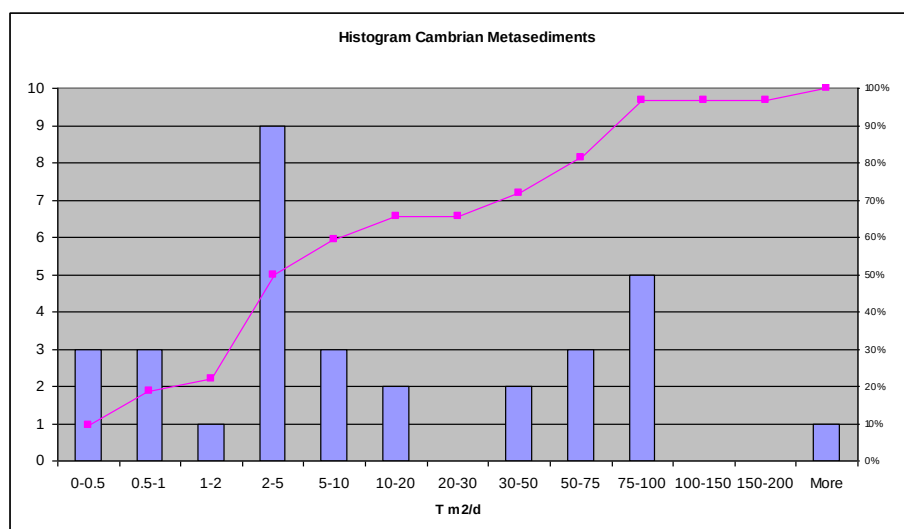


Figure 36 Transmissivity Histogram for the Cambrian Metasediments

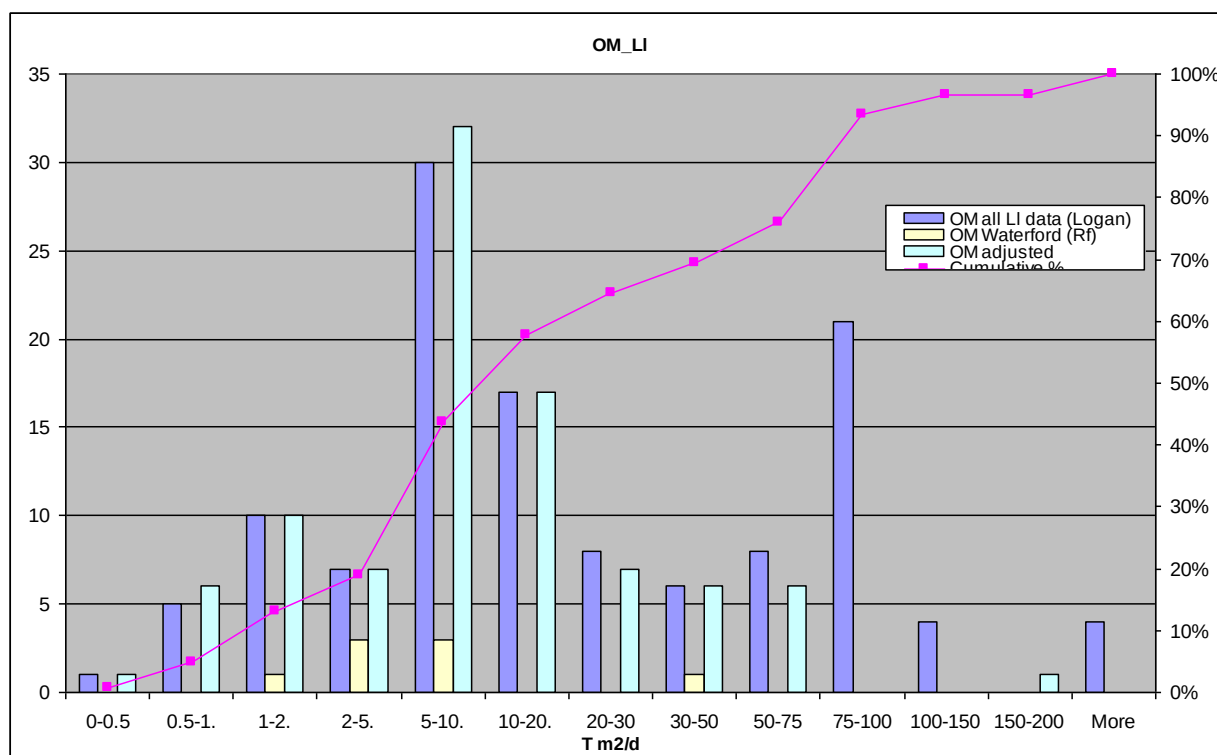


Figure 37 Transmissivity Histogram for the Ordovician Metasediments classed as LI

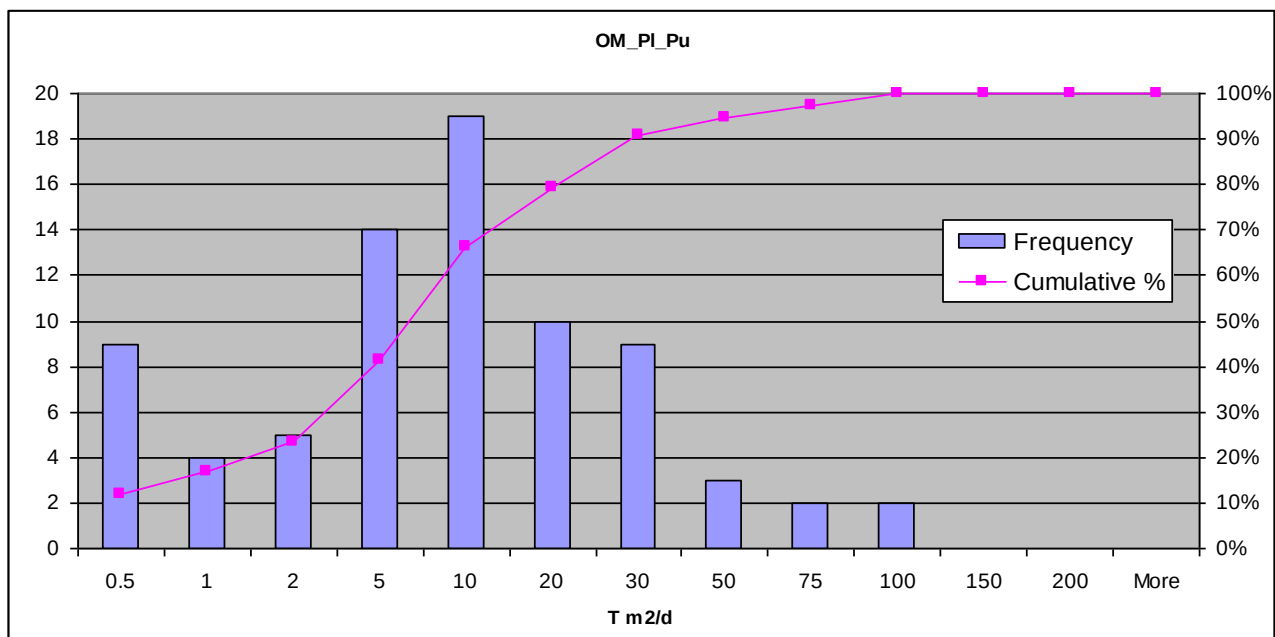


Figure 38 Transmissivity Histogram for the Ordovician Metasediments classed as Pl

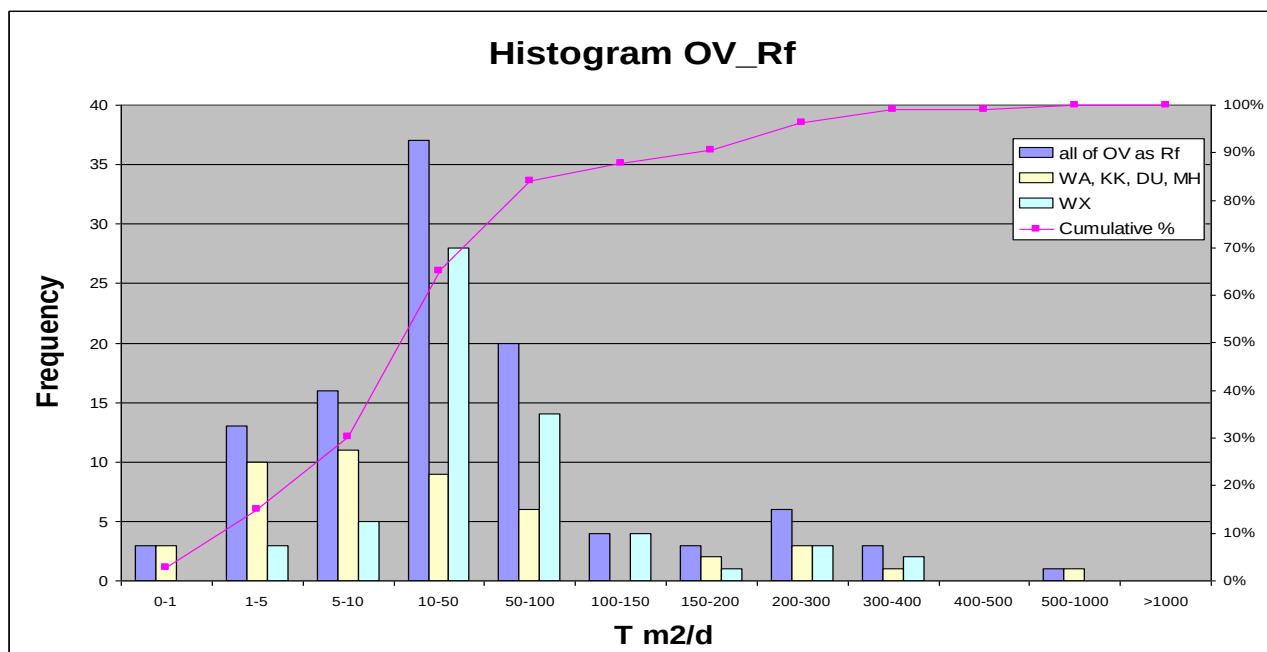


Figure 39 Transmissivity Histogram for the Ordovician Volcanics (Rf), showing the RUG as a whole and the contrast in T across the group mainly in Waterford, Kilkenny and the group in Wexford

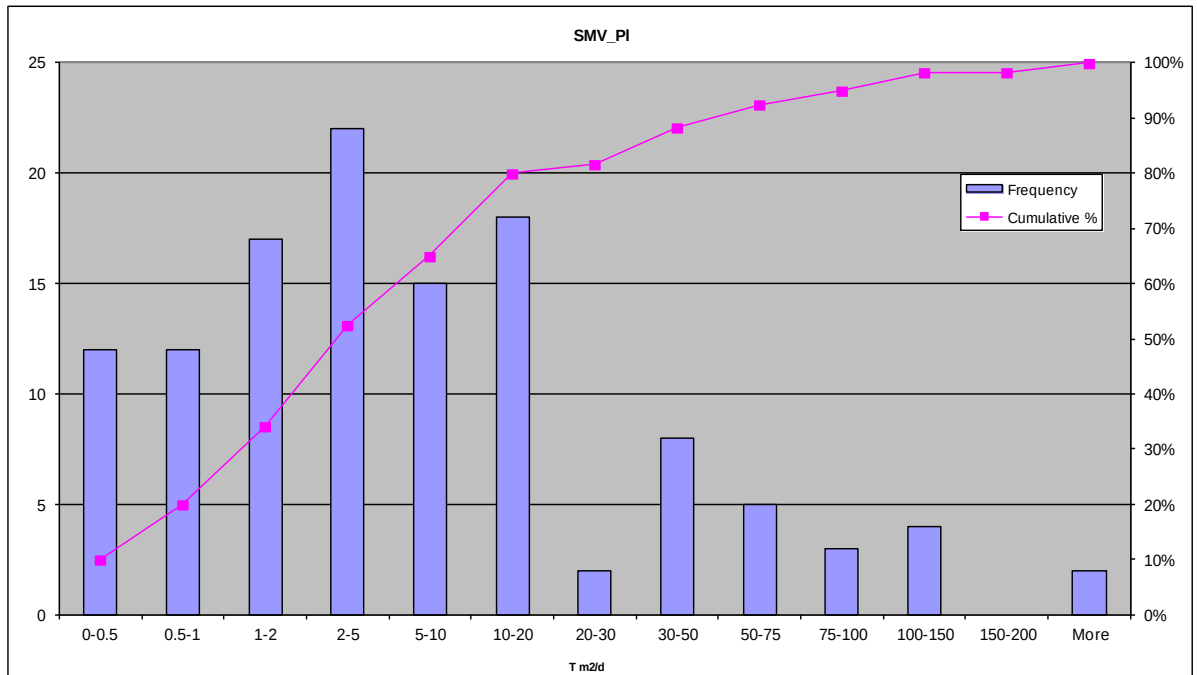


Figure 40 Transmissivity Histogram for the Silurian Metasediments and Volcanics (SMV RUG)

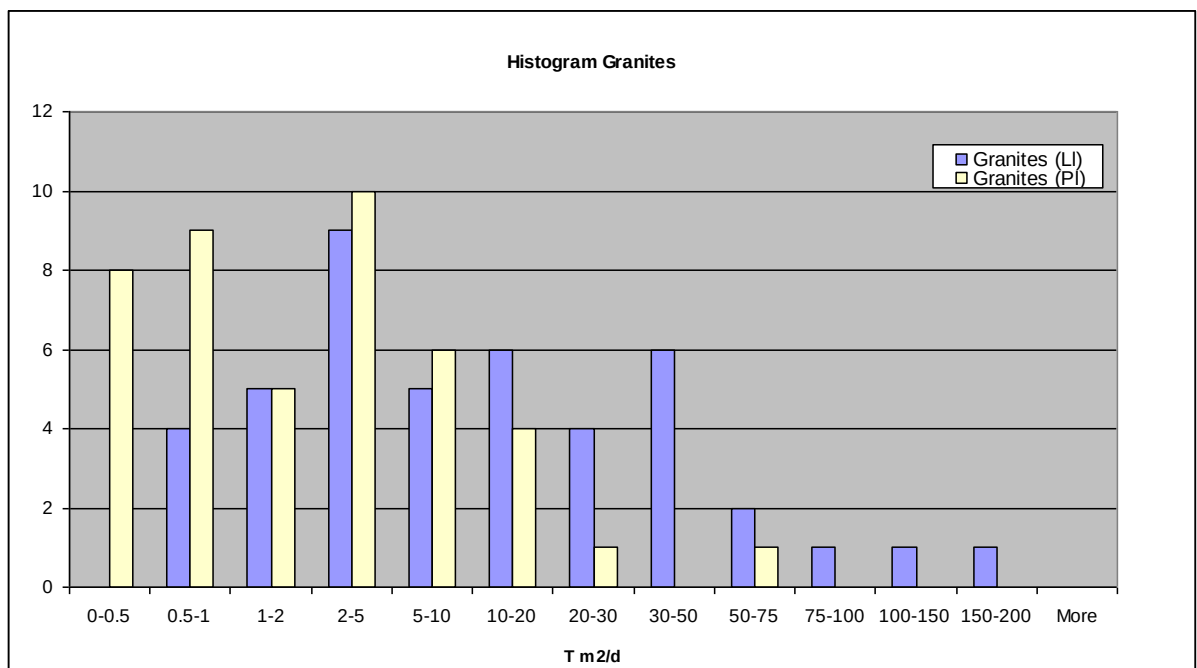


Figure 41 Transmissivity Histogram Granites

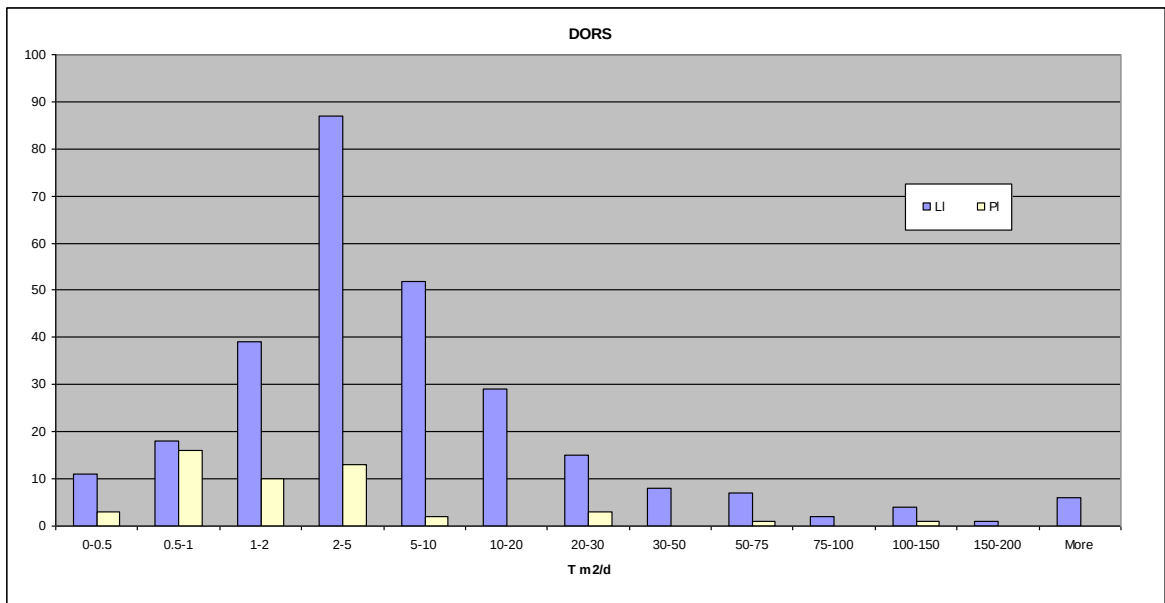


Figure 42 Transmissivity Histogram DORS

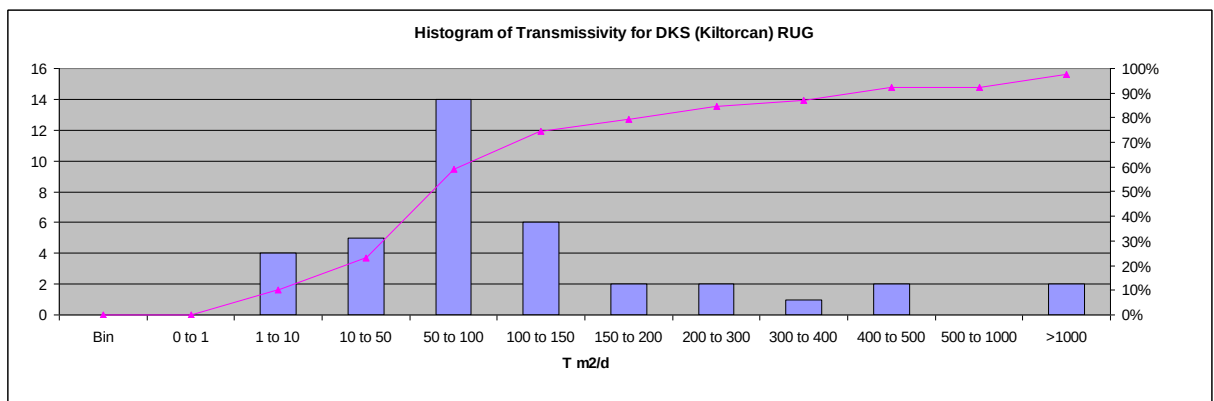


Figure 43 Transmissivity Histogram DKS

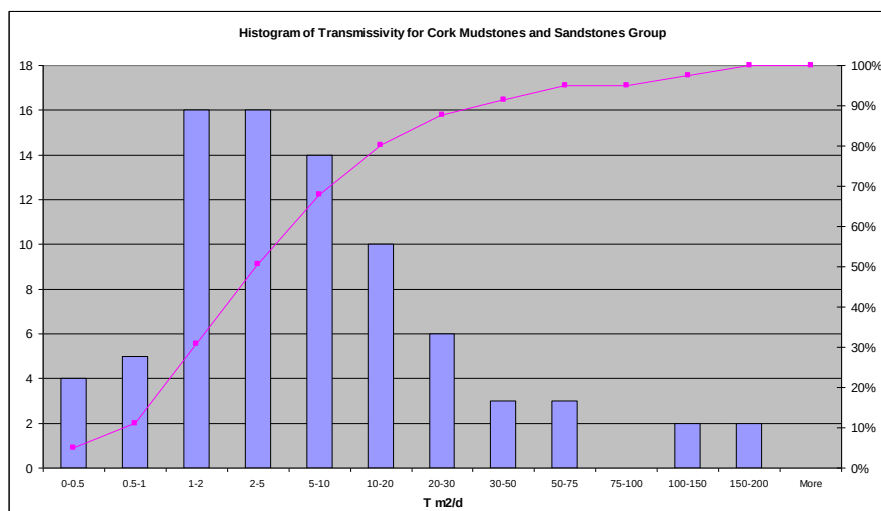


Figure 44 Transmissivity Histogram DMSC

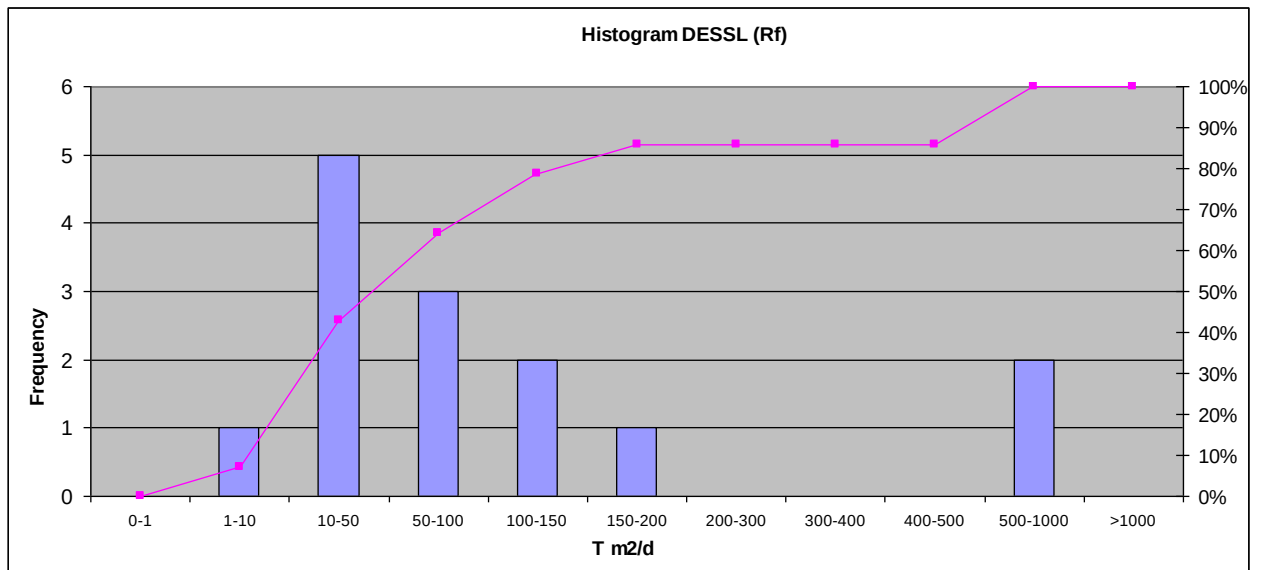


Figure 45 Transmissivity Histogram DESSL (Rf)

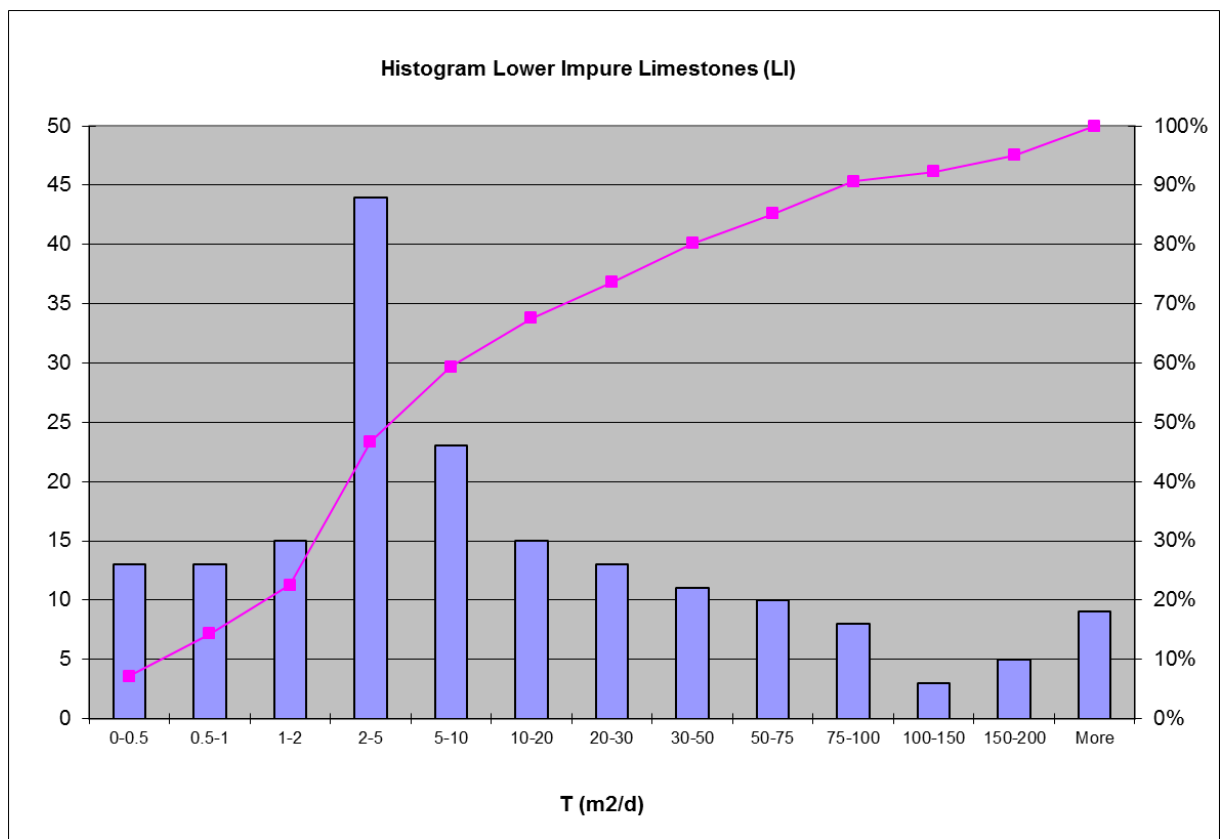


Figure 46 Transmissivity Histogram DLIL (LI)

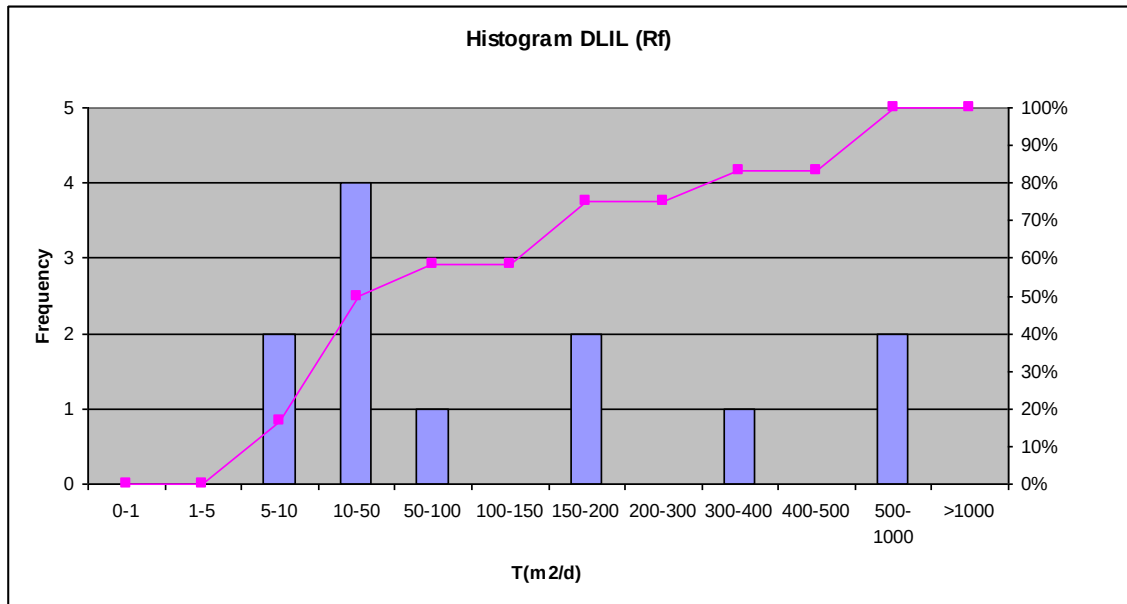


Figure 47 Transmissivity Histogram DLIL (Rf)

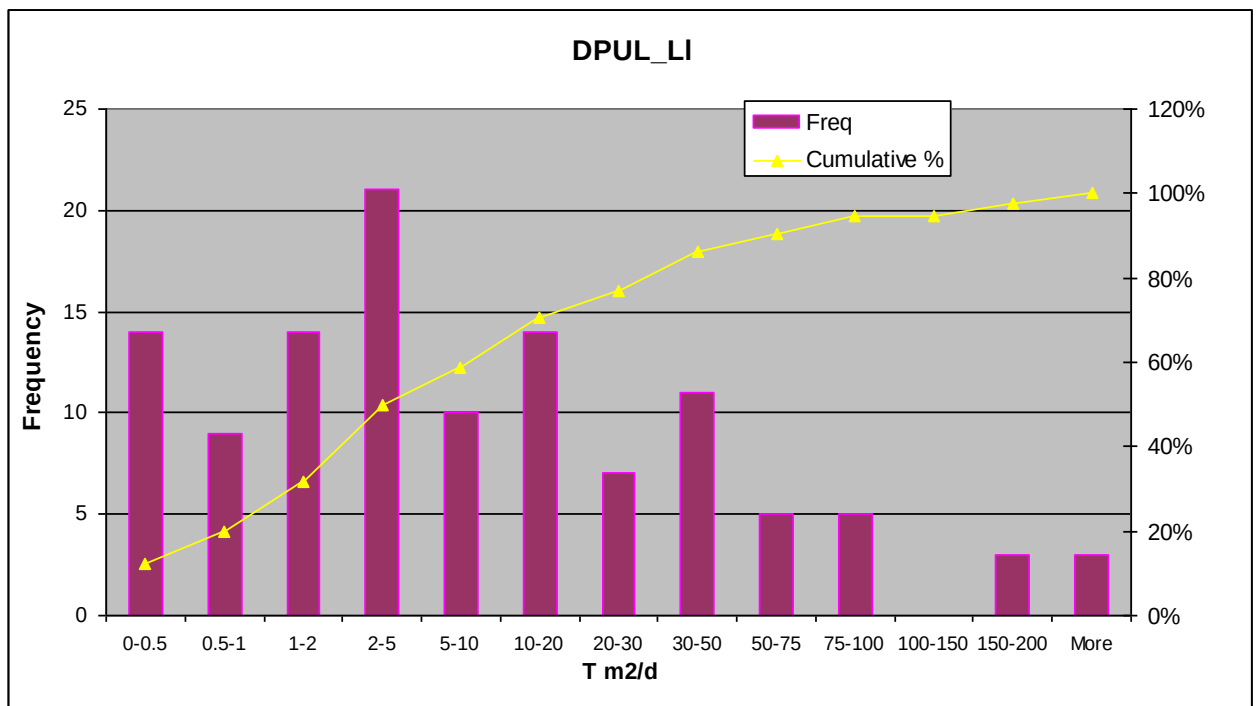


Figure 48 Transmissivity Histogram DPUL

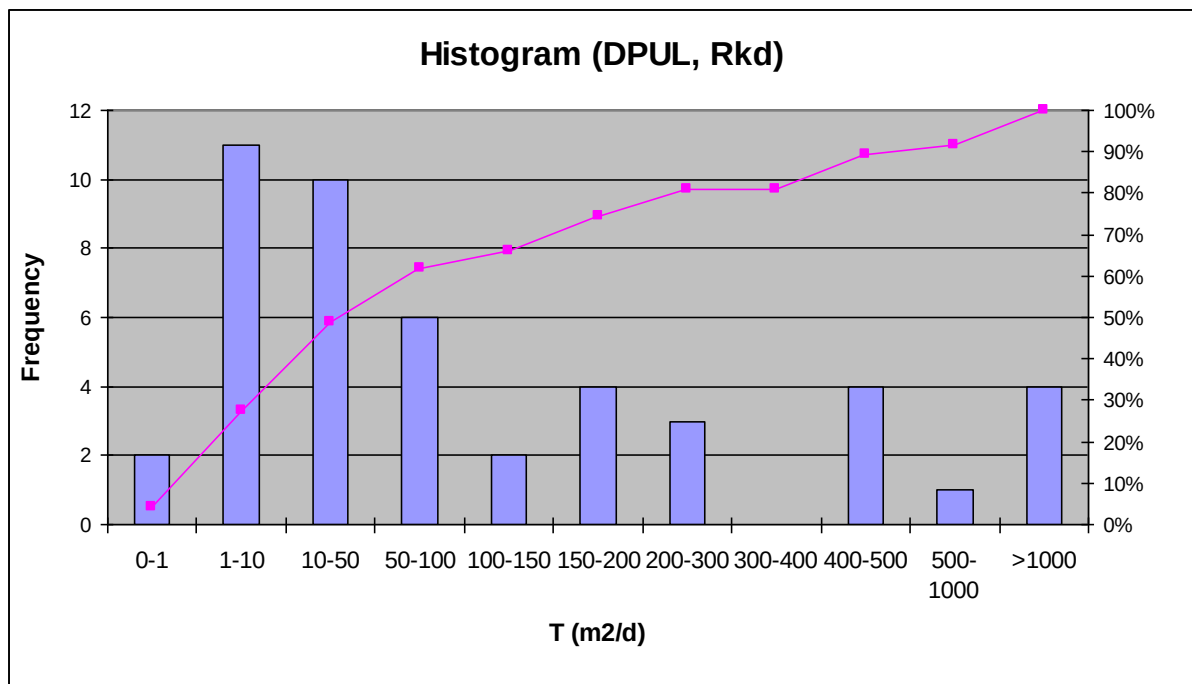


Figure 49 Transmissivity Histogram DPUL (Rk^d)

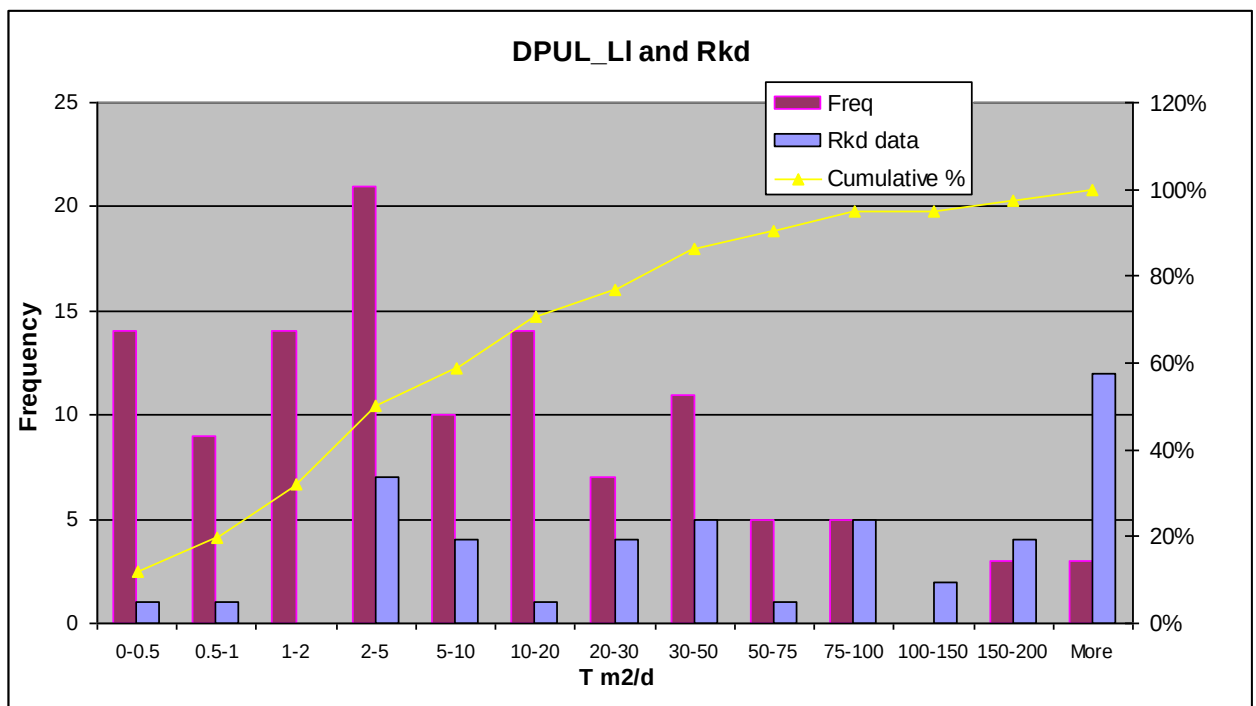


Figure 50 Transmissivity Histogram DPUL (LI and Rk^d using same bin range)

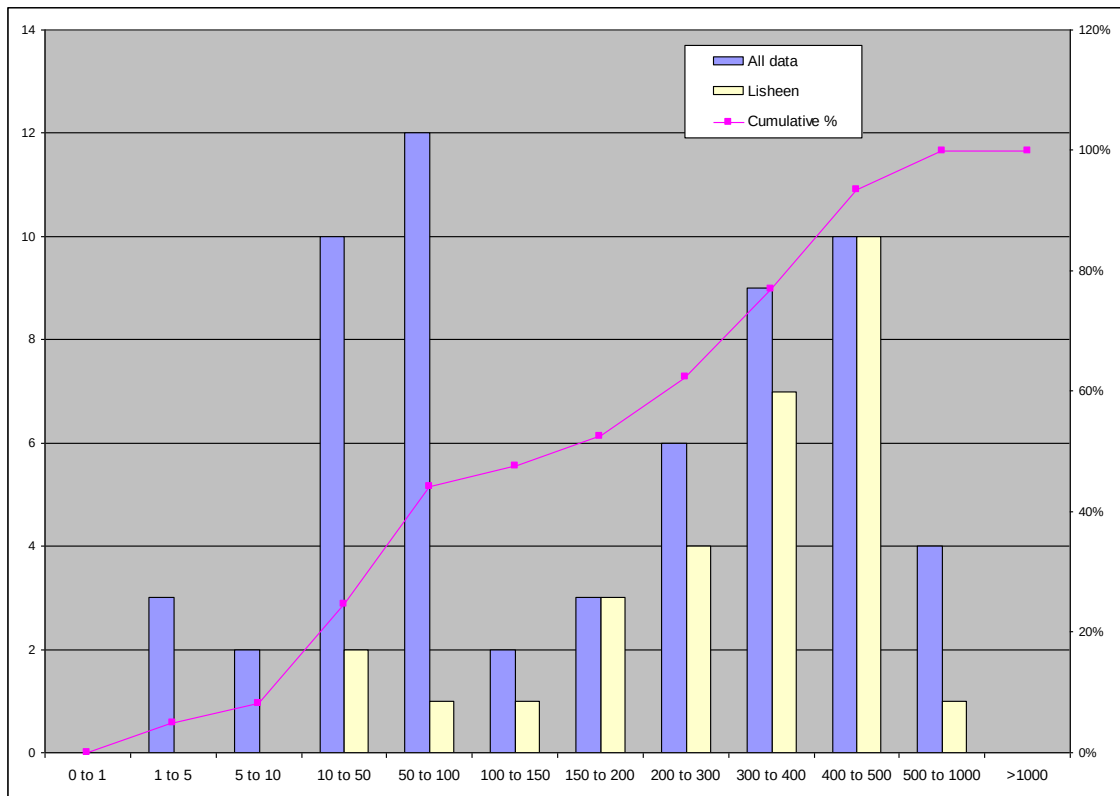


Figure 51 Transmissivity Histogram distinguishing Lisheen data

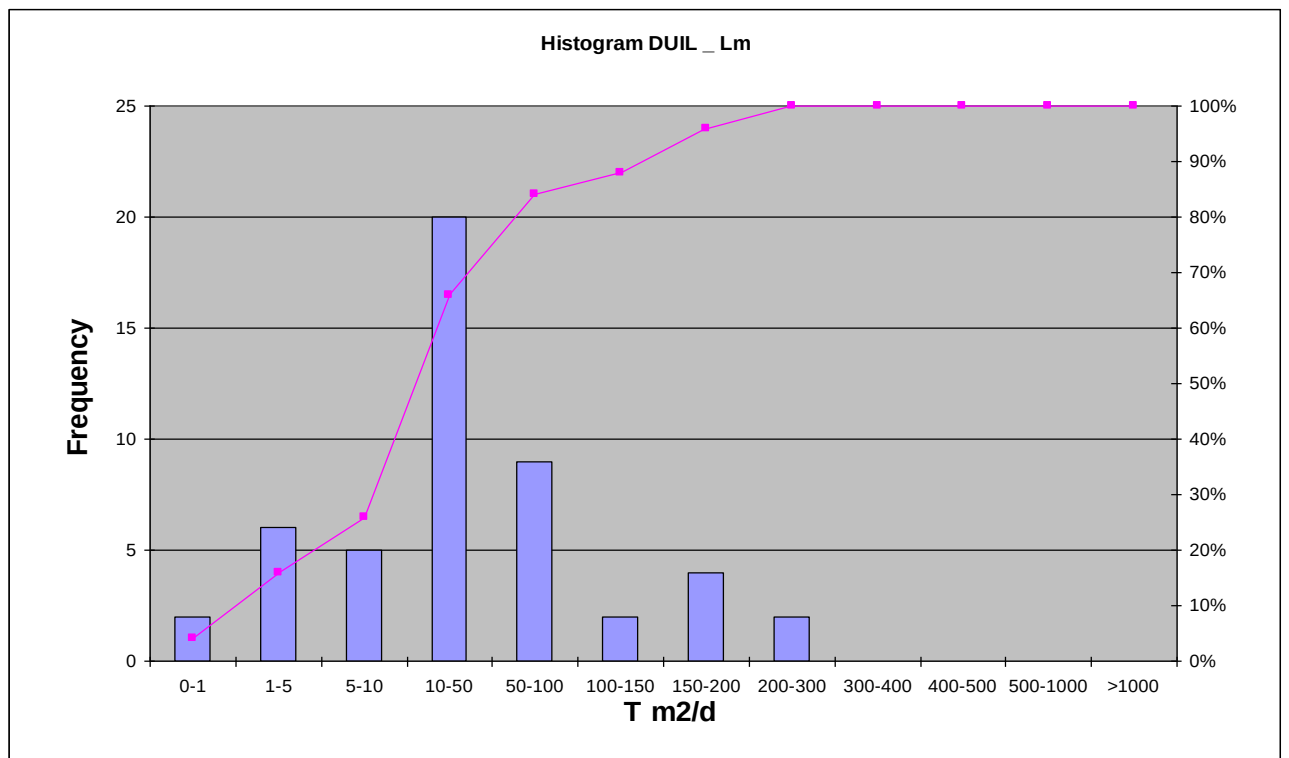


Figure 52 Transmissivity Histogram DUIL classed as Lm

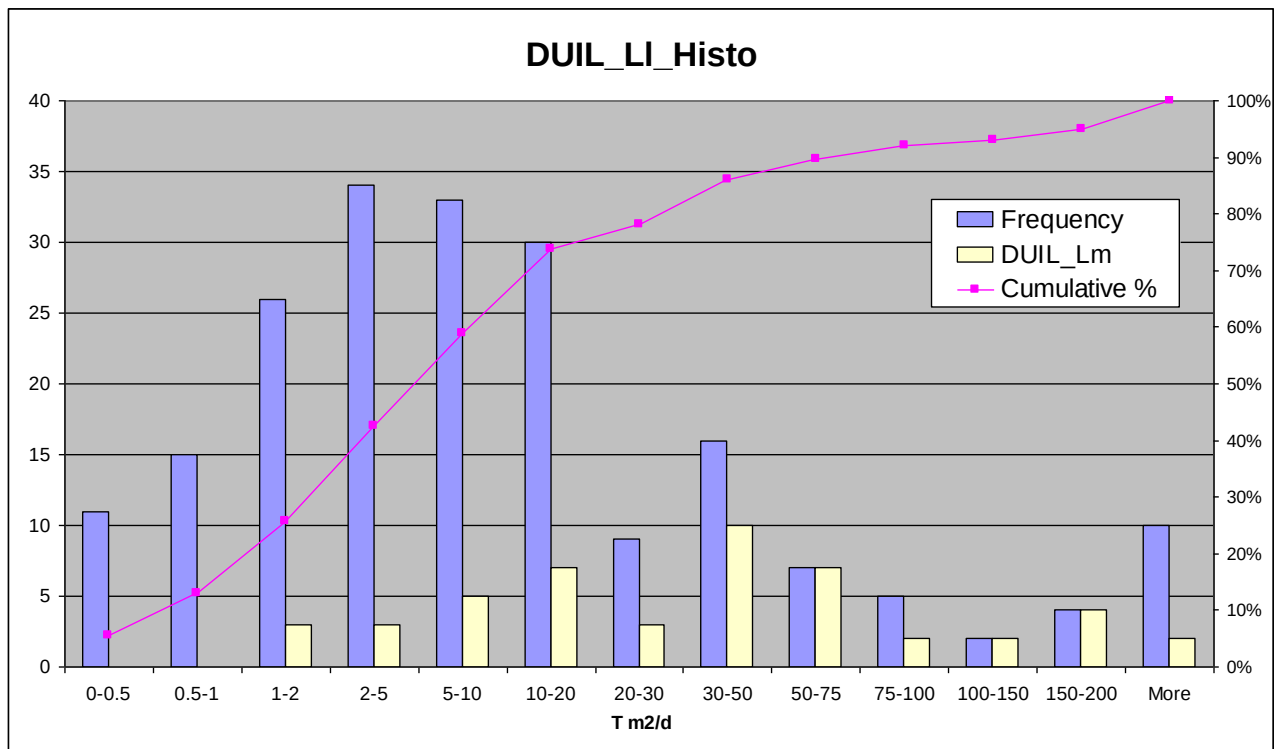


Figure 53 Transmissivity Histogram DUIL classed as LI (data where classed as Lm is also included for comparison)

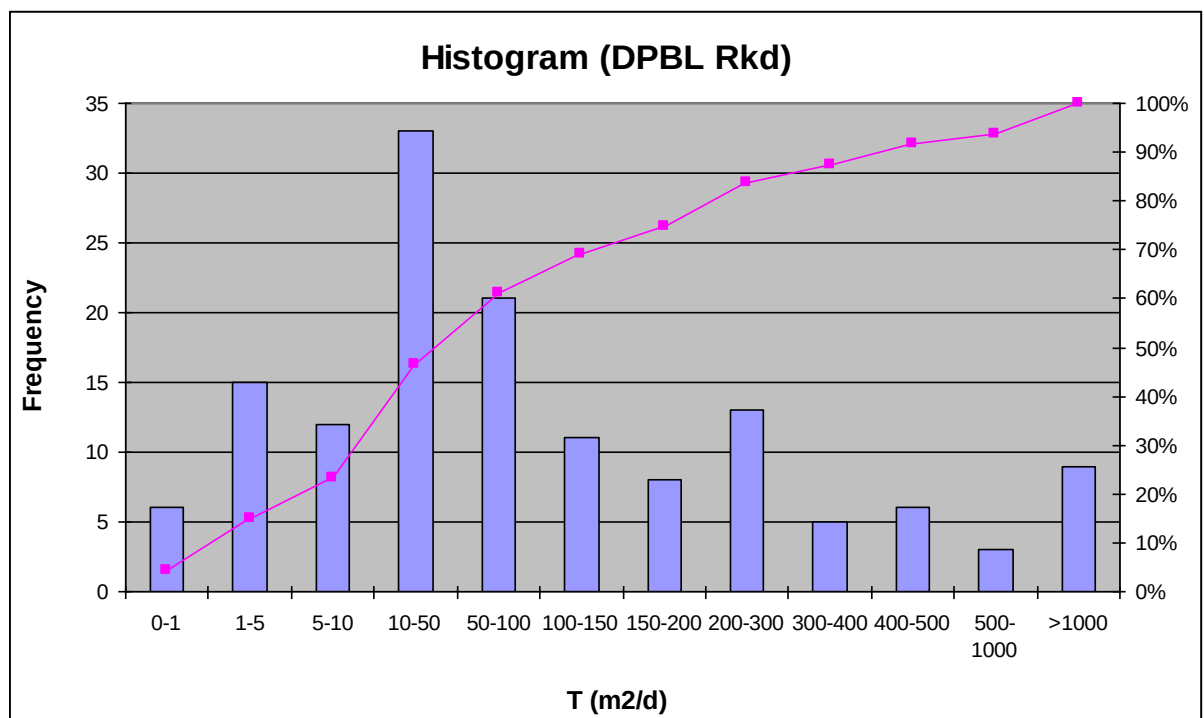


Figure 54 Transmissivity Histogram DPBL classed as Rk^d

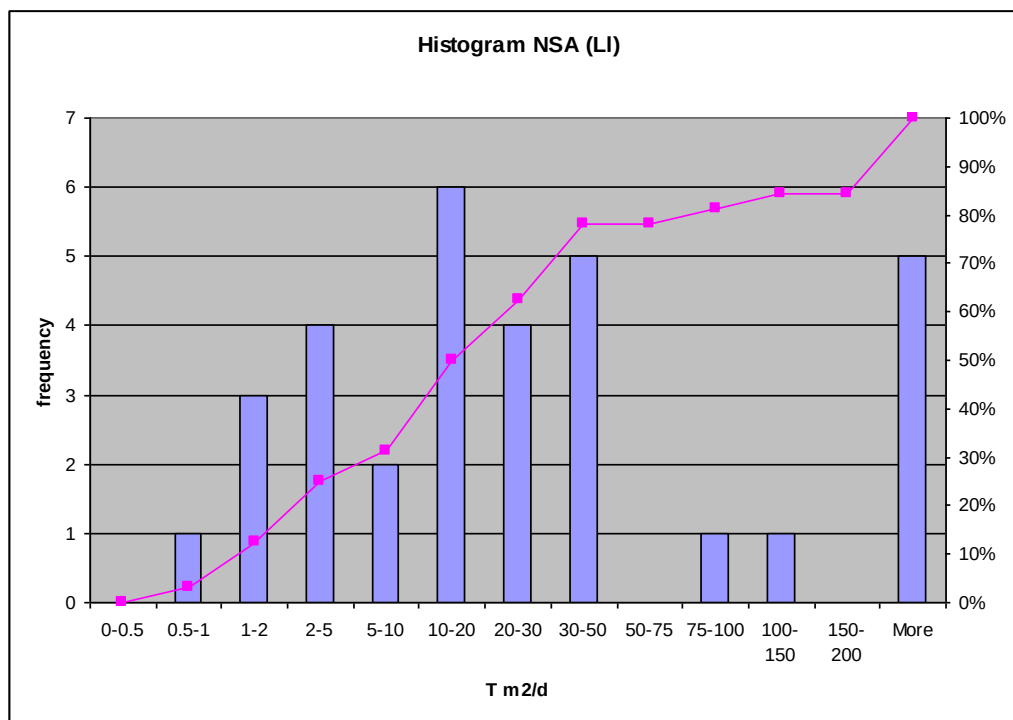


Figure 55 Transmissivity Histogram Namurian Sandstones classed as LI

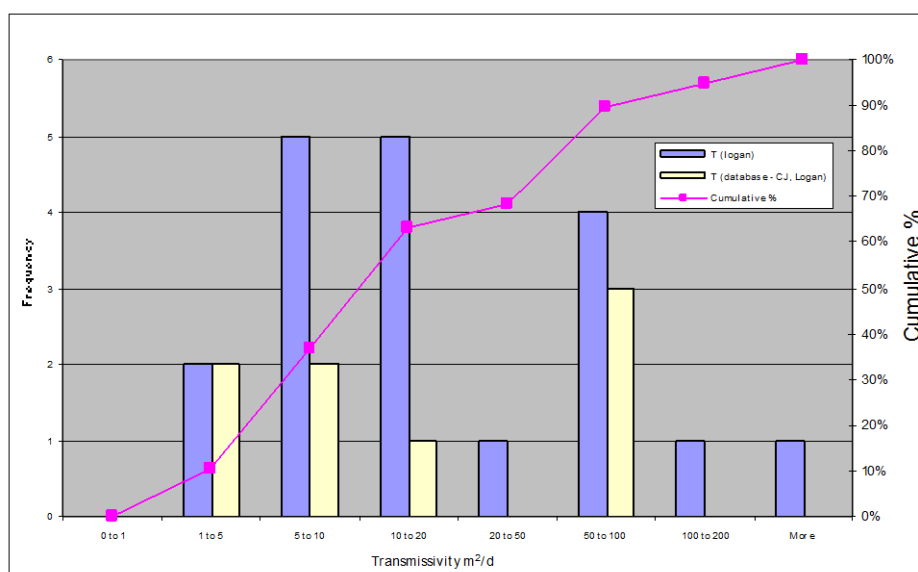


Figure 56 Transmissivity Histogram Westphalian Sandstones Rock Unit Group

