County Cavan
Groundwater Protection Scheme

Volume I: Main Report

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Executive Summary

The Groundwater Protection Scheme for Cavan County Council provides a preliminary assessment of the relative risk to groundwater quality across the county. The main elements of the risk assessment are groundwater vulnerability (primarily subsoil thickness, subsoil permeability and karst features), aquifer potential, and source protection. The source protection element involves the delineation of protection areas around the recharge areas for selected public and group scheme groundwater supplies.

The results can not be used as a substitute for site investigation for particular developments, but have proved very useful in providing County Councils with an independent, defensible, planning tool for a wide range of new developments:

- Major developments (e.g. for landfill site selection, developments requiring waste management and integrated pollution licensing): helping to short-list suitable sites for detailed site investigation.

- Minor developments (e.g. domestic wastewater treatment systems): helping to prioritise the allocation of Local Authority planning staff resources.

The main output of the Protection Scheme is a digital Geographic Information System which is designed to be compatible with existing Cavan County Council planning tools. It provides 'Groundwater Protection Responses' for all areas of the county. These responses incorporate the potential hazard posed by selected activities with the vulnerability, aquifer and source protection assessments to provide site suitability guidance for all areas of the county. The activities in question currently include landfill, IPC landspreading of piggery/poultry wastes, and domestic wastewater treatment systems. Responses for fuel service stations and earth lined stores are currently being developed. The responses are developed through a collaboration of the Geological Survey of Ireland, the EPA and the Department of the Environment, Heritage and Local Government.

An additional output comprises paper maps of the protection scheme, and two report volumes. Volume I outlines the basis for the vulnerability and aquifer zones delineated in the paper maps and GIS. Explanations include assumptions made, calculations/data sources used, and limitations. Volume II examines the groundwater chemistry in County Cavan and outlines the basis for the source protection zones delineated in the maps and GIS. Again, the text includes assumptions made, calculations and data sources used, and limitations.

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1. Introduction

1.1 Groundwater Protection – A Priority Issue for Local Authorities

The protection of groundwater quality from the impact of human activities is a high priority for land-use planners and water resources managers. This situation has arisen because:

- Groundwater is an important source of water supply.
- Human activities pose increasing risks to groundwater quality: there is widespread disposal of domestic, agricultural and industrial effluents to the ground, and volumes of waste are increasing.
- Groundwater provides the baseflow to surface water systems, many of which are used for water supply and recreational purposes. In many rivers, more than 50% of the annual flow is derived from groundwater and more significantly, more than 90% can comprise groundwater in summer. If groundwater becomes contaminated, the rivers can also be affected and so the protection of groundwater resources is an important aspect of sustaining surface water quality.
- Groundwater generally moves slowly through the ground and so the impact of human activities can last for a relatively long time.
- Polluted drinking water is a health hazard and once contamination has occurred, drilling of new wells is expensive and in some cases not practical. Consequently 'prevention is better than cure'.
- Groundwater may be difficult to clean up, even when the source of pollution is removed.
- Unlike surface water where flow is in defined channels, groundwater is present everywhere.
- EU policies and national regulations are requiring that polluting discharges to groundwater must be prevented as part of sustainable groundwater quality management.

1.2 Groundwater – A Resource at Risk

Groundwater as a resource is under increasing risk from human activities, for the following reasons:

- Lack of awareness of the risks of groundwater contamination, because groundwater flow and contaminant transport are generally slow and neither readily observed nor easily measured.
- Contamination of wells and springs.
- Widespread application of domestic, agricultural and industrial effluents to the ground.
- Generation of increasing quantities of domestic, agricultural and industrial wastes.
- Increased application of inorganic fertilisers to agricultural land, and usage of pesticides.
- Greater volumes of road traffic and more storage of fuels/chemicals.
- Manufacture & distribution of chemicals of increasing diversity and often high toxicity, used for a wide range of purposes.

The main threats to groundwater are posed by:

a) Point contamination sources: waste water treatment sites discharging to streams and groundwater, farmyard wastes (silage effluent, soiled water), effluent from on-site systems (septic tanks), leakages, spillages, non-agricultural pesticides, landfill leachate, contaminated sinking streams;

b) Diffuse sources – spreading of organic wastes, fertilisers (organic and inorganic) and pesticides.

While point sources have caused most of the contamination problems identified to date, there is evidence that diffuse sources are increasingly impacting on groundwater.

1.3 Groundwater Protection through Land-use Planning: A Means of Preventing Contamination

There are a number of ways of preventing groundwater contamination, such as improved well siting, design and construction, and better design and management of potential contamination sources. However, one of the most effective ways is integrating hydrogeological factors into land-use policy and planning by means of Groundwater Protection Schemes.

Land-use planning (including environmental impact assessment), integrated pollution control licensing, waste licensing, water quality management planning, water pollution legislation, etc., are the main methods used in Ireland for balancing the need to protect the environment with the need for development. However, land-use planning is a dynamic process with social, economic and environmental interests and impacts influencing to varying degrees the use of land and water. In a rural area, farming, housing, industry, tourism, conservation, waste disposal, water supply, etc., are potentially interactive and conflicting and may compete for priority. How does groundwater and groundwater pollution prevention fit into this complex and difficult situation, particularly as it is a resource that is underground and for many people is 'out of sight, out of mind'? Groundwater Protection Schemes enable planning and other regulatory authorities to take account of both geological and hydrogeological factors in locating developments; consequently they are an essential means of preventing groundwater pollution.

1.4 'Groundwater Protection Schemes' – A National Methodology for Preventing Groundwater Pollution

The Geological Survey of Ireland (GSI), the Department of Environment and Local Government (DELG) and the Environmental Protection Agency (EPA) have jointly developed a methodology for the preparation of Groundwater Protection Schemes (DELG/EPA/GSI, 1999). The publication **Groundwater Protection Schemes** was launched in May 1999, by Mr. Joe Jacob TD, Minister of State at the Department of Public Enterprise. Three supplementary publications are currently available: **Groundwater Protection Responses for On-Site Wastewater Systems for Single Houses ('septic tanks')**, **Groundwater Protection Responses for Landfills** and **Groundwater Protection Responses for Landspreading of Organic Wastes**. Similar 'responses' publications will be prepared in the future for other potentially polluting activities, such as underground storage tanks and farmyards.

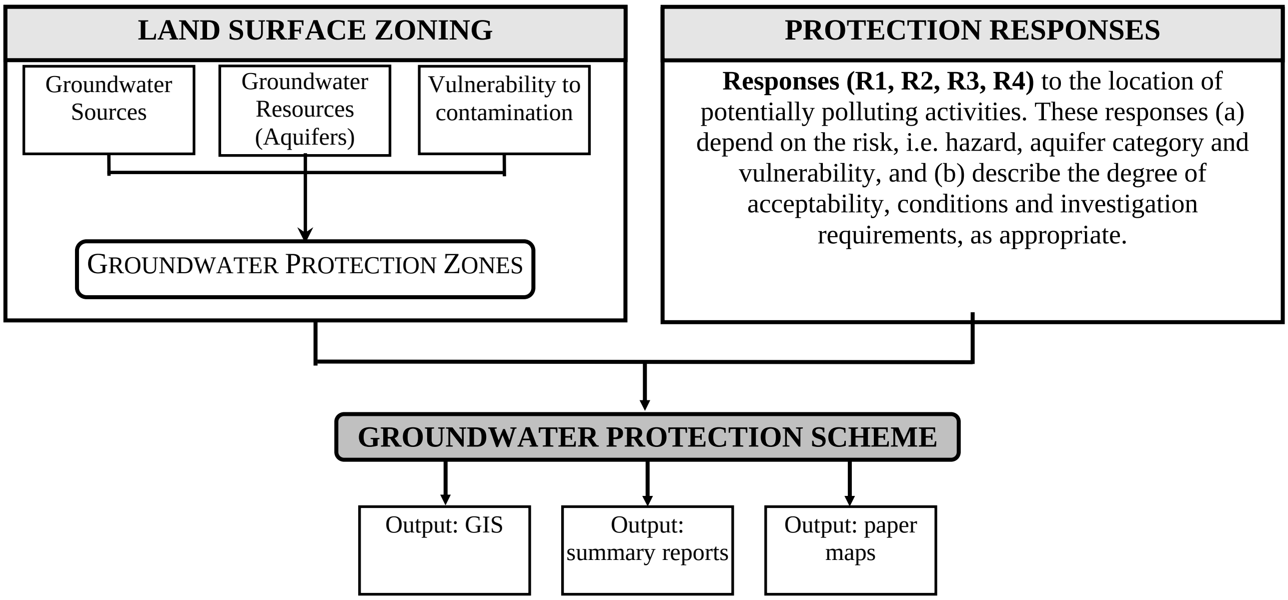
There are two main components of a Groundwater Protection Scheme shown schematically in Figure 1.1:

1. Land surface zoning and
2. Groundwater protection responses for potentially polluting activities.

Land surface zoning provides the general framework for a Groundwater Protection Scheme. The outcome is a map, which divides any chosen area into a number of groundwater protection zones according to the degree of protection required. There are three main hydrogeological elements to land surface zoning:

- Division of the entire land surface according to the vulnerability of the underlying groundwater to contamination. This requires production of a vulnerability map showing four vulnerability categories – extreme, high, moderate and low.
- Delineation of areas contributing to groundwater sources (usually public and group supply sources); these are termed source protection areas.
- Delineation of areas according to the value of the groundwater resources or aquifer category: these are termed resource protection areas.

Figure 1.1 Summary of the main components of a Groundwater Protection Scheme



The vulnerability maps are integrated with each of the other two to give maps showing **groundwater protection zones**. These include source protection zones and resource protection zones.

The location and management of potentially polluting activities in each groundwater protection zone is by means of a **groundwater protection response matrix** for each activity or group of activities, which describes: (i) the degree of acceptability of each activity; (ii) the conditions to be applied; and, in some instances (iii) the investigations that may be necessary prior to decision-making.

While the two components (the protection zone maps and the groundwater protection responses) are separate, they are incorporated together and closely inter-linked in a protection scheme.
Two of the main sections in **Groundwater Protection Schemes** are reproduced in Appendix I. While these describe the two main components of the national Groundwater Protection Scheme, it is recommended that, for a full overview of the groundwater protection methodology, the **Groundwater Protection Schemes** publication (DELG/EPA/GSI, 1999) should be consulted.

1.5 Objectives of the County Cavan Groundwater Protection Scheme

The overall aim of the Groundwater Protection Scheme is to preserve the quality of groundwater in County Cavan for drinking purposes and other beneficial uses, for the benefit of present and future generations.

The objectives, which are interrelated, are as follows:

- to assist the statutory authorities in meeting their responsibilities for the protection and conservation of groundwater resources;
- to provide geological and hydrogeological information for the planning process, so that potentially polluting developments can be located and controlled in an environmentally acceptable way;
- to integrate the factors associated with groundwater contamination risk, to focus attention on the higher risk areas and activities, and to provide a logical structure within which contamination control measures can be selected.

The scheme is not intended to have any statutory authority now or in the future, but to provide a framework for decision-making and guidelines for the statutory authorities in carrying out their functions. As groundwater protection decisions are often complex, sometimes requiring detailed geological and hydrogeological information, the scheme is not prescriptive and should be qualified by site-specific considerations.

1.6 Scope of County Cavan Groundwater Protection Scheme

The Groundwater Protection Scheme is the result of co-operation between Cavan County Council and the Geological Survey of Ireland.

The geological and hydrogeological data for County Cavan are interpreted to enable:

I. delineation of aquifers

II. assessment of the groundwater vulnerability to contamination

III. delineation of protection areas around five public (PWS) and group scheme (GWS) supplies, identified by Cavan County Council (Bawnboy GWS; Ballyconnell PWS; Annagh Lough GWS; Ballymachugh GWS; Kingscourt PWS)

IV. production of a Groundwater Protection Scheme which provides geological and hydrogeological information for the planning process, so that potentially polluting developments can be located and managed in an environmentally acceptable way.

By providing information on the geology and groundwater, this report should enable the balancing of interests between development and environmental protection.

This study compiles, for the first time, all readily available geological and groundwater data for the county and sets in place a database within the Geological Survey of Ireland (GSI), which can be accessed by the local authority and others, and which can be up-dated as new information becomes available.

A suite of environmental geology maps accompany the report. These are as follows:

(i) Primary Data or Basic Maps
- Bedrock geology map: Map 1
- Subsoils (Quaternary) geology map: Map 2
- Outcrop and depth to bedrock map: Map 3
- Hydrogeological data map: Map 4

(ii) Derived or Interpretative Maps
- Aquifer map: Map 5
- Groundwater vulnerability map: Map 6
- Source protection areas: Map 8

(iii) Land-use Planning Map
- Groundwater Protection Scheme maps: Map 7 (resource protection zones) and Map 8 (source protection zones).

The protection scheme deliverable outputs are in the format of a digital Geographical Information System (GIS) dataset, registered to the standard Ordnance Survey map base. This GIS dataset is designed to be compatible with planning department GIS systems in the Local Authorities. As well as the interpretative maps described above, the GIS incorporates site suitability guidance (groundwater protection responses), for each protection zone, for **landfill**, EPA-licensable **landspreading** of organic wastes, and **on-site wastewater treatment systems for single houses** (‘septic tanks’). It is envisaged that the protection responses will be the feature most of interest to the Local Authorities because they are relevant to the planning process.

The GIS and paper maps can be used not only to assist in groundwater development and protection, but also in decision-making on major construction projects such as pipelines and roadways. However, they are not a substitute for site investigation.

It is important to recognise that detailed regional hydrogeological investigations in County Cavan are limited to the Groundwater Resources study of the northeast region (N.E. (R.D.O.), 1981) Environmental Impact Statements and feasibility studies for the development of supply sources. The NERDO report summarises the general aquifer characteristics of the area, including water quality information, and provides a good starting point for assessing the hydrogeology of County Cavan. Despite this information, the available data are somewhat limited and it is not possible to provide a fully comprehensive scientific assessment of the hydrogeology of County Cavan. However, this report provides a good basis for strategic decision-making and for site specific planning.

1.7 Cavan County Development Plan

The County Development Plan states that it is a policy of the Council to:

"provide an adequate and safe supply of piped water ………...." and "….enhance and improve the quality of life in the county by providing a high level of Environmental Protection."

1.8 Structure of Report

The structure of this report is based on the information and mapping requirements for land surface zoning. The Groundwater Protection Zone Map (Map 7) is obtained by combining the Aquifer (Map 5) and Groundwater Vulnerability maps (Map 6). The Aquifer Map, in turn, is based on the Bedrock Map (Map 1) boundaries and the aquifer categories as derived from an assessment of the available hydrogeological data (Map 4). The Groundwater Vulnerability Map is based on the Subsoils Map (Map 2), the Depth to Bedrock Map (Map 3), and an assessment of specifically relevant permeability and karstification information. This is illustrated in Fig. 1.2.

Similarly, the Source Protection Zone Map (Map 8) results from combining vulnerability (Map 6) and source protection areas (Map 8). The source protection areas are based largely on assessments of hydrogeological data. This is illustrated in Fig. 1.3. The Cavan Groundwater Protection Scheme has been divided into two volumes, with Sections 1 to 6 in Volume I, and Sections 7 to 16 in Volume II.

Volume I: Sections 2 and 3 provide brief summaries of the bedrock and subsoils geology, respectively. Section 4 summarises and assesses the hydrogeological data for the different rock units, explains the basis for each of the aquifer categories, and describes the potential for future groundwater development. Section 5 describes the subsoil permeability distribution and the derivation of the groundwater vulnerability categories. Section 6 draws the report together and summarises the final groundwater protection zones delineated for Co. Cavan.
Volume II: Section 7 outlines the available information on regional-scale groundwater quality patterns in the county. Sections 8 to 14 provide an assessment of seven of the larger public groundwater supply sources currently in use in the county.

1.9 Acknowledgements

The preparation of this Groundwater Protection Scheme involved contributions and assistance from many people:

- Cavan County Council staff, particularly Peter Cork, Colm O'Callaghan, Jim McQuaid, and others.
- All the farmers and landowners throughout County Cavan who allowed GSI staff access to take samples of the subsoils.
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- GSI Bedrock Section: Andy Sleeman and many others.
- Donal Daly, formerly of the Groundwater Section, Geological Survey of Ireland

Figure 1.2 Conceptual Framework for Production of Groundwater Resource Protection Zones, Indicating Information Needs and Links

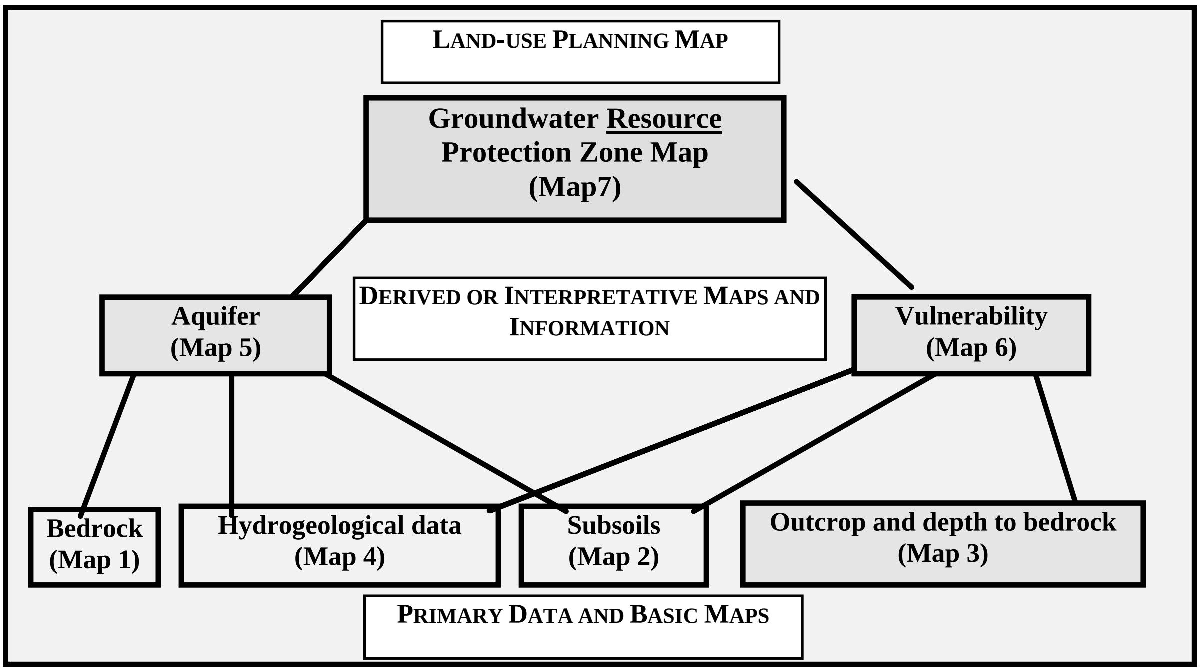
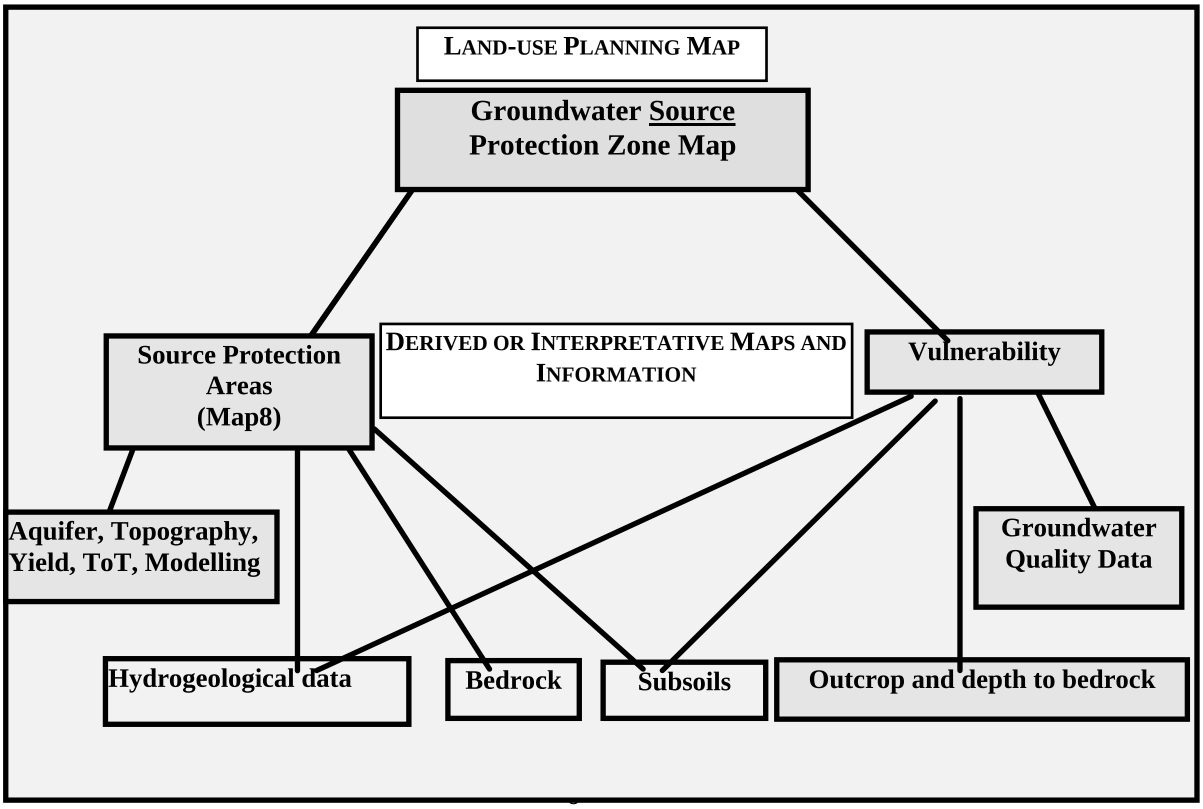


Figure 1.3 Conceptual Framework for Production of Groundwater Source Protection Zones, Indicating Information Needs and Links



2 Bedrock Geology

2.1 Introduction

This Section presents a brief description of the elements of the bedrock geology of Co. Cavan that are relevant to the hydrogeology, namely the rock composition (lithology) and the rock deformation that occurred during the long geological history of the county. A brief outline of the geological succession is presented in Table 2.1. The distribution of the bedrock geology is given in Map 1. The rocks range in age from Ordovician (c. 500 million years old) to the Triassic (c. 200 million years old) and are mainly sedimentary in origin, consisting of limestones, sandstones and shales. Dykes (linear intrusions) of igneous rocks from the Tertiary (c. 60 million years old) are found in the Cuilcagh Mountains, between Swalinbar and Bawnboy, and in the Ordovician and Silurian rocks in central Cavan.

Geological information was taken from a desk-based survey of available data, which comprised the following:

- Bedrock Geology 1:100,000 Map Series, Sheet 7, Sligo-Leitrim; Geological Survey of Ireland (MacDermot, C.V., Long, C.B., and Harney, S.J.; 1996).
- Bedrock Geology 1:100,000 Map Series, Sheet 8 & part of Sheet 9, Monaghan-Carlingford; Geological Survey of Ireland (Geraghty, M.; 1997).
- Bedrock Geology 1:100,000 Map Series, Sheet 12, Longford-Roscommon; Geological Survey of Ireland (Morris, J.H., Somerville, I.D. and MacDermot, C.V.; 2003).
- Bedrock Geology 1:100,000 Map Series, Sheet 13, Meath; Geological Survey of Ireland (McConnell, B., Philcox, M. and Geraghty, M.; 2001).
- Information from geological mapping in the nineteenth century (on record at the GSI).
- Information from Exploration & Mining Division Public Files.

The landscape of County Cavan reflects the varied underlying geology. The majority of the county is composed of resistant Ordovician and Silurian sandstones, siltstones, shales and minor amounts of volcanics, which create a topographic high in the east "pan" part of the county. These rocks are unconformably overlain by softer and more soluble lower and middle Carboniferous limestones, shales and sandstones which comprise the central to northwest of the county. Upper Carboniferous (Namurian) sandstones and shales form the bedrock which caps the mountains in the northwest of the county enclosing the Glenade valley. A small pocket of Permian and Triassic sandstones east of Kingscourt are fault-bound by Carboniferous units, which are in turn faulted against Silurian bedrock. Each of the main rock types are described in Sections 2.2 to 2.5 in the context of composition, distribution and structures.

2.2 Lower Palaeozoic Rocks

The geologic history of County Cavan begins in the ocean. During the Ordovician and part of the Silurian periods (410-510 million years ago, mya), the central to northwest part of Cavan was being formed in a deep sea. By the end of the Silurian, this ocean slowly disappeared as the continents on either side gradually inched towards each other and collided. The zone of this collision, or suture, in Ireland runs from County Louth to the Shannon Estuary, and the associated Ordovician to Silurian aged rocks are referred to as the "Longford-Down Inlier". These rocks, made of deep sea sediments, were formed and subsequently deformed during the collision. Today, this mass of rock forms a topographic high across the middle of the county. A brief description of each rock unit is given below for both the Ordovician and Silurian periods, starting with the oldest rocks.

Table 2.1: Outline of The Geological Succession in Co. Cavan (youngest on top)

EAST & CENTRAL CAVAN

STRATIGRAPHIC DIVISIONS		SUCCESSION	DESCRIPTION
Permian & Triassic		Kingscourt Sandstone Formation	Red sandstone
		Kingscourt Gypsum Formation	Mudstone with gypsum & anhydrite units
Upper Carboniferous (325 Ma)	Namurian	Cabra Formation	Interbedded sandstone & shale
		Corratober Bridge Formation	Interbedded sandstone & shale
Lower Carboniferous (342 Ma)	Visean	Undifferentiated Dinantian Limestones; Undifferentiated Visean Limestones	
		Croghan Limestone	Croghan Lst: Dark cherty limestone & shale
		Milverton Limestone	Milverton Lst: Micrite, crinoidal grainstone / packstone
		Lucan Formation	Lucan Fmtn.: dark limestone & shale
		Argillaceous Limestone	Dark limestone and shale with chert
	Courceyan Limestones	Moathill Formation	Limestone, calcareous sandstone & shale
		Meath Formation	Limestone & calcareous sandstone (Stackallan Member: micrite & mudstone)
Lower Palaeozoic (510 Ma)	Silurian	Taghart Mountain Formation	Turbidite, massive sandstone & siltstone
		Shercock Formation	Fine to coarse grained turbidite
		Oghill Formation	Massive sandstone & microconglomerate*
		Lough Avaghon Formation	Massive sandstone & microconglomerate*
		Slieve Glah Formation	Siltstone, mudstone & thin turbidite
		Kilnaleck Shale Formation	Dark grey laminated shale & mudrock
		Clontail Formation	Calcareous red-mica greywacke**
		Castlerahan Formation	Dark quartz greywacke & conglomerate*
	Ordovician	Laragh Formation	Pyritic, graptolitic black shale
		Carrickatee Formation	Black shale, mafic volcanics & tuffs
		Carrickateane Formation	Greywacke** with argillite & black shale
		Kehernaghkilly Formation	Black shale & minor rhyolitic tuff
		Red Island Formation	Greywacke**, microconglomerate & argillite
		Finnalaghta Formation	Blue-grey greywacke** & black argillite
		Coronea Formation	Turbidite, red shale & minor volcanic
		Corn Hill Formation	Shale, greywacke** & volcaniclastics

NORTHWEST CAVAN

SUCCESSION	DESCRIPTION		
Lackagh Sandstone Formation	Cyclothemic sandstone, siltstone and coal		
Gowlaun Shale Formation	Dark grey, silty, sideritic shale		
Briscloonagh Sandstone Formation	Fine grained sandstone with minor shales		
Dergvone Shale Formation	Shale & minor turbiditic sandstone		
Carraun Shale Formation	Grey / black shale with minor limestone		
Bellavally Shale Formation	Grey micrite, shale, & laminated evaporate (Doobally Sandstone Member : medium grained		
Glenade Sandstone Formation	Pale orthoquartzitic sandstone		
Meenymore Formation	Shale, laminated carbonate & evaporite		
Dartry Limestone Formation	Dark fine grained cherty limestone (with coarse crinoidal member and mudbank limestone)		
Glencar Limestone Formation	Dark fine limestones & calcareous shale	Drumgesh Shale Fmtn.	Dark shale, fine-grained limestone
Benbulben Shale Formation	Calcareous shale with minor calcarenite		
Bundoran Shale Formation	Dark shale, minor fine grained limestones	Calp Limestone	Dark grey to black limestone & shale
Ballyshannon Limestone Formation	Pale grey calcarenite limestone		
Ballysteen Formation	dark muddy limestone & shale		
Ulster Canal Formation	Calcareous sandstone, shale & micrite		
Cooldaragh Formation	Pale brown-grey flaggy, silty mudstone		
Fearnaght Formation	pale conglomerate* & red sandstone		

***Conglomerate** *is a sedimentary rock comprising large rounded fragments (pebbles, cobbles, boulders) in a finer matrix*
*** Greywackes are sandstones or siltstones that are cemented by a high proportion of mud deposited from currents loaded with sediment on subaqueous slopes*

2.2.1 Ordovician Rocks

2.2.1.1 Corn Hill Formation

Rocks from the Corn Hill Formation underlie a tiny area of southwest of Cavan, south of Garty Louth. The Formation consists of grey to brown-green and locally red shales, with minor greywacke, rare metabentonites and a single horizon of mafic volcaniclastic conglomerate.

2.2.1.2 Coronea Formation

Green muddy sandstones (greywackes), red shales and minor lavas. Red shales are abundant in the lower part of the formation.

2.2.1.3 Finnalaghta Formation

Bluish-grey, fine to medium grained, non-calcareous greywacke and pelite, with occasional, thin, dark grey shale horizons and thin black chert beds.

2.2.1.4 Red Island Formation

Medium to coarse grained, muddy sandstones derived from volcanic debris with local conglomerates. Minor grey to grey black shales.

2.2.1.5 Kehernaghkilly Formation

Typically, it is a pale green to dark grey shale-mudstone with pyrite. It also contains some minor pale grey siliceous tuffs (rocks derived from airborne volcanic debris).

2.2.1.6 Carrickateane Formation

Muddy sandstones with minor amounts of black shales and carbonate nodules.

2.2.1.7 Carrickatee Formation

This unit is similar to the Kehernaghkilly Formation; a dark grey to black shale/mudstone and occasional pale grey-green mudstone with pyrite. The formation also contains minor pillow basalts, cobble conglomerates, tuffs (rocks of air-born volcanic debris), and thin-bedded muddy sandstones

2.2.1.8 Laragh Formation

Green, grey and black shale-mudstone-slate containing pyrite and chert.

2.2.2 Silurian Rocks

2.2.2.1 Castlerahan Formation

Dark grey to black, usually massive quartzo-greywacke, with subordinate, grey-green quartzo-greywacke sometimes with microconglomeratic clasts

2.2.2.2 Clontail Formation

Red, mica-rich, muddy sandstone.

2.2.2.3 Kilnaleck Shale Formation

Dark grey and black laminated shales and mudrocks. The Kilnaleck Fault defines the southeastern boundary of the formation.

2.2.2.4 Slieve Glah Formation

Grey to dark grey slaty siltstones and mudstones. This unit also contains occasional thicker bedded, fine to coarse grained (or microconglomeratic) muddy sandstones.

2.2.2.5 Lough Avaghon Formation (& Cootehill Member)

Grey, fine to coarse grained massive muddy sandstones, microconglomerates and amalgamated beds, with interbedded sandstones and mudstones becoming prevalent towards the northwestern part of the unit. A volcanic horizon has been described in this bedrock unit; it also contains minor amounts of dark shales. There are two principal lithotypes in the Cootehill Member: (a) Thin-bedded, calcareous shales, mudstones and muddy sandstones, and (b) Very finely-laminated clayey muds with some laminated siltstones. In addition, horizons of both muddy and clean sandstones are found within this member.

2.2.2.6 Oghill Formation

Grey to grey-green massive muddy sandstones and microconglomerates. It also contains subordinate thin to thick-bedded muddy sandstones and local pyritic shale-mudstones.

2.2.2.7 Shercock Formation

Grey to green-grey, fine to coarse grained marine deposits that range from mudstones to sandstones. This formation also contains massive sandstones.

2.2.2.8 Taghart Mountain Formation

Pale to dark grey, quartz and mica rich marine deposits that range from coarse sandstones to fine mudstones, sandstones and amalgamated beds. It is interspersed with very distinctive, laminated siltstone-dominant horizons.

2.2.2.9 Crossdoney Granite

The Crossdoney Granite and an enclosed area of Monzogranite occur across approximately 15km^2 around the village of Crossdoney. It is a porphyritic granite (large crystals contained within a finer crystal matrix) with ferromagnesian minerals in the north, and is dominated by horneblende-biotite minerals in the southern area of the granite. Sulphide mineralisation is locally common.

2.2.2.10 Other Minor Intrusive Igneous Rocks

A small area of diorite is mapped in the Lower Palaeozoic rocks, northeast of Stradone, and mafic and felsic volcanic tuff is found east of this. A tiny area of felsite is found north of Killnaleck. The ages of these igneous intrusions are unknown, but as they are mapped within the Lower Palaeozoic rocks, they are included in this section.

2.3 The Carboniferous Succession

The Carboniferous succession comprises approximately 29 identified and mapped individual formations which are split over two sub-basins; the Lough-Allen basin and the Carrick-on-Shannon syncline, (Ní Bhroin, 2001). Limestones dominate the succession, which essentially is comprised of basal clastics (transitional marine sandstones, conglomerates, siltstones and mudstones), "shelf" limestones (generally shallow water limestones), "basinal" limestones (generally deep water limestones) and transitional deposits (marginal marine limestones and fluvially deposited conglomerates, sandstones, mudstones and evaporites).

2.3.1 Introduction

Shelf limestones tend to be "cleaner", lighter coloured limestones than basinal limestones because of the smaller proportions of clay in shallow water environments. This has implications for the development of karst and aquifer potential. Shelf limestones found in the low lying areas of northwest Cavan are faulted against deeper and younger basinal deposits. Erosion of the overlying sandstone and shale layers has then exposed the shelf limestones. Basinal deposits are found in the adjacent Carrick basin to the southeast and are conformably overlain by the shales, (with an absence of the shelf limestones). The composition of rocks in the succession is provided in Sections 2.3.2 to 2.4.1.3 and in Table 2.1.

2.3.1.1 Dinantian Limestones (undifferentiated)

A small (ca. 8km^2) outlier of undifferentiated Lower Carboniferous Limestones (Dinantian) has been identified in the Stradone area of Cavan. This group of rocks is described as undifferentiated due to insufficient information, but is mainly composed of a variety of limestones, shales and dolomites.

2.3.2 Basal Formations

The three basal formations can be traced as a thin band stretching northwest from the Redhills area to southeast past Killashandra; their lithologies are described below. All units are conformably deposited.

2.3.2.1 Fearnaght Formation

The Fearnaght Formation subcrop marks the base of the Carboniferous which lies unconformably on the older Ordovician-Silurian metasediments. The formation is described as a mixture of cream coloured quartz conglomerate, red and purple sandstones, and purple and brown quartzites. Deposition occurred in a mixture of freshwater and aerial conditions. The formation is estimated to be a maximum of 20m thick.

2.3.2.2 Cooldaragh Formation

The formation mainly consists of pale brown-grey calcareous siltstones, micrites, mudstones and evaporites. It is estimated to be up to 125m thick.

2.3.2.3 Ulster Canal Formation

The Ulster Canal Formation consists of alternating units, 1m to 4m thick, of light grey and yellow grey sandstone, and some fined grained limestones. The formation is 30m thick on average.

2.3.3 Basin Shelf Deposits

2.3.3.1 Ballysteen Limestone Formation (also known as the Argillaceous Bioclastic Limestone, ABL)

This formation extends as a strip where it is conformably overlying the Ulster Canal Formation, and across a wide area over the Lough Oughter waterways northwest of Cavan town. It is also found around Lough Sheelin in South Cavan. The sequence generally shows a change from relatively clean sandy/silty shallow water limestones to deeper fine grained muddy limestones. The unit is 104m thick, with a 20m thick dolerite intrusion in the uppermost part of the sequence.

2.3.3.2 Ballyshannon Limestone Formation

The Ballyshannon Limestones occurs across a very small area in Cavan, to the east of Ballyconnell. The limestone is generally a light grey, massively bedded grainstone. Stylolites are common, though fossils are scarce. The formation is estimated to be up to 560m thick.

2.3.3.3 Bundoran Shale Formation, Benbulben Shale Formation

These formations are considered together as they have similar lithologies, are conformably overlying and occur to a very limited extent in along the northern border of northwest Cavan. The Bundoran Shale occurs in a very small area along the northern border of the county east of Ballyconnell. The formation is a dark grey calcareous mudstone with thin limestones. The Benbulben Shale is similar to the Bundoran shale, though generally more calcareous and fossiliferous.

The onset of shale deposition marks the transition in depositional environment from shallow sea to pro-deltaic.

2.3.4 Deep Basinal Deposits

2.3.4.1 Drumgesh Shale

This formation covers a significant area of the county, stretching northeast to southwest from Ballyconnell towards Doogary. It consists of a variation of calcareous grey to dark grey muddy limestone to fossiliferous shales, previously referred to as the upper two divisions of the Calp Shales. The lower part of the formation is described as fossiliferous shales and unfossiliferous mudstones with minor calcarenites. The upper division is described as dark fined grained calcarenites. The contact with the overlying Dartry Limestone is gradational. It is estimated to be between 50m and 180m thick in Cavan.

The Drumgesh shale directly overlies the Ballysteen Limestone where it occurs in Cavan, with an absence of the intervening Ballyshannon to Glenade Sandstone Formations. Therefore, deposition of the Drumgesh Shale occurred chronologically later than the Dartry Limestone, although this was within an adjacent sub-basin succession which has since been faulted against the Dartry Limestone.

2.3.5 Basin Shelf Deposits

2.3.5.1 Glencar Limestone Formation

The Glencar Limestone formation is generally composed of fine limestones interbedded with dark calcareous shales. It occurs after the Benbulben shales were laid down, and represent a gradual upward transition from the Shale beds to alternating layers of shale and limestone, with an increasing thickness of impure limestone beds.

2.3.5.2 Dartry Limestone Formation

Extensive exposure of the Dartry Limestone occurs south of Slieve Rushen (northwest Cavan) and almost as far east as Belturbet. The formation is also found in the succession on the east of the Cuilcagh Mountains and in the very northwest of Cavan around Lough MacNean Upper. The unit consists of a clean, massive, thick bedded limestone. The limestone is a biomicrite[1] or calcarenite, i.e. a fine grained concretion formed by deposition of organisms in a calcium carbonate rich solution. The Dartry Limestone contains carbonate mud mounds representing shallow reef areas (Knockmore Limestone member, which is found in the very northeast of Cavan) which are likely to be related to structural highs, and in County Cavan it also contains coarse grained crinoidal silica rich areas representing the areas between reefs. A formation thickness of 400m has been recorded at Swanlinbar.

2.3.6 Transitional Deposits

2.3.6.1 Meenymore Formation

The Meenymore subcrops around the side of Slieve Rushen, on the east side of the Cuilcagh Mountains, and in Glangevlin. The formation represents a depositional environment of coastal to aerial transition known as a supratidal coastal sabkha[2]. It consists of shale and evaporite laminated limestones, mudstones, dolomites, and occasional sandstones. Shales dominate the formation in the Slieve Rushen area. Thickness of the formation is variable.

2.3.6.2 Glenade Sandstone Formation

The Glenade Sandstone is found in the same locations as the Meenymore formation, directly overlying it. It occupies much of the Glangevlin valley. The formation is typically a thick-bedded, homogenous, medium grained, orthoquartzitic sandstone, which is pale brown in colour. It contains coarse grained impersistent sandstones and horizons of resistate pebbles near the base. Formation thickness is

[1] Limestone composed of fossil skeletal remains and carbonate mud in varying proportions.
[2] A flat salt-encrusted coastal plain.

believed to be up to 300m thick, thinning southwards where it occurs in Cavan to a minimum of 80m thick at Slieve Rushen.

2.3.6.3 Bellavally Shale Formation

Four depositional environments formed this formation, resulting in a calcareous shale, a fine grained cemented fossiliferous limestone, thin sandstone beds and siltstones in repeating cycles. The Doobally Sandstone Member is a massive, medium-grained, sandstone which forms a distinctive marker in the formation.

2.3.6.4 Carraun Shale Formation

The Carraun formation is a grey to black fossiliferous shale with mudstones and minor limestones and dolomites.

2.3.7 Namurian Rocks

During the Namurian (310-325 mya) the sea continued to retreat, with rivers becoming more dominant. The majority of sediments deposited in Cavan at this time were laid down in a delta environment, where rivers met the sea. In the Westphalian (300-310 mya), the land became dominated by densely vegetated marshes. Fluctuations of sea levels resulted in the swamping of the vegetation that rotted to form organic rich layers, which eventually became coal. These Upper Carboniferous rocks form the mountains of Cuilcagh, Boleybrack and The Playbank.

2.3.7.1 Dergvone Shale Formation

This shale formation is 150m thick, and consists of four shale subdivisions which occur cyclically through the formation, including fossiliferous shale, non-fossiliferous shale, shale with ironstone bands, and a micaceous silty shale.

2.3.7.2 Briscloonagh Sandstone Formation

This formation was deposited in a delta environment and is 59m in thickness. It consists of silty shale with interbedded sandstones at the base, progressing into coarse grained sandstone

2.3.7.3 Gowlaun Shale Formation

The Gowlaun shale is 78m thick where the thickest exposure is seen, and is similar to the Dergvone Shale but with two dark fossiliferous marine shale bands.

2.3.7.4 Lackagh Sandstone Formation

The formation is over 90m thick, and has a cyclothemic succession of dark mudstones followed by silty mudstones which pass up into interbedded fine sandstones, siltstones and mudstones, and finally into a thick horizon of sandstones which are proportionally dominant in the formation.

2.3.8 Lough Sheelin Area Carboniferous Succession

The Carboniferous basin of which Lough Sheelin is a part has some bedrock formations which are comparable to those in northwest Cavan, with the oldest Fearnaght Formation present in a small area. The Stackallan Member, the Meath Formation and the Moathill Formation are found between this and the Ballysteen Formation, which is in turn overlaid by the Lucan Formation.

Refer to section 2.3.2.1 for a description of the Fearnaght Formation

2.3.8.1 Meath Formation (& Stackallan Member)

The Meath formation occurs as a small fault bound blocks around the north of Lough Sheelin. The formation consists of interbedded muddy limestones, siltstones, sandstones, black shales and evaporates in this area, with a basal concreted limestone unit. Mineral replacement and the creation of vugs have occurred in the formation in the Cavan area. The Stackallan Member consists mostly of concreted limestone and occurs in the lower part of the Meath Formation.

2.3.8.2 Moathill Formation

The Moathill formation consists of calcareous siltstones, fossiliferous limestones, sandstones and shales. It is subdivided into three units, the lower (formerly known as the "Shaly Pale Beds") of which is found in the Lough Sheelin area. The formation is at it's thinnest in the north of its occurrence (such as at Lough Sheelin) where it is described as a pale calcareous cemented sandstone.

For a description of the Ballysteen Formation, refer to section 2.3.3.1.

2.3.8.3 Croghan Limestone Formation

The Croghan Limestones are predominantly muddy limestones with some shale partings. There is evidence of less muddy, oolitic, massive middle unit. The upper layers are dark, chert-rich and 'cleaner' as shale partings are less common up through the formation.

2.3.8.4 Lucan Formation

The Lucan formation extends from Dublin west to Lough Ree and just up into the south of Cavan, around Lough Sheelin. It is characterised by fossiliferous limestones interbedded with shales, calcareous silts and muddy concreted limestones. It is typically a very thick formation (over 184m at the centre of the depositional basin, but probably considerably thinner in the Lough Sheelin area.

2.3.8.5 Visean Limestones (undifferentiated)

Large areas of pale grey limestone are undifferentiated due to their massive structure and similarity in composition. These rocks constitute a small area to the southeast of Lough Sheelin.

2.4 Kingscourt Carboniferous to Triassic Succession

2.4.1 Carboniferous

2.4.1.1 Milverton Group

The Milverton Limestone consists of five formations, although the very small area found in Cavan (faulted against Permian-Triassic rocks) is mapped as undifferentiated in this area. The five subdivisions (McGuinness Formation, Lane Formation, Smugglers Cave Formation, Holmepatrick Formation, and Mullaghfin Formation) are generally clean pale well bedded limestones with occasional sandier and shalier horizons.

2.4.1.2 Corratober Bridge Formation

This formation is the easternmost formation to occur in the county. It consists of cycles of grits (loosely consolidated coarse sandstone) and shales, with grits at the base.

2.4.1.3 Cabra Formation

This formation is predominantly composed of sandstone and shales and is similar to the Corratober Bridge Formation. A sandstone unit, up to 15m thick, occurs in the mid part of the formation. The formation is estimated to be 123m thick in total.

2.4.2 Permian to Triassic

The Permian (250-290 mya) had a severe environment - a harsh, irregular desert bounded by steep fault scarp margins. As the Permian ended and the Triassic (205-250 mya) began, the land was again flooded by a shallow sea, this time from the northeast. Permian and Triassic rocks in Cavan are found in a small area just east of Kingscourt.

2.4.2.1 Kingscourt Gypsum Formation

The base of this formation consists of a conglomerate, which is overlain by a mud-dominant sequence that contains two major evaporite deposits. These evaporites are gypsum and anhydrite, which are currently being mined at Knocknacran.

2.4.2.2 Kingscourt Sandstone Formation

This unit lies directly on top of the Kingscourt Gypsum Formation. It is comprised of siltstones with minor sandstones at the base, with a 200 m thick red sandstone member at the top of the formation.

2.5 Structure and Geological History

The regional structure of the area is influenced by two major structural events known as the Caledonian and Variscan Orogenies.

The earlier Caledonian (late Lower Palaeozoic, c.410 mya) orogeny marked the collision of two continents, Gondwana and Laurentia, which were once separated by an ancient ocean (The Iapetus Ocean). The boundary between the continents is a suture line running from the present-day Shannon Estuary to Clogher Head. The Carboniferous basinal deposits found in northwest Cavan were deposited in this ocean. The collision of the continents resulted in sub-aerial deposits being thrust up and over one another, creating a chain of mountains. In the course of this mountain building, the rocks were faulted and folded, now forming the Silurian rocks and Ordovician rocks in central to east Cavan. The Ordovician and Silurian beds are dipping at a large range of angles and completely overturned in places as a result. The Carboniferous rocks northwest of these, up to Slieve Rushen are dipping gently in a north and northwest direction. Dip directions are variable northwest of this due to basin faulting with the blocks between dipping in different directions. A very gentle anticline occurs in the centre of Glangevlin valley, from where the succession of Upper Carboniferous deposits is exposed moving up the valley into the surrounding mountains.

The Variscan Orogeny (late Carboniferous, c.290 mya) was a north-south compression event with the deformation front located in the south of the country. As a result there are only weak effects of the strain seen in northwest County Cavan.

There is one other feature in the extreme east of Cavan - an area called the "Kingscourt Outlier". This small, faulted wedge of different rocks is located east of Kingscourt, where a block of Lower Carboniferous Limestones, Upper Carboniferous Sandstones, Permian and Triassic rocks are juxtaposed against the Lower Palaeozoic rocks. The Kingscourt Outlier is bounded on the west by the Kingscourt Fault. Though most movement at this fault occurred in the post-Triassic, some movement occurred during the Variscan. This fault defines a topographic high, which can been seen from west of Carrickmacross to Nobber, in County Meath.

3 Subsoil (Quaternary) Geology

3.1 Introduction

This Section briefly deals with the geological materials which lie above the bedrock and beneath the topsoil. The subsoils were deposited during the Quaternary period of glacial history. The Quaternary period encompasses the last 1.6 million years and is sub-divided into the Pleistocene (1,600,000-10,000 years ago); and the more recent Holocene (10,000 years ago to the present day). The Pleistocene, more commonly known as the 'Ice Age', was a period of intense glaciation separated by warmer interglacial periods. The Holocene, or post-glacial, saw the onset of a warmer and wetter climate approaching that which we have today.

During the Pleistocene the glaciers and ice sheets laid down a wide range of deposits, which differ in thickness, extent and lithology. County Cavan was completely covered by an ice sheet, which moved in a general southeasterly direction (Clark & Meehan, 2001). Material for the deposits left behind originated from bedrock and was subjected to different processes within, beneath and around the ice. Some were deposited randomly and so are unsorted and have varying grain sizes, while others were deposited by water in and around the ice sheets and are relatively well sorted and coarse grained. The bedrock subsoil interface in Cavan is indistinct in places due to the degree to which the surface of the bedrock has been crushed and entrained into the base of the till, indicating a significant weight of ice on it.

Mapping of subsoils and compilation of subsoil information in Cavan was undertaken as part of the FIPS Subsoil Mapping Project (Meehan, 2004). This mapping formed the foundation of subsequent subsoil permeability assessments (described in Section 5). Subsoil distribution is presented in Maps 2N and 2S, and discussed briefly in Section 3.2.

3.2 Subsoil Types

There are five main subsoil types identified in Co. Cavan and shown on Map 2:

- tills
- sands and gravels
- alluvium
- peat
- lacustrine sediments

Areas where bedrock comes close to the ground surface are shown on the maps as "rock close".

3.2.1 Tills

Tills (often referred to as boulder clay or drift) are the most widespread subsoil type found in County Cavan as can be seen on Map 2. It is a diverse material which is deposited sub-glacially and it has a wide range of characteristics due to the variety of parent materials and different processes of deposition. Tills are often tightly packed, unsorted, unbedded, and have many different particle and stone sizes and types, which are often angular or subangular. Many of the tills in Cavan have been formed into elongated hills, or drumlins, which are thought to be bedforms of the glacier and give an indication of ice flow direction, as discussed in Section 3.4.

Boundaries based on till texture are not shown on the subsoil Map 2, but symbols indicate the texture at specific locations. Instead, the tills are categorised according to their dominant lithological component, e.g. Lower Palaeozoic sandstone and shale till (TLPSsS).

Gravel tills encompass those areas where isolated areas of gravels with a clay rich matrix have been deposited within the Lower Palaeozoic sandstone and shale till. It includes the rib moraines seen in the very southeast of the county, which could be mistaken for gravel hills as the moraines are discontinuous in places.

The degree of variability in the composition of the tills is such that in the south-east of Cavan, the till type mapped here has been subdivided into different permeability categories. This is further discussed in section 5.4.2. A number of particle size analyses were carried out during the permeability mapping; these results are discussed in the context of subsoil permeability and groundwater vulnerability, in Chapter 5.

3.2.2 Sands and Gravels

Deposition of sand/gravel takes place mainly when the glaciers are melting. This gives rise to large volumes of meltwater with great erosive and transporting power. The subsoils deposited in this environment are primarily well rounded gravels with sand, with the finer fractions of clay and silt washed out. Outwash deposits take the form of fans of stream debris dropped at the glacier front via drainage channels. Deltaic deposits are similar but are formed where drainage channels discharge into a standing body of water. Deposits remaining in the drainage channels form eskers, similar to a river drainage system in arrangement, with tributaries converging downstream.

Cavan does not have extensive deposits of sand and gravel. The majority of sand and gravel deposits are small and discontinuous, with only two sizeable and continuous deposits located northwest Lough Sheelin and to the south and southeast of Lough Ramor. Neither of these deposits has been quarried as they are slightly less clean (i.e. higher clay content) than gravel deposits in counties to the south. The sand and gravel deposits in County Cavan do not reflect the typical ridge (eskers), hummock and hollow (kames and kettle holes) topography found elsewhere in Ireland, with the exception of a very small esker along the county border near Granard. However, fan shaped deposits of outwash deltas are seen around the edge of Lough Sheelin and Lough Ramor.

3.2.3 Alluvial deposits

Alluvial sediments are deposited by rivers and include unconsolidated materials of all grain sizes, ranging from coarse gravels down to finer silts and clays, and they may also contain organic detritus. Alluvial deposits in Cavan are associated with the main rivers including the Erne, Woodford, Annalee and Blackwater Rivers.

3.2.4 Peat

Deposition of peat occurred in post-glacial times with the onset of warmer and wetter climatic conditions. Peat is an unconsolidated brown to black organic material comprising a mixture of decomposed and un-decomposed plant matter, which has accumulated in a waterlogged environment. Peat has an extremely high water content averaging over 90% by volume. Two main types of peat bog are distinguished in Ireland: blanket bog, which is characteristic of upland areas with excessive rainfall, and raised bog, which is characteristic of lowland areas with impeded drainage. Blanket peat is the principal peat type represented in Cavan, covering much of the Cuilcagh Mountains and Slieve Rushen in the northwest and small patches between drumlins in the main area of Cavan to the southeast. Much of the small low-lying interdrumlin areas of peat have been partially excavated and the peat here is referred to as ‘cutover peat’. Fen Peat (which is the early formation stage of a raised bog complex) is also found in two locations in Cavan where the habitats are protected due to the rarity of the fen environment; at Annagh Lough to the south of Belturbet, and also surrounding another lake called Annagh Lough to the east of Ballyconnell.

3.2.5 Lacustrine Clays

Lacustrine clays are deposited sub-aqueously in a quiet environment, so the material is generally fine grained and very homogenous. Lake clays are frequently found around the edges of the many lakes in Cavan, but are usually small in expanse. Two large areas of “clayey lacustrine sediments” are found in the southeast of the county along tributaries of the River Blackwater, and are related to the glacial lakes which existed in the area of Lough Ramor and Lough Sheelin.

3.3 Depth to Bedrock

The depth-to-bedrock (i.e. subsoil thickness) is a critical factor in determining groundwater vulnerability. Subsoil thicknesses vary considerably over the county, from no subsoil (rock at surface) to depths of over 30 metres and even up to 60m in one borehole. The direction of ice movement has spatially influenced the subsoil thicknesses.

Broad, regional-scale variations in depth to bedrock have been interpreted across the county by the Groundwater Section of the GSI, using information from the GSI databases, from field mapping, air photograph and digital elevation model (DEM) interpretation. Depth-to-rock data maps (Map 3) show areas where rock crops out at surface and depth-to-rock data from borehole records where the location accuracy is to within 50m.

The thickest deposits in Cavan are tills which are found throughout the county. Tills in the Cavan "Pan" area, which is generally topographically elevated above the area around the Erne Waterway, can be subdivided into two broad depth-to-bedrock patterns. The area from Lough Sheelin to Drung consists of small patches of rock close, i.e. less than <1m thick, with areas in between of subsoil thickness of up to 10m. In the area from the Erne waterway, east to Stradone, and south to Lough Sheelin, there is a greater density of rock close areas, which have a mixture of subsoils less than 3m thick (typical around the shores of Lough Sheelin) and subsoils of up to 5m thick in between shallow subsoils. Drumlins are generally till cored, and increase in height in a westwards direction from 3m thick to over 10m thick.

A large topographically low-lying area from the Erne Waterway to Slieve Rushen is underlain by subsoils generally greater than 10m thick, although inter-drumlin areas within the Erne waterway area are generally between 3m and 5m thick.

The mountainous areas of Slieve Rushen and Cuilcagh constitute rock and shallow rock with subsoils of less than 3m thick above 200m on Slieve Rushen and above 300m elsewhere in the northeast of the county, although peat in these areas is up to 5m thick. Low lying valley areas around Swanlinbar and Slieve Rushen are between 3m and 10m in thickness. Subsoils in the Glangevlin valley area are generally between 5m and 10m thick, with drumlins representing areas of subsoils over 10m in thickness.

3.4 Ice Flow Direction

Drumlins can be used as directional indicators of ice flow, since the steeper side of drumlins faces up-ice, with the down-ice portion of the drumlin being longer and more sloped (Bennett and Glasser, 1996). A study of landform and bedform ice flow indicators in the southeast of County Cavan has been carried out by Meehan (1999), showing ice flow directions being from the northwest to the southeast. It is likely that the ice dome originated in the mountainous area of northwest Cavan.

4 Hydrogeology and Aquifer Classification

4.1 Introduction

This Section summarises the relevant and available hydrogeological and groundwater information for County Cavan. A brief description of the hydrogeology of each aquifer grouping is given, followed by its aquifer category based on the GSI aquifer classification scheme. The hydrogeological data for the county are summarised on Map 4 and the aquifers are shown on Map 5.

4.2 Data Availability

The assessment of the hydrogeology of County Cavan is based primarily on analyses and conclusions given in the National Aquifer Report (GSI, in preparation). Additional available drilling, abstraction and pump testing data from Geological Survey, Cavan County Council, and consultants' files were also compiled and entered into a computer database at the Geological Survey. In summary, the following data and reports were assessed:

- National Aquifer Report (GSI, in preparation).
- Groundwater abstraction rates for local authority sources, group scheme sources, and for a limited number of other high yielding private wells and springs.
- Specific capacity[3] and discharge data in County Cavan and surrounding counties.
- Information on large springs.
- Reports by engineering and hydrogeological consultants.

4.3 Rainfall, Evapotranspiration and Recharge

According to Met Éireann information, mean annual rainfall in County Cavan during 1961–1990 varied from 895 mm in the lowlands to more than 1900 mm over the Cuilcagh Mountains (Fitzgerald and Forrestal, 1996).

Potential recharge has been estimated for more localised areas around public supply sources using Met Éireann rainfall and potential evapotranspiration data (see Volume II). The actual annual recharge (i.e. potential recharge less surface water runoff) depends on the relative rates of infiltration and surface runoff, which is, in turn, influenced by subsoil permeability and saturation. In low permeability or waterlogged areas, actual recharge may be less than 5% of the potential recharge.

4.4 Background to Aquifer Classification

4.4.1 Introduction

The factors used in aquifer classification are outlined in Section 4.4.4. The classifications of each rock unit in Cavan are provided in Sections 4.5 to 4.15. According to the aquifer classification used by the GSI (DELG/EPA/GSI, 1999), there are three main aquifer categories, with each category sub-divided into two, three or four classes:

Regionally Important (**R**) **Aquifers**

(i) Karstified bedrock aquifers (**Rk**)
(ii) Fissured bedrock aquifers (**Rf**)
(iii) Extensive sand/gravel aquifers (**Rg**)

Locally Important (**L**) **Aquifers**

(i) Sand/gravel (**Lg**)
(ii) Bedrock which is Generally Moderately Productive **(Lm)**
(iii) Bedrock which is Moderately Productive only in Local Zones **(Ll)**

[3] Specific capacity is the rate of abstraction per unit drawdown: units are $m^3 d^{-1} m^{-1}$

(iv) Karstified bedrock aquifers **(Lk)**

Poor (P) Aquifers

(i) Bedrock which is Generally Unproductive except for Local Zones **(Pl)**
(ii) Bedrock which is Generally Unproductive **(Pu)**

4.4.2 Bedrock Aquifers

Irish bedrock aquifers are not generally thought to have significant pore-space permeability. Consequently, flow is thought to depend on the development of a network of secondary permeability within fractures and bedrock aquifer categories have been designed to take account of the following factors:

- the overall potential for groundwater development in each rock unit;
- the localised nature of higher permeability zones (e.g. fractures) in many of the bedrock units;
- the highly karstic nature of some of the limestones;
- all bedrock types will generally give enough water for domestic supplies and therefore all are called 'aquifers'.

Karstification and dolomitisation are two processes which strongly influence the development of secondary permeability and aquifer potential in Irish bedrock units. Each is explained briefly below. The terms will occur in several of the classifications provided in Sections 4.5 to 4.15.

Karstification

Karstification is the process whereby limestones are slowly dissolved away by acidic waters moving through them. This process occurs most often in the upper bedrock layers and along some of the pre-existing fissures and fractures in the rocks, which become slowly enlarged. This results in the progressive development of distinctive karst landforms such as collapses, caves, swallow holes, sinking streams, turloughs and dry valleys, and a distinctive groundwater flow regime where drainage is largely underground in solutionally-enlarged fissures and conduits. The solution is influenced by factors such as: the type and solubility of the limestone; the degree of jointing, faulting and bedding; the chemical and physical character of the groundwater; the rate of water circulation; the geomorphic history (upland/lowland, sea level changes, etc.); and the subsoil cover. One of the consequences of karstification is the development of an uneven distribution of permeability, which results from the enlargement of certain fissures at the expense of others, and the concentration of water flow into these high permeability zones.

There are gradations in the degree of karstification from slight to intensive. All pure bedded limestones are known or assumed to be karstified to some degree. In contrast, pure unbedded limestones (e.g. Waulsortian Limestones) are only susceptible to significant karstification when very fractured, as in the southwest of Ireland. Where fracturing and faulting in such rocks is minimal (e.g. in the Midlands), karstification is limited to such a degree that it does not contribute in any significant way to groundwater flow in the bedrock aquifer.

In order to assist in the understanding and groundwater development of pure limestone aquifers, the GSI has compartmentalised the broad range of karst regimes into three categories. Regionally important limestone aquifers in which karst features are more significant are classed as **Rk**. Within the range represented by **Rk**, two sub-types are distinguished, termed **Rk**^{c} and **Rk**^{d}:

- **Rk**^{c} are those aquifers in which the degree of karstification limits the potential to develop groundwater. They have a high 'flashy' groundwater throughput, a large proportion of flow is concentrated in conduits, numerical modelling using conventional programs is not usually applicable, well yields are variable with a high proportion having low or minimal yields, large springs are present, storage is low, locating areas of high permeability is difficult and therefore groundwater development using bored wells can be problematical.

- **Rk^{d}** aquifers are those in which flow is more diffuse, storage is higher, there are many high yielding wells, and development of bored wells is less difficult. These areas also have caves and large springs, but the springs have a more regular flow. In general, these aquifers can be modelled (at an appropriate scale) using conventional programs.

Limestone aquifers in which karstification is present, but which are not large enough, or do not have enough groundwater throughput, to be classified as 'Regionally important', are classified as Locally important karstified aquifers (**Lk**). No distinction is made between the different sub-types of karstification.

Dolomitisation
Dolomitisation is a weathering process that often occurs in limestone where calcium ions are replaced by magnesium ions in the crystal lattice of dolomite (Ca Mg $(CO_3)_2$). Hydrogeologically, the most important consequence of dolomitisation is that it results in an increase in the porosity and permeability of the carbonate rock. Dolomitised rocks are a highly weathered, yellow/orange/brown colour and are usually evident in boreholes as loose yellow-brown sand with significant void space and poor core recovery. Dolomitisation often occurs along fault zones, can cross bedrock lithology boundaries and results in unpredictable very high permeability zones. In general, the cleaner the original limestone, the greater the degree of dolomitisation occurring.

4.4.3 Sand/Gravel Aquifers

Sand/gravel deposits have a dual role in groundwater development and supply. Firstly, in some cases they can supply significant quantities of water for supply and are therefore classed as aquifers, and secondly, they provide storage for underlying bedrock aquifers. A sand/gravel deposit is classed as an aquifer if the deposit is highly permeable, more than 10 m thick and greater than one square kilometre in aerial extent. The thickness of the deposit is often used rather than the more relevant saturated zone thickness as the information on the latter is rarely available. In many instances it may be assumed that a deposit with a thickness of 10 m will have a saturated zone of at least 5 m. This is not the case where deposits have a high relief (for example eskers or deposits in high topographic areas) as these gravels are often dry.

Table 4.1 Sand/gravel Aquifer Classification

	Regionally important	**Locally important**
Aerial extent	> 10 km^2	1-10 km^2
Saturated thickness	> 5 m	> 5 m
Permeability	High	High

Sand/gravel aquifers are therefore classified based on the permeability, aerial extent, and the thickness of the unsaturated zone (see Table 4.1). In the absence of permeability test data, gravels with a fines content of less than approximately 8% are generally considered to have sufficient permeability for aquifer development (O'Suilleabhain, 2000).

A regionally important gravel aquifer should have an aerial extent of at least 10 km^2. This is to ensure that, assuming an average annual recharge of 400 mm, there will be enough recharge to provide a supply of one million cubic metres per year from the whole aquifer.

4.4.4 Aquifer Classification Criteria

As yield is one of the main concerns in aquifer development projects, yields from existing wells are conceptually linked with the main aquifer categories outlined in Section 4.4.1:

- Regionally important (**R**) aquifers should have (or be capable of having) a large number of 'Excellent' yields: in excess of approximately 400 m^3/d (4000 gph).
- Locally important (**L**) aquifers are capable of 'Good' well yields 100-400 m^3/d (1000-4000 gph).
- Poor (**P**) aquifers would generally have 'Moderate' or 'Poor' well yields - less than 100 m^3/d.

However, in practice, existing well yield information is often difficult to use because reliable, long-term yield test data are quite rare (particularly for the less productive aquifers). In practice, then, the following criteria are used in aquifer classification:

- Permeability and transmissivity[4] data from formal pumping tests, where discharge and water level readings have been taken over a period of many hours or days.
- Productivity data from wells where either formal pumping tests have been undertaken or where at least one combined reading of discharge and drawdown data are available. The GSI has developed the concept of 'productivity' as a semi-quantitative method of utilising limited well test data (Wright, 2000; see Appendix II). A 'productivity index' is assigned to a well from one of five classes: I (highest), II, III, IV, and V (lowest), using a graphical comparison of well discharge with specific capacity.
- Occurrence of springs with 'high' flows (greater than 2,160 m^3/day total flow).
- Occurrence of wells with 'excellent' yields (greater than 400 m^3/day discharge).
- Hydrological information such as drainage density (where overlying subsoils are thin), and baseflows or flows in rivers (better aquifers will support higher baseflows and summer flows). Dry Weather Flow (DWF) is the annual minimum daily mean flow with a probability of exceedance of 0.98 (i.e. with a return period of 50 years). An area-specific dry weather flow (ASDWF) of 2 l/s/km^2 is considered to indicate the presence of a good aquifer.
- Lithological and/or structural characteristics of geological formations which indicate an ability to store and transmit water. Clean washed and sorted sands and gravels, for example, are more permeable than poorly sorted glacial tills. Pure limestones are also more permeable than impure (clayey/shaly) limestones. Areas where folding and faulting has produced extensive joint systems tend to have higher permeabilities than areas where this has not occurred.

All factors are considered together; productivity and permeability data are only given 'precedence' over lithological and structural inferences where sufficient data are available. The classification of all rock units in Cavan is presented in Sections 4.5 to 4.15. A summary can be found in Section 4.2, and on Map 5.

Some bedrock units have been grouped if they are of similar geological age and have similar lithological/structural characteristics. In considering the classifications provided, it is important to note that:

- The bedrock aquifer classifications are based on the bedrock units described in Sections 2.2 to 2.5 and depicted on Map 1.
- Irish hydrogeology is unusually complex and variable. As a consequence, there will often be exceptionally low or high yields which do not conform to the aquifer category given.
- The top few metres of all bedrock types are likely to be relatively permeable, even in the poor aquifers.
- There may be localised areas where recharge is restricted. This could occur, for example, where the vulnerability is low, or where a small portion of the rock unit has been faulted away from the main body of the unit. In these situations, the development potential even of regionally important aquifers may be limited. In considering major groundwater development schemes at particular sites, it will be important to consider the long term balance between recharge and abstraction, as well as the aquifer potential.

[4] Transmissivity is the product of permeability and the effective saturated thickness of the aquifer

Table 4.2 Summary of Aquifer Classification in County Cavan

Aquifer Grouping	Geological Units	Occurrence in Cavan	Aquifer Class*	Main basis for Classification	Section #
Permo-Triassic Sandstones, Mudstones and Gypsum					
Kingscourt Sandstone (KS)		East Cavan	**Lm**	Well yields and productivities, lithology.	4.15
Kingscourt Gypsum (KG)		East Cavan	**Pl**	Lithology, water level variation.	4.15
Namurian Sandstones and Shales					
Lackagh Sandstone (LH), Briscloonagh Sandstone (BR)		Northwest Cavan	**Pl**	Lithology, limited yield data.	4.14
Gowlaun Shale (GO), Dergvone Shale (DE)		Northwest Cavan	**Pu**	Lithology	4.14
Cabra (CB), Corratober Bridge (CO)		East Cavan	**Lm**	Well yields and productivities, lithology.	4.14
Dinantian Upper Impure Limestones					
Calp & Kilmore Slump Member, Glencar Limestone		Central Cavan, near Lough Oughter	**Ll**	Well productivities and yields, lithology.	4.13
Lucan		South Cavan, near Lough Sheelin	**Ll**	Well productivities and yields, lithology.	4.13
Dinantian Pure Bedded Limestones and Dinantian Pure Unbedded Limestones					
Dartry Limestone (and Members) (DA, crDA, DAcr, DAcw, DAmk, DAkn)		Northwest Cavan	**Rkc/Rk/ Lk**	Karst features, tracing, lithology.	4.12
Ballyshannon Limestone (BS)		North Cavan	**Rk**	Karst features, productivity, yields and lithology.	4.12
Croghan Limestone (CL)		Central Cavan SW of Crossdoney	**Lk**	Lithology.	4.12
Milverton Limestone (MLV)		East Cavan	**Rkd**	Karst features, productivity, yields and lithology.	4.12
Undifferentiated Visean Limestones (VIS)		South Cavan, near Lough Sheelin	**Rkd**	Lithology.	4.12
Stackallan Member of Meath Formation (MEst)		South Cavan, near Lough Sheelin	**Lm**	Structure, Lithology.	4.12
Dinantian Mixed Sandstones, Shales and Limestones					
Undifferentiated Dinantian Limestones (DIN)		Central Cavan, near Tullyvin	**Lm**	Lithology.	4.11
Meenymore (ME), Bellavally Shale (BE) & Doobally Sandstone Member (BEdo)		Northwest Cavan	**Ll**	Lithology, yield and productivity in similar rock units elsewhere.	4.11
Dinantian Shales and Limestones					
Carraun Shale (CN)		Northwest Cavan	**Pl**	Lithology	4.10
Benbulben Shale (BB), Bundoran Shale (BN)		Northwest Cavan	**Ll**	Lithology	4.10
Drumgesh Shale (DH)		Central Cavan	**Ll**	Lithology, limited yield and productivity data.	4.10
Drumgesh Shale (DH)		Northeast Cavan	**Lm**	Structure, lithology, juxtaposition with productive aquifers.	4.10

Aquifer Grouping	Geological Units	Occurrence in Cavan	Aquifer Class*	Main basis for Classification	Section #
Dinantian Sandstones					
Glenade Sandstone (GD)		Northwest Cavan	**Lm**	Lithology, yields in similar rock units nearby, limited yield and productivity data.	4.9
Fearnaght (FT)		Northeast Cavan	**Rf**	Structure, lithology, juxtaposition with productive aquifers.	4.9
Fearnaght (FT)		Central Cavan, near Lough Oughter	**Lm**	Lithology, structure.	4.9
Dinantian Lower Impure Limestones					
Ballysteen Limestone (BA)		Northeast Cavan	**Rf**	Structure, well yields and productivities, juxtaposition with productive aquifers.	4.8
Ballysteen Limestone (BA)		Central Cavan, near Lough Oughter	**Ll**	Lithology, well yields and productivities.	4.8
Argillaceous Limestones		South Cavan, near Lough Sheelin	**Ll**	Lithology, well yields and productivities.	4.8
Dinantian (early) Sandstones, Shales and Limestones					
Ulster Canal (UC), Cooldaragh (CH)		Northeast Cavan	**Rf**	Well yields and productivities, structure, juxtaposition with productive aquifers.	4.7
Ulster Canal (UC), Cooldaragh (CH)		Central Cavan, near Lough Oughter	**Ll**	Lithology.	4.7
Moathill (MH), Meath (ME)		South Cavan, near Lough Sheelin	**Ll**	Well yields and productivities, lithology.	4.7
Silurian Metasediments and Volcanics					
Clontail (CL), Kilnaleck Shale (KK), Lough Avaghon (LA), Cootehill Member (LAcl), Oghill (OL), Castlerahan (RA), Slieve Glah (SG), Pollareagh Member (SGph), Shercock (SK), Taghart Mountain (TM)		Southeast/Central Cavan – from Kilnaleck to Cootehill to Mullagh	**Pl**	Lithology, dry weather flows, well yields and productivities.	4.5
Ordovician Metasediments, Ordovician Volcanics					
Coronea (CA), Corn Hill (CH), Carrickatee (CK), Carrickateane (CT), Finnalaghta (FA), Kehernaghkilly (KY), Laragh (LH), Red Island (RI), Volcanics (mv)		Mainly south-Central Cavan – from Lough Gowna to Redhills	**Pl**	Lithology, dry weather flows, well yields and productivities.	4.5
Granites and other Igneous Intrusive rocks					
Monzogranite (Ad), Crossdoney Granite (Cg), Diorite (Di), Felsite (F)		Central Cavan - at Crossdoney and near Tullyvin	**Pl**	Lithology. Dry weather flows in nearby similar rock unit.	4.6

*Rk: Regionally important karstic. Rf: Regionally important fissured. Lm: Locally important moderately productive. Ll: Locally important only in local zones. Lk: Locally important karstic. Pl: Poor generally unproductive except for local zones. Pu: Poor Aquifers which are generally unproductive.

4.5 Classification of the Ordovician Metasediments, Ordovician Volcanics, and Silurian Metasediments and Volcanic Aquifers

The Lower Palaeozoic (Ordovician and Silurian age) rocks in Cavan generally comprise sandstones and shales; Ordovician rocks tend to be shalier and also contain rocks of a volcanic origin. The Ordovician and Silurian age rocks in Co. Cavan are part of a larger area of these types of rocks, which is known as the Longford-Down Inlier (McConnell *et al.*, 2001). The distribution of the rock types is presented on Map 1, while the aquifers are depicted on Map 5. The different formations that comprise this aquifer group are listed in Table 4.2.

In general, the rocks are characterised by low fissure permeability. Shaly layers within these rocks prevent clean fractures from opening up under tectonic pressure. Fractures can become filled with fault gouge, a clay material created by the disintegration of the rock material under tectonic forces. This material seals up fractures, restricting the flow of groundwater. The coarser, thicker sandstone units are likely to have a greater degree of fracturing than the more plastic interbedded shales. Brittle volcanic layers may also have a greater degree of fracturing. Permeabilities in the upper few metres of the surface weathered zone are often high although they decrease rapidly with depth. Results mainly from the drilling of private domestic wells or for small industrial companies have shown that local zones of higher permeability are present, indicated by the 'high' yields encountered. These yields are often associated with fractures and faults. It is not possible, given the present data, to delineate the areas of higher permeability within such formations.

Many small springs can be observed on, and at the base of slopes. There are no known high yielding springs within the Ordovician or Silurian aquifers. In areas where the rock is exposed at the surface, the land is often poorly drained, and the stream density is relatively high. A number of Dry Weather Flow values are available from gauges located within these aquifers (Table 4.3). The values in the Ordovician and Silurian aquifers in the northeast are low (from 0.04 to 0.54 l/s/km^2), indicating a poor aquifer.

Table 4.3 Dry Weather Flow values for gauges within the Lower Palaeozoic (Ordovician and Silurian) aquifers of the Longford-Down-Louth-Meath Inlier

River	Gauging station	Location	Underlying rock unit	Rock age	ASDWF (l/s/km^2)
Annalee	36016	Rathkenny, Co. Cavan	Red Island Formation (RI)	Ordovician	0.17
Annalee	36010	Butlers Br., Co. Cavan	Coronea Formation (CA)	Ordovician	0.04
Blackwater (Kells)	07011	O'Dalys Br. Co. Meath	Clontail Formation (CL)	Silurian	0.34
Moynalty	07017	Rosehill, Co. Meath	Clontail Formation (CL)	Silurian	0.54
Glyde	06014	Tallanstown, Co.Louth	Clontail Formation (CL)	Silurian	0.55
White (Dee)	06033	Coneyburrow Br. Co. Louth	Salterstown Formation (SA)	Silurian	0.10
Dee	06023	Dromgoolestown, Co. Louth	Salterstown Formation (SA)	Silurian	0.32
Kildorrough	26149	Kildorrough, Co. Cavan	Castlerahan Formation (RA)	Silurian	0.344

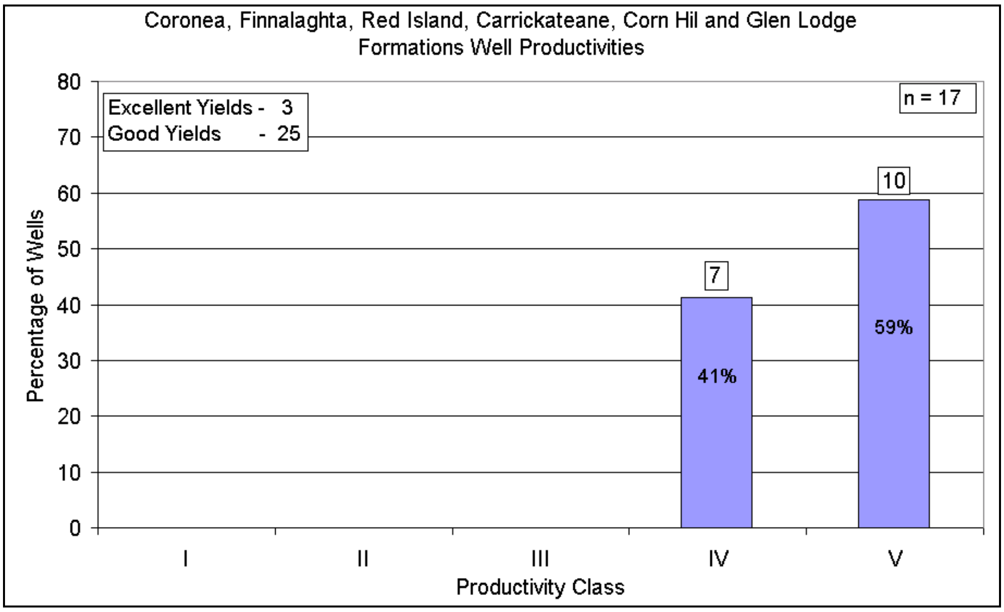
Notes: Dry Weather Flows From EPA data. Adjusted areas and flows are derived by subtracting contributing areas and dry weather flows from upstream gauges. An Area Specific Dry Weather Flow (ASDWF) of 2 l/s/km^2 is considered to indicate the presence of a good aquifer.

Productivity (see Appendix II) and yield data were compiled and analysed within the counties the Ordovician aquifer occurs in. Twenty-eight wells in the Ordovician aquifers of the Longford-Down

Inlier (Figure 4.1) had either Excellent or Good yields. Seventeen wells had productivity values. There are no records of wells with class I, II or III productivities.

Well productivity data for the same area generally confirm the Silurian rocks to be poor aquifers. However, of the few data points (ten productivity values), five are class III. Excellent yielding wells exist in the Silurian aquifer of the Longford-Down Inlier. There are three Excellent well yields and 19 Good well yields. It is therefore possible that there are areas of higher permeability within this otherwise poor aquifer.

Figure 4.1 Well Productivities in the Ordovician aquifers of the Longford-Down inlier



Woods & Wright (2001) suggest that the groundwater levels in Ordovician rock units are variable, but are usually less than 10 m below ground surface, and that the aquifers are generally unconfined. Water level data collected over a ten year period for a 26 m deep well in Co. Kildare show that water levels fluctuate by up to 8 m annually. The large annual fluctuation in the hydrograph indicates the low storage potential and/or bulk permeability in these rock units. Examination of GSI’s well records indicates that groundwater levels are usually less than 15 m below surface in Silurian rock units.

Although fractured, Ordovician and Silurian rocks generally have a low permeability and are mostly regarded as a poor aquifer. Such rocks will often yield enough water to a well to supply a house or small farm (0.2-0.5 l/s), and occasionally in major fracture zones, may yield a good deal more. However, since the yields often depend on the permeability developed in the uppermost few meters of broken and weathered rock, the yields will often decrease markedly in dry spells as the water table falls, and these supplies may therefore be unreliable (Geraghty *et al.* 1997). Groundwater in the Silurian sandstones and shales can be confined by either the clayey till and peat deposits which usually overlie the rocks, or by lower permeability bedrock layers within the sequence. Low lying areas have better groundwater development potential as artesian (flowing) conditions can be encountered and there is good natural protection afforded in the immediate vicinity of the sources by the low permeability materials. Sustainable supplies will be only be accessible from the fault zones.

On the basis of the factors discussed above and summarised in Table 4.4, Ordovician and Silurian Metasediments and Volcanics are classed as a **Poor Aquifer which is generally unproductive except for local zones (Pl)**.

Table 4.4 Summary of factors used to classify the Lower Palaeozoic (Ordovician and Silurian) aquifers of the Longford-Down Inlier

Factor	**Ordovician rocks in the Longford–Down Inlier**	**Silurian rocks in the Longford–Down Inlier**
Lithology	Shale, greywackes, volcanics	Greywackes, Sandstones, siltstone, shales & mudstones
Structure	Fault intensity low	Localised permeable areas formed from structural deformation of the rocks.
Hydrology	Low DWF values	Low to moderate DWF values
Well Hydrographs	None available	None available
Well Productivity	Graph peaks at V, no values above IV	Values are skewed to the lower end of the productivity classes.
Borehole Yields	25 Good Yields 3 Excellent Yields	19 Good Yields 3 Excellent Yields
Aquifer Properties	None available	None available
Classification	**Pl**	**Pl**

4.6 Classification of Granites and Other Igneous Intrusive Rock Aquifers

This aquifer group consists of igneous intrusive rocks, the most widespread rock type being granites. Other rock types within this aquifer group are mainly fine-grained igneous dykes (linear ‘wall-like’ features). The distribution of this rock type is presented on Map 1, while the aquifer is depicted on Map 5. The different formations that comprise this aquifer group are listed in Table 4.2.

In general, Irish granites do not provide large groundwater supplies but can generally provide reliable water supplies for domestic and farm supplies. Fresh granite has no primary permeability, a porosity normally less than 1%, and any pores present are generally small and unconnected (Davis and De Wiest, 1966). Permeability in the granites has developed through fracturing and weathering, which is generally restricted to the top 100 m below ground (Daly, E.P., 1994). Granites are competent rocks and therefore respond to strain by brittle fracture. The degree of fracturing varies laterally and with depth. Tension joints, which are common in granites, are only found close to the surface. Regional joints become tight and impermeable at depth. The fractures do not become in-filled because the granites have a low clay content.

Granite is a relatively coarse-grained rock, which is massive and unbedded. This means that development of groundwater flow will be restricted to the upper weathered portion, and to areas of faulting and fracturing, as contrasted with sedimentary rocks, where preferential flowpaths can occur along lithological differences. Because of its coarse grained nature, granite can weather to a coarse sand, thus locally enhancing its water storage capacity. Finer grained volcanics are typically hard rocks which like granites, fracture cleanly, which may enhance the groundwater flow along faults and fractures.

Area Specific Dry Weather Flows (ASDWF) from rivers flowing over granites in nearby Co. Louth show moderately low values (Table 4.5). These may be associated with the weathered granites overlying the poor fractured granite bedrock aquifers.

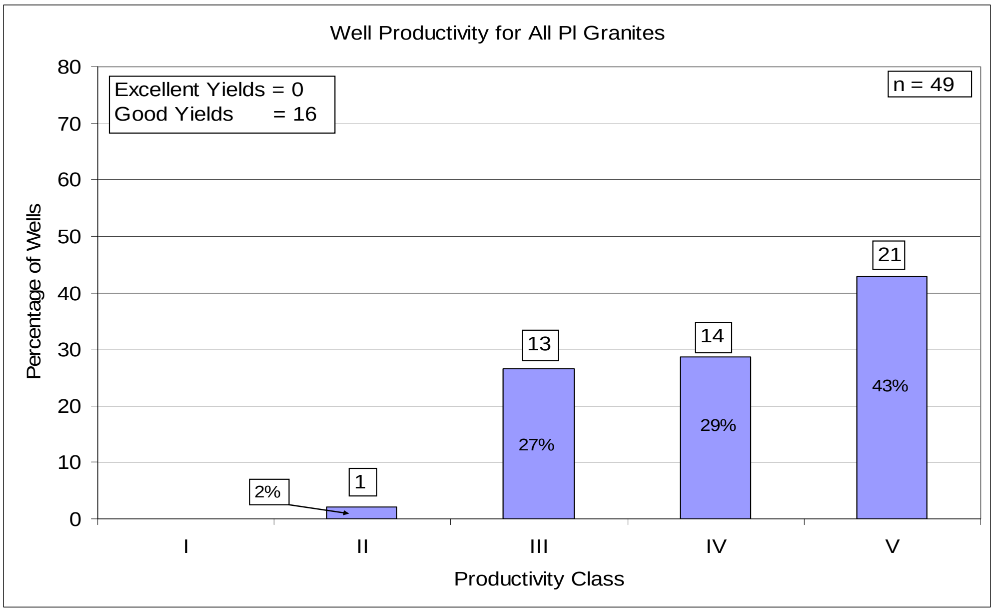
Table 4.5 Dry Weather Flow values for river gauges on nearby Granite aquifers, Co. Louth

County	Gauge	River	Rock	ASDWF (l/s/km^2)
Curralhir, Co. Louth	06031	Flurry	Granophyre (Gr)	0.51
Ballygoly, Co. Louth	06030	Big	Granophyre (Gr)	0.69

Notes: Dry Weather Flows from EPA data. Adjusted areas and flows are derived by subtracting contributing areas and dry weather flows from upstream gauges. An Area Specific Dry Weather Flow (ASDWF) of 2 l/s/km^2 is considered to indicate the presence of a good aquifer.

In Co. Cavan, hydrogeological data are sparse: there are only two wells recorded in the aquifer, both of which have 'Poor' yields. Across Ireland, available productivity and yield data were assessed for the granites as part of the National Aquifer Report (GSI, in preparation). Most well data come from the Leinster granite. These are extrapolated to data-poor granite areas of Ireland. For the area outside the Tullow granite, 49 productivity data are available: these are skewed to the lower end of the range. Six Good yields are recorded, but no Excellent yields.

Figure 4.2 Well Productivities in Irish Granite and other igneous intrusive rock aquifers (excluding Tullow)



On the basis of the factors discussed above and summarised in Table 4.6, Granites and other igneous intrusive rocks are classed as a **Poor Aquifer which is generally unproductive except for local zones (Pl)**.

Table 4.6 Summary of factors used to classify the Granites and other igneous intrusive rock aquifers

Factor	Central Cavan, northwest Cavan
Lithology	Granites, fine-grained sills, dykes, other intrusions
Structure	Fault intensity low. Jointing in upper part.
Hydrology*	Low to moderate DWF values
Well Hydrographs	None available
Well Productivity*	Productivities skewed to lower values.
Borehole Yields*	6 Good Yields 0 Excellent Yields
Aquifer Properties*	None available
Classification	**Pl**

**Notes: Values derived from all Irish granites except the Tullow pluton.*

4.7 Classification of the Dinantian (early) Sandstone, Shale and Limestone Aquifers

The distribution of the rock type is presented in Map 1, while the aquifer is depicted in Map 5. The different rock units that comprise this aquifer group are listed in Table 4.2. Two different successions are recorded: in south Cavan, the Moathill and Meath Formations bend around the north of Lough Sheelin; the Ulster Canal and Cooldaragh Formations occur in a NE-SW trending strip across Monaghan, central Cavan (bending around the south of Lough Oughter), and into Leitrim.

This rock unit group comprises a mixture of siltstones, sandstones, mudstones, shales and limestones. As the rock units are often less than 100 m thick, the surface occurrence of many of the rock units in this group is quite limited, and boreholes often penetrate these units into the underlying sandstones. The narrow outcrop/subcrop of this aquifer means it is difficult using the current river gauge network to calculate river low flows specific to the rock units in this group. Overall, there are few data available on the aquifer properties of the Dinantian (early) Sandstones, Shales and Limestones. There are no high yielding springs recorded in these rock units at any location. Different aquifer classifications are assigned for different areas in this rock unit group. The factors used in the classification are discussed below, and summarised in Table 4.7.

4.7.1 Northeast Cavan-Monaghan region

In the part of the aquifer that occurs in County Monaghan and northeast County Cavan, there is a strong structural influence on the productivity of these rock units. Fracturing and faulting cuts across the aquifer in a largely north-south direction. The fracturing and faulting limits the influence on groundwater flow of the low permeability fine-grained shaly beds which occur in these units.

There are two public supply wells (at Scotshouse-Clones) at which rigorous pumping tests were undertaken. Transmissivities were estimated as 80 m^2/d and 420 m^2/d, with corresponding bulk permeability estimates of 2.4 m/d and 7.5 m/d. Available productivity and yield data for these rock units indicate a relatively productive aquifer. Eight wells with Excellent yields and 11 wells with Good yields are recorded. Productivity data are spread across classes II, III and IV, concentrated in class II.

In this area, the Cooldaragh Limestone and the Ulster Canal rock units are part of a regional flow system which includes the neighbouring rock units of the Ballysteen Limestone, Ballyshannon Limestone and Dartry Limestone. On the basis of aquifer properties, well yields and productivities, and structure, the rock units of the Dinantian (early) Sandstones, Shales and Limestones in the Monaghan and northeast Cavan region are classified as a **regionally important fissured aquifer (Rf)**. Note that this aquifer is not large enough on its own to qualify for Regionally Important aquifer status; however, it is juxtaposed with other productive rock units (see Sections 4.8.1 and 4.12).

4.7.2 Central Cavan-Leitrim region

West of Milltown, well yield and productivity data indicate that the same bedrock aquifer is less productive than in northeast Cavan-Monaghan. The location of the dividing line was made on the basis of large-scale geological structure. However, the exact location of the change in aquifer characteristics is difficult to define due to lack of data and the probable gradational nature of the change.

In these shaly rocks, although fractured, generally low permeabilities occur. These aquifers often yield enough water to a well for a house or small farm (0.2-0.5 litres/second), and in major fracture zones may occasionally yield much more. However, yield often depends on the permeability in the uppermost few metres of broken and weathered rock, and may decrease in dry spells as the water table falls. Six Poor yielding wells and three wells with Moderate yields are known in this aquifer; there are no productivity data available to assess.

On the basis of lithology, well yields and productivities, the rock units of the Dinantian (early) Sandstones, Shales and Limestones in the central Cavan-Leitrim region are classified as a **locally important aquifer** which is **moderately productive only in local zones (Ll).**

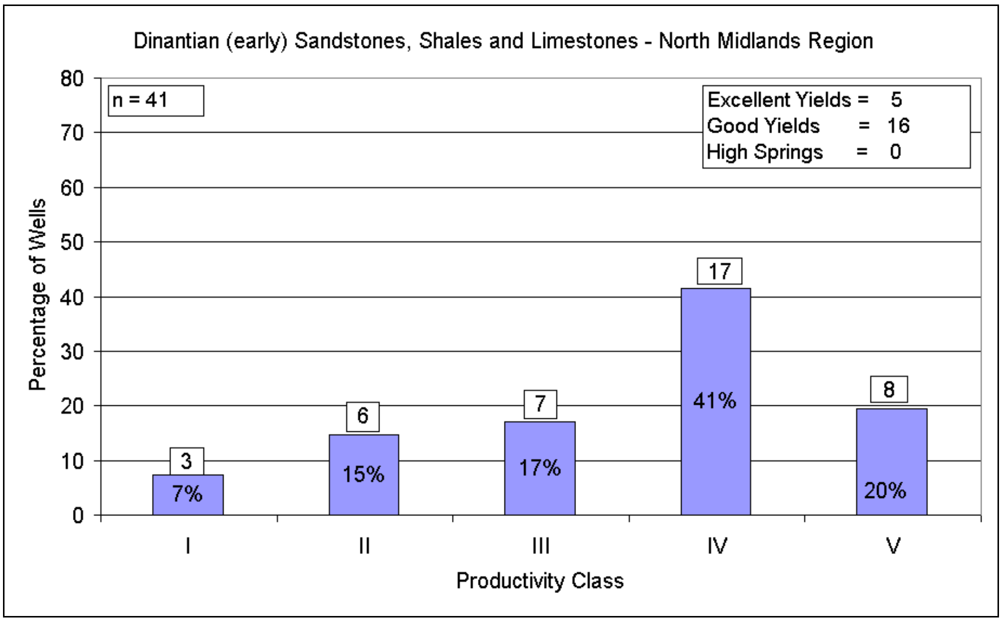
4.7.3 South Cavan and North Midlands region

The rocks units in the North Midlands region are part of the Navan Group. In south Cavan, these comprise the Meath and Moathill rock units. The Navan Group consists of a complex mixture of siltstones, mudstones, shales, sandstones and shaly limestones. The Meath rock unit is described as a sandy limestone with limited amounts of shale. The Stackallan Member (assessed for aquifer classification purposes with the pure bedded limestones, Section 4.12) is a pure limestone which can be dolomitised. Some karstification has been recorded for both these units (McConnell *et al.*, 2001). The Moathill rock unit has a higher shale content than the purer Meath Formation and Stackallan Member, and would therefore be expected to have a lower permeability.

Productivity and yield data were examined for all rock units in the Navan Group. Well data for the Meath Formation was not noticeably better than the other rock units. Therefore, all the rock units of the Navan Group (excepting the Stackallan member) are considered together for the purposes of aquifer classification.

Five Excellent yielding wells and 16 wells with Good yields have been recorded in this rock unit group in the North Midlands area. Most of the data are concentrated in Classes IV and V, but there are also some wells with productivity data in classes I, II and III (Figure 4.3).

Figure 4.3 Well Productivities in the Dinantian (early) Sandstones, Shales and Limestones in the North Midlands region (including South Cavan)



On the basis of the lithology, the productivity and yield data and the absence of High yielding springs the rock units of the Dinantian (early) Sandstones, Shales and Limestones in the North Midlands region are classified as a **locally important aquifer** which is **moderately productive only in local zones (Ll).**

Table 4.7 Summary of factors used to classify the Dinantian (early) Sandstone, Shale and Limestone Aquifers

Factor	**Northeast Cavan-Monaghan**	**Central Cavan-Leitrim**	**South Cavan (part of North Midlands succession)**
Rock Type	Varied Limestone, Siltstones and Mudstones (UC, CH)	Varied Limestone, Siltstones and Mudstones (UC, CH)	Varied Limestones, Sandstones and Shales (MH, ME*)
Structure	North-northeast south-southwest fracturing and faulting enhances permeability	NNW-SSE faults.	NE-SW and E-W faults; often dry.
T values	80-420 m^2/d	No data	No data
Productivity	Mainly Class II, some Class III and IV	No data	Mainly Class IV and V, some Class I, II & III.
Borehole Yields	8 Excellent yields 11 Good yields	No Excellent or Good yields known	5 Excellent yields 16 Good yields
Springs	No High yielding springs	No High yielding springs	No High yielding springs
Dolomite	n/a	n/a	Some in Meath Formation and Stackallan Member*
Karst	n/a	n/a	Some
Classification	**Rf****	**Ll**	**Ll**

** The Stackallan member (MEst) of the Meath Formation (ME) is discussed with the Dinantian Pure Bedded Limestones (Section 4.12).*
*** Not large enough on its own to qualify for Regionally Important aquifer status; however, it is juxtaposed with other productive rock units.*

4.8 Classification of the Dinantian Lower Impure Limestone Aquifers

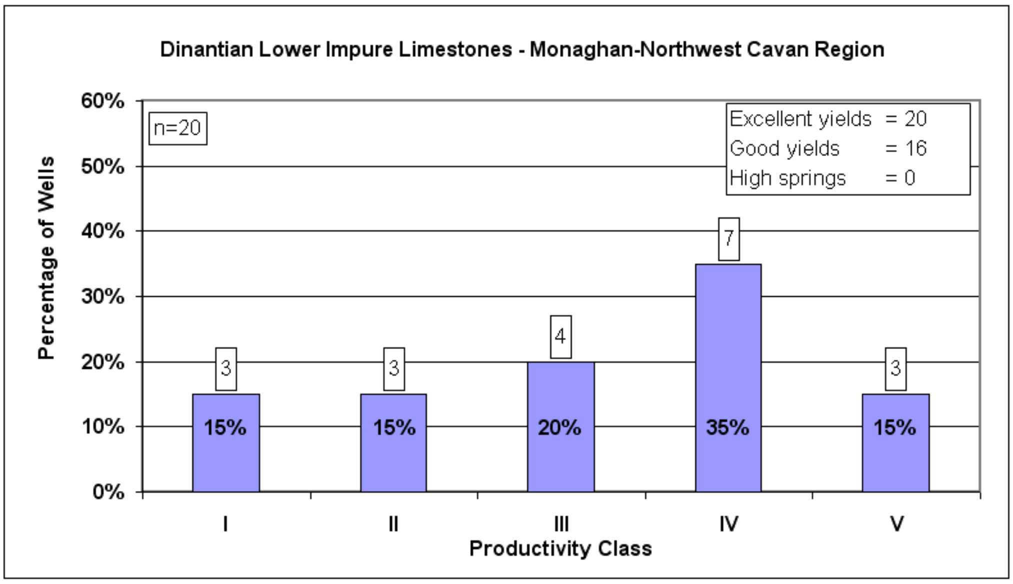
The distribution of the rock unit is presented in Map 1, while the aquifer is depicted in Map 5. In County Cavan the aquifer grouping comprises the stripy dark grey shaly limestones of the Ballysteen Limestone rock unit, which occur in a NE-SW trending strip across central Cavan, and the Argillaceous limestones, which are found near to Lough Sheelin.

Groundwater flow occurs along fractures and faults within these rocks. In general, the lower impure limestones contain substantial amounts of clayey material and thus are generally not susceptible to solution or karstification. The upper portion of the Ballysteen rock unit is more thinly bedded and clay-rich, making widespread circulation of groundwater and dissolution of the limestone less likely than in the lower part. In addition to making the rock less brittle, the clay minerals and thin layers can smear along fault planes, potentially reducing the bulk permeability of the rock unit in intensely deformed regions. Different aquifer classifications are assigned for different areas in this rock unit group. The factors used in the classification are discussed below, and summarised in Table 4.8.

4.8.1 Northeast Cavan-Monaghan region

In the part of the aquifer that occurs in County Monaghan and northeast County Cavan, there is a strong structural influence on the productivity of these rock units. There are a number of large N-S faults cross-cutting the folds, and numerous smaller faults. The fracturing and faulting limits the influence on groundwater flow of the low permeability fine-grained shaly beds which occur in these units. In the area, there are 20 Excellent yielding wells and 16 known wells with Good yields. Productivity values spread across all classes relatively evenly, although there is a peak in class IV (Figure 4.4).

Figure 4.4 Well Productivities in the Dinantian Lower Impure Limestones in the Northeast Cavan-Monaghan region



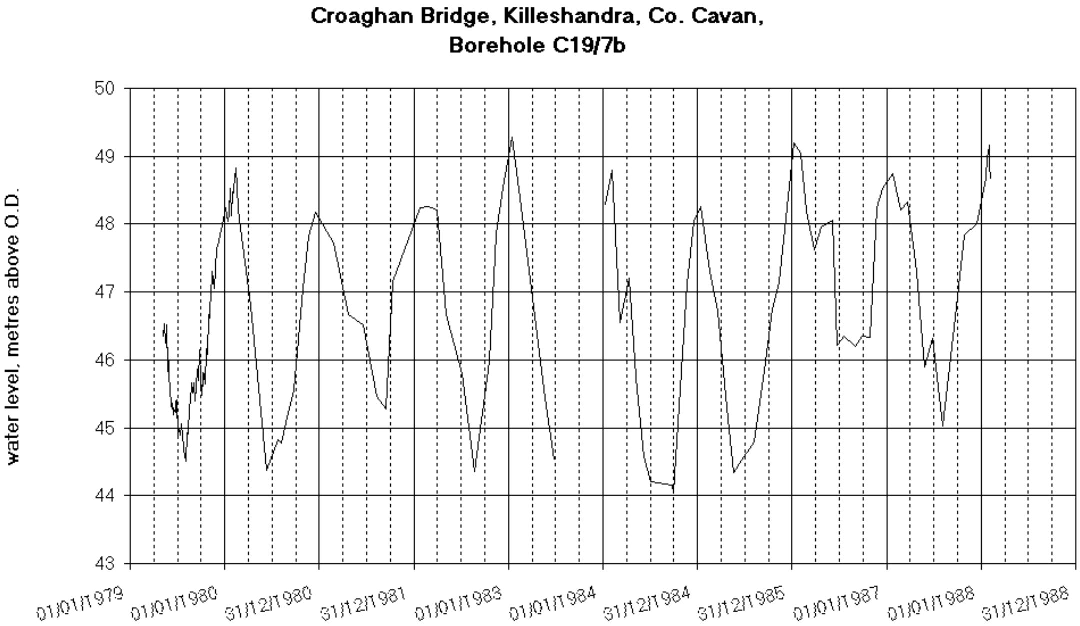
In this area, the Ballysteen Limestone rock unit is part of a regional flow system which includes the neighbouring Cooldaragh Limestone, Ulster Canal, Ballyshannon Limestone and Dartry Limestone rock units. On the basis of well yields and productivities, and structure, the rock units of the Dinantian Lower Impure Limestones in the Monaghan and northeast Cavan region are classified as a **regionally important fissured aquifer (Rf)**. Note that this aquifer is not large enough on its own to qualify for Regionally Important aquifer status; however, it is juxtaposed with other productive rock units (see Sections 4.7.1 and 4.12).

4.8.2 Central Cavan-Leitrim and South Cavan regions

West of Milltown, well yield and productivity data indicate that the same bedrock aquifer is less productive than in northeast Cavan-Monaghan. The location of the dividing line was made on the basis of large-scale geological structure. However, the exact location of the change in aquifer characteristics is difficult to define due to lack of data and the probable gradational nature of the change.

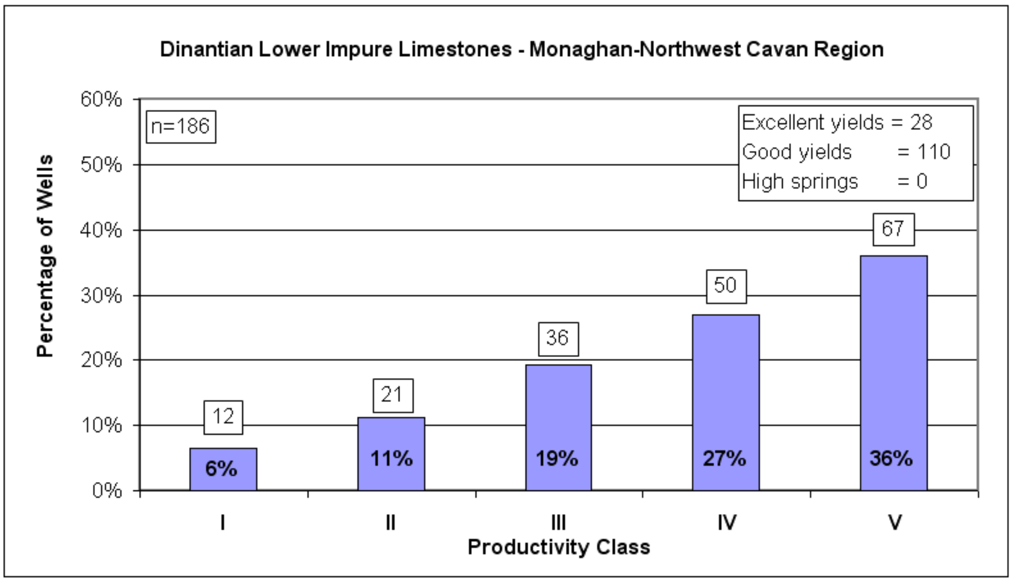
In these rock units there is almost no deep permeability; groundwater movement in these rock units occurs relatively slowly and is often concentrated in the weathered and shallow subsurface zone in the upper few metres or tens of metres of fractured bedrock. Therefore, the bulk (large-scale) fracture permeability, with the possible exception of areas near faults, is generally low. Flow directions are expected to approximately follow the local surface water catchments. Flow paths are short, and discharges are frequently to small springs or to the normally effluent (gaining) streams and rivers that traverse the aquifer. Groundwater levels are typically less than 15 m below ground level, and vary up to 5 m. Groundwater levels recorded as part of the NERDO study (AFF and GSI, 1981) near Killashandra show a typical seasonal variation of 3.5-4 m (Figure 4.5).

Figure 4.5 Borehole hydrograph in the Killashandra area, Co. Cavan (AFF and GSI, 1981)



In general, groundwater development in the lower impure limestones is often not particularly successful: yields are often at the lower end of the scale (Poor to Moderate or Good), with corresponding lower productivity values (predominantly III to V, Figure 4.6). The fractured upper and more permeable layer is unlikely to provide sustainable enough supplies for larger wells, and will often contain lesser quality water than the deeper permeable horizons. However, as the number of data available to assess the Ballysteen rock unit (and its equivalents) shows, it is an aquifer that is widely used to satisfy domestic and other small groundwater supply demands.

Figure 4.6 Well Productivities in the Dinantian Lower Impure Limestones in the Central Cavan-Leitrim and South Cavan-North Midlands regions



Obtaining good yields usually depends on locating fault zones and/or dolomitisation at depth. In general, optimum well yields from the lower impure limestone aquifer will be obtained from boreholes drilled into one of the many fault zones and penetrate at least 50-100 m of the aquifer. Geophysics has been used successfully to locate fault zones. Gravel/sand deposits above the bedrock unit may also help to provide flow and storage to aquifer and protect against pollution.

High concentrations of iron, manganese and hydrogen sulphide may occur, providing considerable problems for those with private wells. This effect is sometimes the result of contamination, but is often a consequence of the combination of both the natural iron sulphide in the shalier parts of the rock formation, and the generally slow groundwater circulation.

On the basis of lithology, well yields and productivities, the rock units of the Dinantian Lower Impure Limestones in the central Cavan-Leitrim and North Midlands-South Cavan regions are classified as a **locally important aquifer** which is **moderately productive only in local zones (Ll).**

Table 4.8 Summary of factors used to classify the Dinantian Lower Impure Limestone Aquifer

Factor	**Northeast Cavan-Monaghan**	**South Cavan-North Midlands**	**Central Cavan-Leitrim**
Rock Type	Impure (muddy) limestone with muddy layers and occasional evaporite minerals.	Impure (muddy) limestone with muddy layers.	Impure (muddy) limestone with muddy layers; occasional evaporite minerals.
Structure	Significant NNE-SSW fracturing and faulting enhances permeability	Moderate degree of faulting. NE-SW and E-W faults.	Moderate degree of faulting. NNW-SSE faults.
T values	No data	5 – 50 m^2/d	No data
Productivity	Limited data are spread across all categories	Skewed to lower productivity classes	No data for this area. Will be as for South Cavan-North Midlands
Borehole Yields	20 Excellent yields 16 Good yields	28 Excellent yields 110 Good yields	No Excellent or Good yields known; 14 Moderate and 11 Poor yields recorded.
Springs	No High yielding springs	No High yielding springs	No High yielding springs
Dolomite	Not recorded. Evaporite minerals present.	n/a	n/a
Karst	Not recorded.	Not recorded.	Not recorded.
Classification	**Rf** *	**Ll**	**Ll**

** Not large enough on its own to qualify for Regionally Important aquifer status; however, it is juxtaposed with other productive rock units.*

4.9 Classification of the Dinantian Sandstone Aquifers

The distribution of the rock units in this aquifer group is presented in Map 1, while the aquifers are depicted in Map 5. In County Cavan the aquifer grouping comprises the Fearnaght Sandstone and the Glenade Sandstones. The Fearnaght Sandstone rock unit is found in a narrow NE-SW trending strip across central Cavan that curves below Lough Oughter. It comprises cream, red and purple conglomerates and sandstones, and is estimated to be a maximum of 20 m thick. The rock unit is adjacent to the Dinantian (early) Sandstones, Limestones and Shales (Section 4.7), and Dinantian Lower Impure Limestones (Section 4.8). The Glenade Sandstone rock unit is a thick-bedded pale brown sandstone. It ranges in thickness from 80 m to 300 m. This rock unit occurs under the higher areas in the northwest of Cavan. The factors used in the classification are discussed below, and summarised in Table 4.9.

Groundwater in these sandstones circulate primarily though fissures, as these rocks do not have significant intergranular permeability. These rock units are predominantly sandstones and conglomerates with limited shale content. Coarse-grained rocks such as sandstones and conglomerates tend to deform by rupturing or brittle fracture resulting in more frequent fractures and joints. These rocks will therefore tend to have higher fissure permeabilities than fine grained rocks such as shales. The limited amount of shaly fine grained material in this rocks means that faults and fractures, where they occur, will be more likely to remain open allowing groundwater flow. Fissure permeability is generally more developed in the top 20-30 m of fractured and weathered rock, and in the vicinity of fault zones. Where there has been more intense faulting and folding these zones of high permeability will be more common.

4.9.1 Central Cavan region

The dominant lithologies of the Fearnaght rock unit are sandstone and conglomerate, which have the potential to develop fissure permeability. The sandstones and conglomerates were deposited on an erosion surface (unconformity). Prior to their deposition, the older Ordovician rocks were eroded, leaving a weathered and irregular surface. Where a weathered surface exists it increases the likelihood of the existence of preferential flow paths that can act as a focus for groundwater flow. This is additionally likely when the first sediments laid down after deposition resumed are coarse conglomerates.

There are very limited well data available for these rock units. Based on the lithology of the units and the potential for increased groundwater flow along the unconformable contact, the Fearnaght Sandstone rock unit (excluding the northeast Cavan-Monaghan area) is classified as **locally important aquifers which are generally moderately productive (Lm).**

4.9.2 Northeast Cavan-Monaghan region

The Fearnaght rock unit in the northeast Cavan-Monaghan area is part of a regional flow system that includes the neighbouring rock units of the Ballysteen Limestone, Ballyshannon Limestone and Dartry Limestone (Sections 4.8.1 and 4.12). The Fearnaght Formation in the northeast Cavan-Monaghan is therefore classified as a **regionally important fissured aquifer (Rf).** The location of the dividing line was made on the basis of large-scale geological structure. However, the exact location of the change in aquifer characteristics is difficult to define due to lack of data and the probable gradational nature of the change. The grouped flow system is dominated by the NNE-SSW fracturing and faulting which cuts across these units.

4.9.3 Northwest Cavan region

To date there has been little development or investigation of groundwater in the sandstones of the northwest. There are very limited data available: only four wells with productivity data are known, three class III and one class II. There are only twelve wells in total for which yield data are available, of which nine were Good yields. An investigation near Sligo Town of sandstone units similar to the Glenade Sandstone (Daly, 1975) concluded that boreholes drilled through the entire formation should give yields in the region of 500-1000 m^3/d. In this study, several fissures and water inflows were encountered in the test boreholes (the deepest at 50m in a 57m deep borehole), indicating development of fissure permeability.

Based on the dominant sandstone lithology of the Glenade Sandstone, and its similar depositional history to the Mullaghmore Sandstone near Sligo for which Excellent yields were suggested (Daly, 1975), these rock units are classified as a **locally important aquifer which is generally moderately productive (Lm).**

Table 4.9 Summary of factors used to classify the Dinantian Sandstone Aquifers

Factor	**Central Cavan**	**Northeast Cavan-Monaghan**	**Northwest Cavan**
Rock Type	Sandstone and conglomerate.	Sandstone and conglomerate.	Thick-bedded quartzitic sandstone.
Structure	Moderate degree of faulting. NW-SE faults. Erosion surface focuses groundwater flow.	Frequent NNE-SSW faulting and associated fracturing. Erosion surface focuses groundwater flow.	Open fractures. Higher permeability zones likely in vicinity of NW-SE and E-W fault zones. Limited faulting.
T values	No data	No data	No data
Productivity	-	-	1 class II, 3 class III
Borehole Yields	-	-	9 Good Yields
Springs	No High yielding springs	No High yielding springs	No High yielding springs
Dolomite	-	-	-
Karst	-	-	-
Classification	**Lm**	**Rf**	**Lm**

4.10 Classification of the Dinantian Shale and Limestone Aquifers

The distribution of the rock unit group is presented in Map 1, while the aquifer grouping is depicted in Map 5. The rock units are composed predominantly interbedded shales and limestones with little or no sandstone content. They occur mainly in the uplands in the northwest of the county, and also in a NE-SW trending band across the centre of County Cavan. The different rock units that comprise this aquifer group are listed in Table 4.2.

Groundwater in these rock units will circulate primarily though fractures and faults. However, fine-grained rocks such as mudstones and shales deform chiefly plastically rather than by jointing, and are likely to have low fissure permeability. Fractures are also often infilled by weathered material, reducing their ability to transmit groundwater. Consequently, development of fissure permeability will generally tend to be confined to weathered zones close to the surface of the rock and in the vicinity of fault zones. In general, development of interconnected fissuring at depth and across wide areas is unlikely in these shaly rocks. There are some areas, however, where a high frequency of faulting has significantly improved the permeability of some rock units. In the Monaghan-northeast Cavan area, numerous north-south faults cross-cut the Drumgesh Shale (and adjacent rock units). These faults and associated additional fracturing are thought to increase the permeability of the rock units in the area. Decisions on aquifer classifications are discussed below and are summarised in Table 4.10.

4.10.1 Northeast Cavan-Monaghan region

The Drumgesh Shale is found in a NE-SW trending band across central Cavan. It is composed of interbedded shales and limestones. The rock unit ranges from shale with some limestone interbeds in its lower part, to less shaly very fine dark limestone in the upper part, where there is a gradational contact with the overlying Dartry Limestone. While the overall nature of this unit may be shaly, groundwater flow is likely to occur along the non-shale, high permeability zones that develop in the purer limestone interbeds.

In the Monaghan-northeast Cavan area, numerous north-south faults cross-cut the Drumgesh Shale (and adjacent rock units). These faults and associated additional fracturing are thought to increase the permeability of this rock unit in the area east of Milltown. The location of the line separating more from less productive areas of the aquifer was made on the basis of large-scale geological structure. However, the exact location of the change in aquifer characteristics is difficult to define due to lack of data and the probable gradational nature of the change.

Well yield and productivity data are sparse. Only six wells with productivity data are available; productivities range from class I to class III. Four Excellent and 13 Good yielding wells are recorded. Weathered dolomitised limestones and cavities have been encountered at depth in limestone interbeds in the Drumgesh Shale. Borehole logs for two productivity class II wells in the Drumgesh Shale indicate that the productive zones correspond to the weathered, clean dolomitised portion of the well (Swartz & Daly, 2002).

On the basis of available well data, intensity of fracturing and the presence of high permeability zones within the purer limestone interbeds, the Drumgesh Shale in the northeast Cavan-Monaghan area is classified as a **locally important aquifer which is generally moderately productive (Lm)**.

4.10.2 Northwest and Central Cavan region

The rock units occurring in the northwest and centre of Co. Cavan are: the Carraun Shale, Benbulben Shale, Bundoran Shale and Drumgesh Shale. As there are limited hydrogeological data available for the Dinantian Shales and Limestones, aquifer classification is based primarily on information about lithology and fissuring within these rock units, together with inferences from similar rock types around the country.

The Carraun Shale (CN) occurs only in the Lough Allan uplands. It is primarily composed of shale with thin subordinate limestones. No well data are available for this rock unit. Based on the dominant shaly lithology of this rock unit, which is likely to inhibit the development of fissure permeability, the Carraun Shale is classified as **a poor aquifer, generally unproductive except for local zones (Pl).**

The Bundoran and Benbulben Shales are found east of Ballyconnell and around Swanlinbar respectively. They are composed of interbedded shales and limestones. There are very limited well data available for these rock units; over the whole area these rock units occur, there are ten Good yielding wells recorded. The high degree of fine-grained shaly material in these rock units is likely to restrict groundwater circulation. Although higher permeability zones may be developed in the vicinity of fault zones and in purer limestone interbeds, in general the dominant shaly lithology of these rock units means higher permeabilities will generally be confined to local zones. These rock units are classified as **locally important aquifers, generally productive only in local zones (Ll).**

There are few data available for the Drumgesh Shale where it occurs in County Cavan west of Milltown, and in Leitrim. Ten Good well yields are recorded, together with three well productivities in Classes III, IV and V. No data are available relating to weathering and dolomitisation. Primarily on the basis of lithology, and in the absence of any information regarding dolomitisation or dissolution, the Drumgesh Shale in Central Cavan (west of Milltown) and in Leitrim is classified as **locally important, generally productive only in local zones (Ll).**

Table 4.10 Summary of factors used to classify the Dinantian Shale and Limestone Aquifers

Factor	Northeast Cavan-Monaghan	Central and Northwest Cavan		Northwest Cavan
Rock Type	Drumgesh Shale: Shales & mudstones with subordinate limestones and dolomites.	Drumgesh Shale: Shales & mudstones with subordinate limestones.	Bundoran and Benbulben Shales: interbedded shales and limestones	Carraun Shale: shale with thin subordinate limestones
Structure	Frequent North-south faulting and associated fracturing.	-	Significant localised NE-SW faulting in Benbulben.	-
T values	200 m^2/d	No data	No data	No data
Productivity	1 Class I; 4 Class II; 1 Class III	1 each of Class III, Class IV and Class V	-	-
Borehole Yields	3 Excellent yields 13 Good yields	14 Good yields	10 Good yields	-
Springs	No High yielding springs	No High yielding springs	No High yielding springs	No High yielding springs
Dolomite	Dolomite and cavities recorded.	None recorded but potentially in purer limestone interbeds.	-	-
Karst	-	-	-	-
Classification	**Lm**	**Ll**	**Ll**	**Pl**

4.11 Classification of the Dinantian Mixed Sandstone, Shale and Limestone Aquifers

The distribution of the rock type is presented in Map 1, while the aquifer is depicted in Map 5. The aquifer grouping consists of rock units composed of interbedded sandstones, shales and limestones. The different rock units that comprise this aquifer group are listed in Table 4.2 and discussed below.

The Meenymore rock unit is found on the flanks of Slieve Rushen and the Cuilcagh Mountains. The Meenymore is comprised of shales interbedded with laminated limestones, mudstones, sandstones and dolomites. It also contains evaporite deposits. At Drumhurrin, a borehole intersected over 6 m of gypsum at a depth of 140 m, close to the base of the rock unit. The rock unit ranges in thickness from no more than 20 m thick near Meenymore, County Leitrim to approximately 240 m on Slieve Rushen. The variations in thickness of the unit are partly because of the topography of the upper surface of the underlying Dartry Limestone, but also because of regional and fault-controlled local differential subsidence (Sevastopulo & Jackson, 2001). The Bellavally Shale occurs in the Lough Allen uplands, above the Meenymore rock unit. It is comprised of grey limestone, shale, laminated dolomicrite or micrite with evaporite beds, silty mudstone and thin bedded sandstones and siltstones. The unit is 33 m thick northeast of Drumshambo, County Leitrim, but is uniformly thicker in County Fermanagh (Mac Dermot *et al*, 1996). The Doobally Sandstone member consists of sandstone with subordinate shales and siltstones. It is thickest at 17m near Doagh, and thins southward to no more than 1.5m thick in Leitrim.

In the Stradone area, there was insufficient information to differentiate the Dinantian rocks on the bedrock map (Geraghty, 1997). They have been assigned as undifferentiated Dinantian (DIN) and include a variety of limestone, shales and dolomites.

Groundwater in the Dinantian Mixed Sandstones, Shales and Limestones in Ireland will circulate primarily though fissures, as these rocks do not possess significant intergranular permeability. The rock units in the group are composed of a mixture of interbedded shales and limestones with some sandstone which would generally be expected to have low fissure permeability, except where more open faulting and associated fracture occur in the sandstone beds and where dissolution and dolomitisation of purer limestone interbeds or evaporites have enhanced permeability. Development of fissure permeability will generally tend to be confined to weathered zones close to the surface of the rock and in the vicinity of fault zones. While the presence of shale is likely to result in lower permeabilities, the varied nature of the rock units in this group, with the presence of sandstone and limestone beds means that these rock units are unlikely to be consistently poorly permeable. However, the shales will act to restrict large-scale development of permeability and development of interconnected fissuring at depth unless there is a high density of faulting and associated fracturing. High sulphate concentrations deriving from the dissolution of evaporite minerals may occur in groundwaters abstracted from these rock units.

As there are limited hydrogeological data available for the Dinantian Sandstones Shales and Limestones, aquifer classification is primarily based on what is known about the lithology and fissuring within these rock units, and inferences from experiences in areas where more data are available. The assessments of aquifer classification are discussed below, and summarised in Table 4.11.

In the absence of any well data or other information relating to the hydrogeology of these rock units the Bellavally Shale and Doobally Sandstone are classified on the basis of lithology and inferences from data available for the similarly variable Boyle Sandstone. While the presence of shale is likely to result in lower permeabilities, given the variability in the lithology of these rock units they are unlikely to be consistently poorly permeable and are classified as **locally important aquifers, generally moderately productive except in local zones (Ll).**

There are no well data available for the Meenymore Formation where it occurs skirting the Lough Allen uplands. Based on lithological descriptions alone the Meenymore Formation would seem to be very similar to the majority of the rock units in this group which have been classified as **locally important aquifers, moderately productive only in local zones (Ll).**

Described as a variety of limestones, shales and dolomites, there are no well data available for the rock unit near Stradone. In the absence of more detailed information on the lithology of these rocks, and given the suggested presence of limestones and dolomites, the Undifferentiated Dinantian (DIN) is classified as **locally important aquifers generally moderately productive (Lm).**

Table 4.11 Summary of factors used to classify the Dinantian Mixed Sandstone, Shale and Limestone Aquifers

Factor	**Bellavally Shale (BE), Doobally Sandstone (BEdo), Meenymore (ME)**	**Dinantian Undifferentiated Limestone (DIN)**
Rock Type	Mixed sandstone, shale and limestone.	Limestones, shales and dolomites.
Structure	-	-
T values	5 – 70 m^2/d *	-
Productivity	Spread across classes III, IV and V*	-
Borehole Yields	Several Good yields, one Excellent yield in analogous rock unit.	Many Excellent well yields in analogous rock unit.
Springs	No High yielding springs	No High yielding springs
Dolomite	Depositional dolomite and evaporites.	Dolomite described.
Karst	-	-
Classification	**Ll**	**Lm**

**Values are for the Boyle Sandstone, a similar rock unit*

4.12 Classification of the Dinantian Pure Bedded Limestone and Dinantian Pure Unbedded Limestone Aquifers

The rock units in the Dinantian Pure Bedded Limestone group generally comprise pure, pale grey, well-bedded, fine-to coarse-grained limestones and are listed in Table 4.2, and described in Table 2.1 and Section 2.3. These limestones are often fossiliferous, and can have considerable variations in grain size and the degree of re-crystallisation, and the occurrence of chert and shale bands. The Unbedded Pure Limestones are described with the bedded limestones, since they have very similar aquifer characteristics; in other areas of the country, pure limestones that are unbedded often have poorer aquifer characteristics than pure bedded limestones.

The rocks outcrop and subcrop mainly across north central County Cavan, with smaller occurrences in the very north, east and south of the county. The limestone area in the very north of the county is part of the ‘Northwestern Plateau’. The limestones that underlie much of north central Cavan (from Brackley and Bunerky Lough in the west, to east of Ballyconnell, to Derrycassan Lough in the south) are the same as those of the Northwestern Plateau. They differ in that the north central Cavan area is lower-lying, and is also covered with thicker subsoils. In the far east of the County, the pure limestone belongs to the Milverton Group, which mainly occurs in Counties Monaghan and Meath. The pure bedded limestones in the south of the county are either part of the Meath Group (see Table 2.1) or are Undifferentiated Visean limestones. The distribution of the rock unit group is presented in Map 1, while the aquifer classification is depicted in Map 5.

In general, the absence of clay minerals within the pure limestone beds and their generally shale-free nature makes them more brittle than their impure limestone counterparts, resulting in the greater development of fracturing, and hence permeability. These rocks, because of their purity, are also susceptible to solution and karstification. The rock’s permeability depends on the presence of fissures, faults and joints along which groundwater can flow. Jointing developed in the limestones has allowed the percolation and flow of water in an extensive fracture network. Bedding planes can also act as preferential flow pathways. The enlargement by solution of these planar features often further enhances the bulk permeability of the pure bedded limestones. Karstification can be accentuated along structural features such as fold axes and faults and can result in high permeability and throughput in relatively narrow zones.

The development of karst results in distinctive features of topography, hydrology and hydrogeology. The main characteristic karst features include turloughs, swallow holes, sinking streams, sparse or intermittent streams, limestone pavement, dry valleys, caves and large springs.

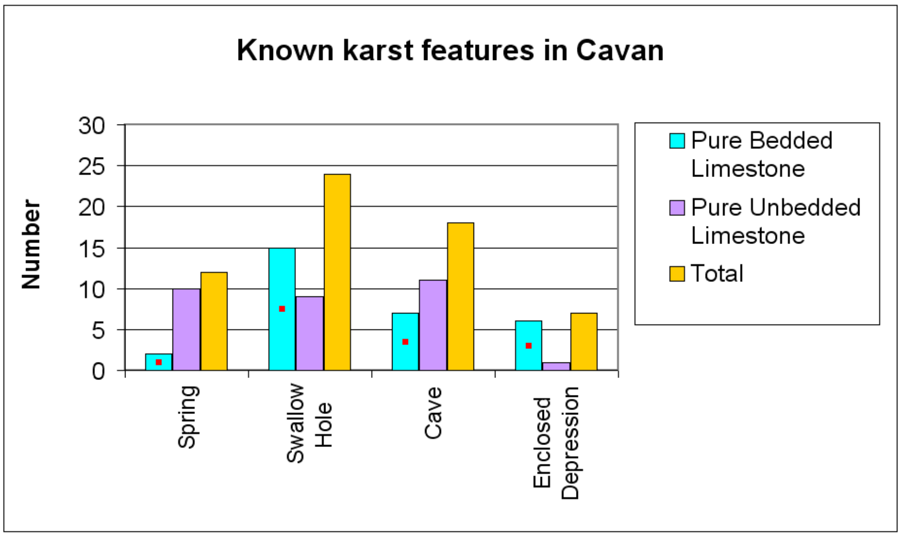
4.12.1 North Cavan (the Northwest Plateau) and North Central Cavan

The Northwestern Plateau that spans Counties Sligo, Leitrim, Cavan and Fermanagh is largely a dissected plateau with caps of shale and sandstone on some of the mountains. Most karst features (including caves and potholes) in the northwestern area have developed around the edges of the mountains and on the sides of the associated valleys, which are capped with impermeable rocks off which streams drain (Map 4). In areas where the shale caps have been eroded and surface drainage is therefore not concentrated, swallow holes have not developed and the surface is characterised by enclosed depressions, dry valleys and limestone pavements. Recharge is generally through a diffuse system of enlarged joints.

The River Shannon itself emerges at a karst feature, the 'Shannon Pot' in Co. Cavan. While this was once thought to be the source of the River Shannon, research by Gunn (1982) suggests that the Shannon originates in Co. Fermanagh on the Cuilcagh Mountains, sinks, and then travels underground via the Shannon Caves to re-emerge at the Shannon Pot.

The numbers of different karst features known in County Cavan are shown graphically in Figure 4.7.

Figure 4.7 Known karst features in the Dinantian Pure Bedded and Unbedded Limestone Aquifers in County Cavan.

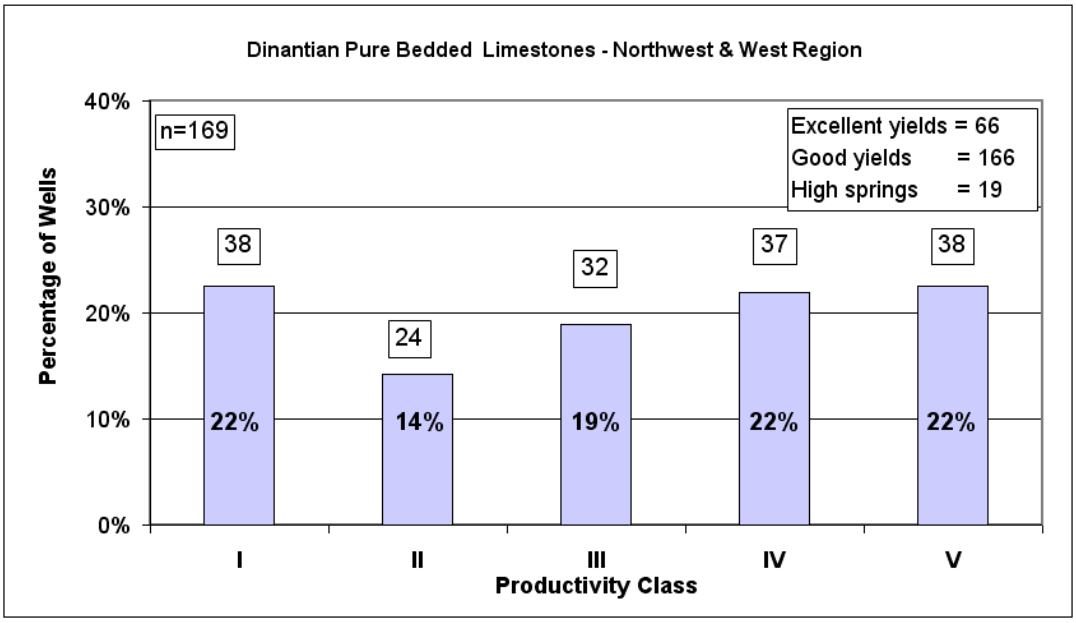


Within the areas underlain by these rocks, where subsoil cover is thin or comprises high permeability gravels, stream densities tend to be low and there is typically a high degree of interconnection between surface waters and groundwaters. Where subsoil is thicker and/or lower permeability, drainage densities are controlled primarily by subsoil characteristics. Recharge will tend to be diffuse.

Little groundwater data exist for the Northwestern Plateau area. However, it is thought that, like the Burren area (for which much work has been carried out), there is no continuous water table surface over much of the upland area. Instead, water is channelled along conduits and fissure systems and therefore rises to different levels across the region. In the lower-lying areas of north central Cavan, a more continuous water table is probable.

As with most karstic systems, permeability and transmissivity data are very variable. National data indicate that transmissivities can range from <2m^2/d to several 1000's m^2/d. Well productivity data for both upland and lowland karst limestones in the West and Northwest (from Co. Clare to Co. Cavan) are spread across all categories (Figure 4.8). Usually in karstified limestones, well productivities are variable and most high productivities tend to correspond to intersected karst conduits. Low productivity or failed wells can be common, reflecting the lack of flow between individual conduits. In this type of aquifer, across the west and northwest, there are 19 High yielding springs, indicating significant concentration of flow (see Section 4.4.4), in addition to 66 known Excellent yielding wells and 166 Good yielding wells. In County Cavan, there are 6 known Excellent yielding wells and 15 Good yielding wells. There are two Class II, one Class IV and two Class V productivity wells known in Cavan. Tracer testing in the northwest of Cavan indicate that groundwater flow velocities range from about 50 m/hr up to 250 m/hr (average 120m/hr).

Figure 4.8 Well Productivities in the Dinantian Pure Bedded Limestone Aquifers in Northwest and West

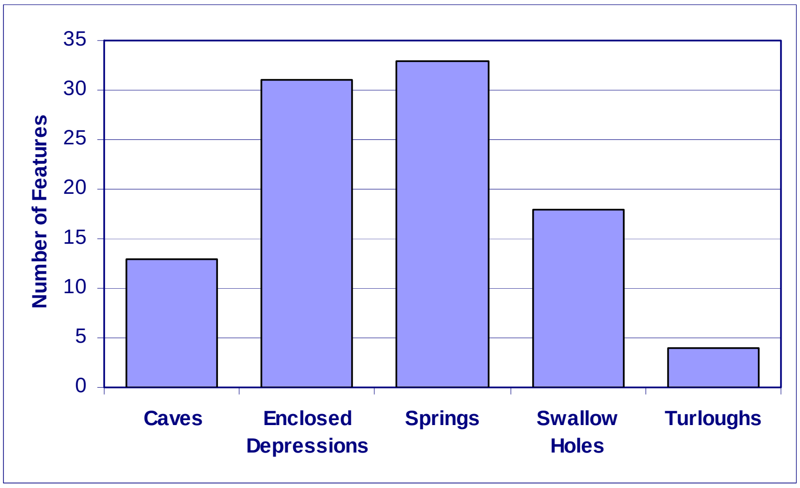


Depending on the known nature of the karstification (e.g. highly conduitised), and the size of the limestone, the Dinantian Pure Bedded Limestones and Pure Unbedded Limestones (listed in Table 4.2) are classified as **regionally important karstified aquifers (Rk)**, or **regionally important karstified aquifers that are dominated by conduit flow (Rkc)**, or **locally important karstified aquifers (Lk)**.

4.12.2 East Cavan

A small area (<1 km^2) of east Cavan, approximately ½ km east of Kingscourt, is mapped as Milverton Group Limestone. This is described as clean, 'conspicuously' bedded limestones showing evidence of karstification. It is also reported to be dolomitised (Jackson, 1955), which increases the permeability and porosity of the limestone. Karst features are found throughout this aquifer in County Monaghan (Figure 4.9). Extensive field mapping of the karst features in this aquifer has not been carried out, and the number of karst features on record is likely to be only a small proportion of those present. Numerous springs are recorded within this aquifer, although not all of these are related to karstification.

Figure 4.9 Recorded karst features in the Milverton Group Limestones in County Monaghan (from Swartz and Daly, 2002)



Limited tracer tests at some of the sinkholes and springs in Co. Monaghan were undertaken to investigate the hydrogeological characteristics in the vicinity of a landfill site at Annahaia Townland (Mullen, 1986). The maximum velocity measured during the test was 60 m/hr (1.4 km/d). A high degree of interconnection between surface water and groundwater is expected, as water flows into swallow holes and rises at springs. Fifteen wells have useful data for this aquifer; all of these wells have Good yields, eight of which have yields above 400 m^3/d (Excellent yields). Well productivities fall into classes I (two) and II (five) and III (one).

On the basis of karstification and yield information, mainly in County Monaghan, but bearing in mind the very limited size of the occurrence in County Cavan, this limestone is classed as a **locally important karstified aquifer (Lk)**.

4.12.3 South Cavan

The pure bedded limestones in the south of the county comprise: the Stackallan member of the Meath rock unit (see Section 4.7.3 and Table 4.2); and Undifferentiated Visean Limestones.

The Stackallan limestone can be dolomitised, and karst has been recorded in it (McConnell *et al.*, 2001). In South Cavan, the Stackallan limestone is compartmentalised by faulting, and is limited in thickness, ranging from 200 m to about 1,000 m width on the map. Due to their highly faulted nature and limited extent, these limestones are classed as a **locally important aquifer, generally moderately productive (Lm)**.

Little is known about the Undifferentiated Visean Limestones. They are described generally as limestones that were deposited in shallow seas, so they are likely to be pure and bedded. These characteristics lend themselves to fracturing and karstification. The area of these limestones within County Cavan is limited, but the entire rock unit is almost 50 km^2. It is therefore classed as a **regionally important karstified aquifer that are dominated by diffuse flow (Rkd)**.

4.12.4 Central Cavan

Approximately 5 km southwest of Crossdoney, there is a very small (<0.2 km^2) area of Croghan limestone. It is bounded by faults, and is surrounded by the Lower Palaeozoic altered sandstones and shales (Section 4.5). From what is known about the Croghan Limestone elsewhere, it assumed that this small inlier of limestone will be karstified to some degree. It is therefore classed as a **locally important karstified aquifer (Lk)**.

The aquifer classifications are summarised in Table 4.12.

Table 4.12 Summary of factors used to classify the Dinantian Pure Bedded Limestones and Pure Unbedded Limestones

Factor	**South Cavan**		**East/Central Cavan**	**North and Northwest Cavan**
Rock Type	Pure Bedded Limestone – Stackallan Limestone (MEst)	Pure Bedded Limestone – Undifferentiated Visean Limestone (VIS)	Pure Bedded Limestone – Milverton Group (MLV); Croghan Limestone (CL)	Pure Bedded Limestone; Pure Unbedded Limestone – Dartry Limestone and members (DA, DAcr, DAkn, DAmk, DAcw, crDA)
Structure	Highly faulted	-	Fault-bounded	Faulted and fault-bounded by N-S and E-W faults.
T values	No data	No data	Data in Monaghan indicate 20-270 m^2/d.	<1-1,000's m^2/d.
Productivity	No data	No data	Concentrated in Classes I and II.	Productivities across all Classes.
Borehole Yields	No data	No data	8 Excellent yields 7 Good yields.	66 Excellent yields; 166 Good yields in this limestone type.
Springs	No High yielding springs.	No High yielding springs.	No High yielding springs.	High yielding springs in this limestone type.
Dolomite	Identified	-	Not described	
Karst	Reported	Presumed	Significant	Significant
Classification	**Lm**	**Rkd**	**Lk ***	**Rkc/Rk/Lk ****

** Note: classification of Lk due to restricted size.*
*** Note: classification depends on extent and nature of karstification, and size of contiguous limestone area.*

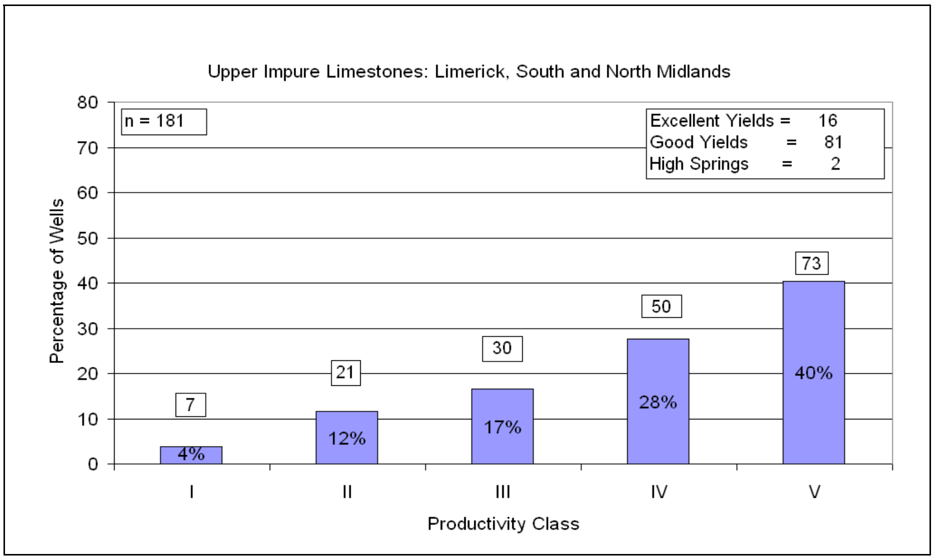
4.13 Classification of the Dinantian Upper Impure Limestone Aquifers

The distribution of the rock type is presented in Map 1, while the aquifer is depicted in Map 5. The aquifer grouping generally comprises impure, dark grey to black, well-bedded, fine- to coarse-grained limestones. In County Cavan, the grouping includes the Calp, the Kilmore Slump member, the Glencar Limestone and the Lucan rock unit (Table 4.2) where they occur in small areas in the centre and south of the County. These rock types occupy large areas of East Connaught, the Midlands and North Leinster.

In these rock units there is often almost no deep permeability; groundwater movement is mainly restricted to the weathered and shallow subsurface zone, and is often concentrated in the upper few metres or tens of metres of fractured bedrock and in cleaner limestone beds. Therefore, the bulk (large-scale) fracture permeability, with the possible exception of areas near faults, is generally low. Even where highly transmissive fault zones are encountered, the ability to sustain the flow is generally absent. This is because, although the fault zone is permeable, there are insufficient connected fracture networks that can create sufficient storage or can transmit water quickly enough to the fault zone. Hence, the aquifer does not store sufficient water to maintain outputs during long periods without recharge. The water table usually closely mirrors topography. In low-lying areas, groundwater levels are often within 1-2m of ground surface, and usually within 10m of ground level in more elevated places. A relatively high density of streams and surface ditches is common (Daly *et al*., 1998).

As part of the National Aquifer mapping, well productivity and yield data for this rock unit group were examined systematically across the country in order to identify trends in the data. A map of well productivities and yields shows that their values vary from area to area. In the Limerick, South and North Midlands area, productivities are skewed to lower values (Figure 4.10). Sixteen "Excellent" yields, 81 "Good" yields, and one "High" yielding spring are noted. There are no High yielding springs in this rock unit in Cavan/North Midlands. There are numerous small seeps and springs within the Upper Impure Limestones. The Upper Impure Limestones are not generally noted for the development of karst features.

Figure 4.10 Well Productivities in the Dinantian Upper Impure Limestones in the Limerick, South and North Midlands regions



High concentrations of iron, manganese and hydrogen sulphide are also common, providing considerable problems for those with private wells. This effect is sometimes the result of contamination, but is often a consequence of the combination of both the natural iron sulphide in the shalier parts of the rock formation, and the generally slow groundwater circulation.

Based on generally low productivity values, the occasional Excellent borehole yield and the limited development of fracturing and jointing except in the vicinity of fault zones, the Upper Impure Limestone in this region is classed as a **locally important aquifer** which is **moderately productive only in local zones (Ll)**. These factors are summarised in Table 4.13.

Table 4.13 Summary of factors used to classify the Dinantian Upper Impure Limestone Aquifers

Factor	**Limerick, South and North Midlands**
Rock Type	Impure, thin-bedded limestone with shale layers.
Structure	Moderate degree of faulting and folding. Folding intensity decreases northwards.
Hydrology	Moderately high drainage density. Drainage generally poor.
Well Hydrographs	-
T values	5-90 m^2/d
Well Productivity	Skewed towards the lower productivities (Categories IV and V).
Borehole Yields	Good yields frequently attainable, Excellent yields possible.
Springs	Small springs and seeps common. No High springs known in Co. Cavan.
Dolomite	Patchily dolomitised in areas.
Karst	Karst patchily developed. Known over most of area.
Classification	**Ll**

4.14 Classification of the Namurian Aquifers

Namurian-age rock units encompass a range of rock types which generally comprise shales, siltstones and sandstones. In County Cavan, the majority of these rock units cap the hills in the uplands northwest of Lough Allen. There is also a very small area in the east of County Cavan, near to Kingscourt. The distribution of the rock type is presented in Map 1, while the aquifer is depicted in Map 5. The different rock units that comprise this aquifer group are listed in Table 4.2 and discussed below.

In general, the Namurian rock unit permeabilities depend on the presence of faults and joints along which groundwater can flow. In the shaly portions of the unit, movement of water along faults and joints is likely to be impeded by infilling of weathered shale and clay. The more productive portions of the unit are likely to be the thicker beds of sandstone, where brittle fracturing is likely to have occurred, and where groundwater flow is likely to be better developed.

High concentrations of iron, manganese and hydrogen sulphide are common in groundwater from the Namurian aquifers, providing considerable problems for those with private wells. This effect is sometimes the result of contamination, but is often a consequence of the combination of both the natural iron sulphide in the shalier parts of the rock formation, and the generally slow groundwater circulation.

4.14.1 Northwest Cavan

In northwest County Cavan, the Namurian rocks are typically folded into NW-SE trending synclines, which are relatively open. Given the high shale content and therefore low permeability of this aquifer, flow paths are short, and seeps and low flow springs are commonplace. Relatively high densities of streams and surface ditches are common.

The fractured upper and more permeable layer is unlikely to provide sustainable enough supplies for larger wells, and will often contain lesser quality water than the deeper permeable horizons. If gravel/sand deposits occur above the bedrock aquifer, they can help to provide flow and storage to the aquifer, and to protect against pollution. In general, optimum well yields from the Namurian aquifers will be obtained from boreholes drilled into one of the fault zones and penetrate at least 50-100m of the aquifer.

As there are limited hydrogeological data available for the Namurian rocks, aquifer classification is primarily based on what is known about the lithology and fissuring within these rock units, and inferences from experiences in areas where more data are available.

Based on a lithology of mixed sandstones, siltstones and some shales, productivity values clustering in Categories III to IV and limited development of fracturing and jointing except in the vicinity of fault zones, the Namurian sandstones – Lackagh Sandstone (LH) and Briscloonagh Sandstone (BR) – are classed as a **poor aquifer, generally unproductive except for local zones (Pl).**

Based on low productivity and yield values and expected low permeabilities in shale rocks, the Namurian shales (Gowlaun Shale (GO), Dergvone Shale (DE)) are classed as a **poor aquifer that is generally unproductive (Pu)**.

4.14.2 East Cavan

In the east of the county, the rocks dip westwards in fault-bounded blocks. In the Kingscourt area, the Cabra and Corratober Bridge Formations (Undifferentiated Namurian) appear to have high productivities and Excellent borehole yields. Despite being less than 20 km^2 in area (in total, with about 0.25 km^2 occurring in County Cavan), 10 productivity category I and II wells are found, and 'Excellent' yielding wells are the norm. A transmissivity of around 100 m^2/d has been estimated, again indicating that these rocks can supply significant quantities of water, sufficient to provide for public water supplies.

Although the Namurian aquifer in the Kingscourt area has high productivity boreholes, due to its limited size it is classed as a **locally important, generally moderately productive aquifer (Lm)**.

The assessments of aquifer classification discussed above are summarised in Table 4.14.

Table 4.14 Summary of factors used to classify the Namurian Aquifers

Factor	Northwest Cavan		East Cavan
Rock Type	Namurian Shales – Gowlaun Shale (GO); Dergvone Shale (DE)	Namurian Sandstones – Lackagh Sandstone (LH) and Briscloonagh Sandstone (BR)	Undifferentiated Namurian – Cabra (CB) and Corratober Bridge (CO) Formations
Structure	Gentle synclinal folds; N-S and WNW-ESE cross-cutting faults.		Fault-bounded, faults known within major blocks.
T values	No data	No data	Data in Monaghan indicate 100 m^2/d.
Productivity	No data	Concentrated in Classes III to IV.	Concentrated in Classes I and II.
Borehole Yields	No data	No data	Excellent yields are the norm.
Springs	Numerous small springs, no High yielding springs.		No High yielding springs.
Dolomite	-	-	-
Karst	-	-	-
Classification	**Pu**	**Pl**	**Lm**

4.15 Classification of the Permo-Triassic Sandstone, Mudstone and Gypsum Aquifers

Rocks of Permo-Triassic age occupy a small area in the very east of County Cavan. The rock units are mapped as small fault-bound band to the southwest of Carrickmacross that extends into Counties Monaghan and Meath. The Kingscourt Sandstone unit is composed of approximately 80 m of siltstone overlain by 200 m of sandstone. The Kingscourt Gypsum unit is composed of mudstones with thick (10-20 m) gypsum deposits. A water table map prepared as part of the NERDO report (AFF and GSI, 1981) focuses on the Mullaghfin Limestone, but suggests that groundwater in these rock units flows south-southeast towards the River Lagan. The factors used to assign aquifer classifications to these rock units are discussed below, and summarised in Table 4.15.

4.15.1 Kingscourt Sandstone Aquifer

Groundwater flow in this aquifer is expected to be largely along faults and fractures within the sandstones. Fractures developed in the sandstone portions of these units are likely to be open. Additionally, this sandstone unit is poorly cemented and often very weathered, which will further increase permeability. Sandstones of similar age and depositional environment found in Northern Ireland are reported to have significant primary porosity, meaning that the permeability is not dependent wholly upon fractures and fissures.

Due to the limited extent of this rock unit, there are few hydrogeological data available for these rocks. The hydrogeological map of Northern Ireland shows these materials as a “highly productive aquifer in which intergranular flow is significant”, and having a transmissivity of 100 m^2/d (BGS, 1994). It is assumed this is also the case in the Kingscourt Sandstones, although little research has been done on this topic. The fact that the sandstones are weathered, not very well cemented and fractured suggests that they are probably capable of transmitting significant volumes of groundwater.

Three Excellent wells are recorded in the Kingscourt Sandstone, with productivities ranging from class I to III. As part of the NERDO work, a well was drilled at Mullantra in 1981 to investigate the water supply potential of these sandstones (AFF and GSI, 1981). The sandstone encountered in the well was very friable and liable to collapse. The well yielded 915 m^3/d, with a specific capacity of 23 m^3/d/m (productivity class II) and a transmissivity of 48 m^2/d. Additionally, the aquifer was found to be locally confined by over 40 m of till (boulder clay) at this location. Two trial wells drilled for the Kingscourt water supply (in Counties Cavan and Meath) indicated estimated yields of 500 m^3/d and 1030 m^3/d, respectively. Specific capacities for these wells are 15 and 105 m^3/d/m (productivity classes I and III).

Overall, well yields, productivities and transmissivities from these units suggest that these rocks are capable of supplying significant quantities of water. Since it is not aerially extensive, however, the Kingscourt Sandstone **is classified as a locally important, generally moderately productive aquifer (Lm)**.

4.15.2 Kingscourt Gypsum Aquifer

The Kingscourt Gypsum unit is composed of mudstones with thick (10-20 m) gypsum deposits. The high proportion of bedded, fine grained material is likely to restrict groundwater circulation in this aquifer. Where faults cut the aquifer, they are likely to increase permeability, although the high clay content of the mudstones will hinder clean fracturing. Groundwater flow through the aquifer is likely to be restricted to the upper few metres, where weathering and fracturing are probably most intense.

Water levels in one well in the Kingscourt Gypsum were monitored for over a year, showing an annual variation of 6.9 m. This is indicative of low aquifer storativity and/or low permeability. There is little hydrogeological information available for these rocks, with only one well with a yield of over 400 m^3/d recorded in this unit. Mining has revealed karst features within the gypsum units that can transmit groundwater. However, the quality of water from the gypsum units would be unacceptable for drinking as a result of high sulphate concentrations.

Given the fine grained nature of this unit, widespread secondary permeability is unlikely to occur. This suggests that it is a **poor aquifer, which is generally unproductive except for local zones (Pl)**.

Table 4.15 Summary of factors used to classify the Permo-Triassic Sandstone, Mudstone and Gypsum Aquifers

Factor	Kingscourt Sandstone	Kingscourt Gypsum
Rock Type	Bedded sandstones, weakly cemented.	Bedded mudstones and gypsum
Structure	Fault-bounded	Fault-bounded.
T values	20-100 m^2/d.	-
Productivity	Limited data in Classes I, II and III.	-
Borehole Yields	3 Excellent yields.	1 Excellent yield.
Springs	No High yielding springs known.	No High yielding springs known.
Dolomite	-	-
Karst	-	Karst known from surface features and from subsurface workings.
Classification	**Lm ***	**Pl**

** Regionally important aquifer classification not given due to limited extent.*

5 Groundwater Vulnerability

5.1 Introduction

The term 'Vulnerability' is used to represent the intrinsic geological and hydrogeological characteristics that determine the ease with which groundwater may be contaminated by human activities (DELG/EPA/GSI, 1999).

The vulnerability of groundwater depends on:

- the time of travel of infiltrating water (and contaminants)
- the relative quantity of contaminants that can reach the groundwater
- the contaminant attenuation capacity of the geological materials through which the water and contaminants infiltrate.

All groundwater is hydrologically connected to the land surface along a 'pathway' through the overlying geological layers; the effectiveness of this connection determines the relative vulnerability to contamination. Groundwater that readily and quickly receives water (and contaminants) from the land surface is more vulnerable than groundwater that receives water (and contaminants) more slowly and in lower quantities. The quantity of contaminants which reach groundwater is a function of the vertical hydraulic gradient and the following natural geological and hydrogeological attributes of any area:

(i) the type and permeability of the subsoils that overlie the groundwater
(ii) the thickness of the unsaturated zone through which the contaminant moves
(iii) the recharge type – whether point or diffuse

In other words, vulnerability is based on evaluating the relevant hydrogeological characteristics of the protecting geological layers along the pathway, and the possibility of bypassing these layers. In summary, the entire land surface is divided into four vulnerability categories: **E**xtreme, **H**igh, **M**oderate and **L**ow based on the geological and hydrogeological characteristics. Further details of the hydrogeological basis for vulnerability assessment can be found in the 'Groundwater Protection Schemes' (DELG et al., 1999).

The subsoil types described in Section 3 have been assessed and incorporated into permeability regions, which are described in this chapter. Permeability boundaries may cross mapped subsoil units in order to show areas of similar permeability. The Vulnerability Map (Map 6) shows the vulnerability of the first groundwater encountered, in either sand/gravel or bedrock aquifers, by contaminants released at depths of 1-2 m below the ground surface. The vulnerability maps are intended to be a guide to the likelihood of groundwater contamination, if a pollution event were to occur. It does not replace the need for site investigation. Additionally, the characteristics of individual contaminants are not considered.

The vulnerability map is derived by overlaying the permeability categories with the subsoil thickness, and superimposing areas with the potential for point recharge (e.g. swallow holes). There are three subsoil permeability categories: "high", "moderate" and "low"; and five depth to rock categories: shallow rock (<1m), "<3 m", "3 to 5 m", "5 to 10 m" and ">10 m". Table 5.1 describes how the criteria combine to derive a vulnerability assessment.

Table 5.1 Vulnerability Mapping Guidelines (adapted from DELG et al., 1999).

Subsoil Thickness	**Hydrogeological Conditions**				
	Diffuse Recharge: Subsoil Permeability and Type			**Point Recharge**	**Unsaturated Zone**
	High Permeability (sand/gravel)	**Moderate Permeability** (e.g. sandy subsoil)	**Low permeability** (e.g. Clayey subsoil, clay, peat)	(e.g. within 30 m radius of swallow holes)	(Sand/gravel aquifers only)
0 - 3.0 m	Extreme	Extreme	Extreme	Extreme	Extreme
3.0 - 5.0 m	High	High	High	N/A	High
5.0 - 10.0 m	High	High	Moderate	N/A	High
> 10.0 m	High	Moderate	Low	N/A	High

Notes:
(i) N/A = not applicable.
(ii) Permeability classifications relate to the engineering behaviour as described by BS5930.
(iii) Release point of contaminants is assumed to be 1-2 m below ground surface.
(iv) Outcrop and shallow subsoil (i.e. generally <1.0 m) areas are shown as a sub-category of extreme vulnerability.

5.2 Sources of Data

Specific vulnerability field mapping and assessment of previously collected data were carried out as part of this project. Fieldwork assessments were based on drilling of one hundred and forty-three subsoil sampling holes whereby the permeability of the different subsoil deposit types (Map 2) was assessed, so that they could be subdivided into the three permeability categories. Assessment and sampling of exposed subsoil sections was also undertaken (forty-two sites), and focused particularly on permeability boundaries. Subsoil assessment involved:

- Description of the engineering properties in the vicinity of the drilled locations using techniques based on BS5930:1999 (British Standards Institution, 1999).
- Collection of subsoil samples for laboratory particle size analyses (63 samples in total).
- Assessments of recharge acceptance indicators such as natural and artificial drainage density and vegetation.

Details on analytical methodologies are presented in Section 5.3.

The following additional sources of data were used to assess the vulnerability and produce the map:

- the FIPS-IFP Soil Parent Materials Map (see Chapter 3, Map 2);
- the Bedrock Geology Map sheets 7, 8, 12 and 13, and associated booklets;
- the Geological Survey of Ireland well database;
- the Department of Communications, Energy & Natural resources Open Files database;
- the Geological Survey of Ireland karst database. This was used to give information on areas of point recharge;
- the Geological Survey of Ireland geotechnical database;
- the Water Framework Directive interim vulnerability map and associated drilling data;
- Cavan County Council roads section Site Investigation Reports;
- Selected T-test and BS5930 results from site suitability assessments.

5.3 Permeability Assessment Methodology

The permeability and vulnerability categories are qualitative regional assessments of the subsoils based on how much potential recharge is infiltrating and how quickly potential contaminants can reach groundwater. The permeability of subsoils is largely a function of (a) the grain size distribution; (b) the amount (and sometimes type) of clay size particles present; and (c) the degree of sorting and organisation by size of grains. It can also be influenced by other factors such as discontinuities (e.g. cracks, plant roots and isolated higher permeability beds or lenses) and density/compactness. In glacial tills, which are the most common subsoils in Cavan, these permeability characteristics also determine the engineering behaviour of the materials (Swartz, 1999) as described using the subsoil description and classification method, derived from BS5930:1999 (British Standards Institution, 1999). This method is therefore used to assess the permeability of the subsoils at each exposure, supported by recharge and drainage observations in the surrounding area.

Each of the approaches used in assessing the permeability is discussed briefly here:

Subsoil Description and Classification Method: (derived from BS5930). Using this method, subsoils described as sandy CLAY or CLAY have been shown to behave as low permeability materials. Subsoils classed as silty SAND and sandy SILT, on the other hand, are found to have a moderate permeability (Swartz, 1999). In general, sands/gravels which are sorted and have a low fines content are considered to have a high permeability. However, some sands and gravels found in Cavan are not as sorted as many fluvially deposited gravels elsewhere, and have sufficient clay and silt content in the matrix to behave as a moderate permeability material.

Particle size analyses: The particle size distribution of sediments describes the relationships between the different grain sizes present. Well-sorted sediments such as water-lain gravel (high permeability) or lacustrine clays (low permeability) will, on analysis, show a predominance of grain sizes at just one end of the scale. Glacial tills, on the other hand, are more variable and tend to have similar proportions of all grain sizes. Despite their complexity, evaluation of the grain size analyses for a range of tills in Ireland has established the following relationships (Swartz, 1999; Fitzsimons, pers. comm., 2002):

i. Samples described as moderate permeability based on observations of recharge indicators (vegetation, drainage density) typically have less than 35% silt plus clay.
ii. These 'moderate permeability' samples also tend to have less than 12% clay.
iii. Samples described as low permeability frequently have more than 50% silt plus clay.
iv. These 'low permeability' samples also tend to have more than 14% clay.
v. High permeability sand/gravel deposits tend to be sorted and have less that 7.5% silt plus clay (O'Suilleabhain, 2000).

Parent Material of the Subsoil: The parent material, usually the bedrock, plays a critical role in providing the particles which have created the different subsoil permeabilities. Sandstones, for example, give rise to a high proportion of sand size grains in the deposit matrix, clean limestones provide a relatively high proportion of silt, while shales, shaly limestones and mudstones break down to the finer clay size particles. A good knowledge of the nature of the bedrock geology is, therefore, critical. It is also useful to know the direction of movement of the glaciers and the modes of deposition of the sediments as these will dictate where the particles have moved to, how finely they have been broken down, and what the relative grain size make-up and packing are. Understanding the processes at work enable predictions to be made where observations are lacking.

Recharge Characteristics: Examining the drainage and recharge characteristics in an area gives an overall representative assessment of the permeability. Poor drainage and vegetation suggest low permeability subsoils if iron pans, underlying low permeability bedrock, high water tables, or excessively high rainfall can be ruled out. Well-drained land suggests a moderate or high permeability if artificial drainage can be ruled-out (Lee, 1999). Much of the land in East Cavan has been improved, with large amounts of artificial drainage over a series of schemes stretching from the 1940's until the mid 1990's ("Farm Improvement Scheme", "Land Project Scheme", "Western Drainage Scheme" and the "Dry reclamation Scheme". In fact, County Cavan has had the highest amount of Government financial support for artificial drainage schemes in Ireland (pers. comm. Oliver Creegan, Dept. of Agriculture, 2006). As a result, this approach is quite difficult to use successfully in Cavan.

Soil Type: Although no specific topsoil map exists for Cavan, the Soil Map of Ireland and explanatory bulletin (Gardiner & Radford 1980) can be used to indicate broad drainage characteristics, especially where specific site recharge observations are not available. Poorly drained soils such as surface water gleys are usually related to underlying low permeability subsoil; the more free draining soils such as grey brown podzolics are more typical of the sandy and silty moderate permeability subsoil. The availability of a county specific topsoil map would have increased the confidence of some permeability boundaries, especially in areas where permeability varies.

Quantitative Analysis. From a limited number of national field permeability measurements, the boundary between moderate and low permeability is estimated to be in the range of 0.0007-0.007 m/d. While the moderate to high boundary has not yet been looked at in detail, one study suggests that this boundary may be in the region of 10m/d (O'Suilleabhain, 2000). However, permeability measurements are highly scale dependent: laboratory values, for example, are often up to two orders of magnitude smaller than field measurements, which in turn are smaller than regional assessments measured from large scale pumping tests. Thus, for regional permeability mapping, qualitative assessments incorporating the engineering behaviour of the subsoil and recharge characteristics are more appropriate than specific permeability measurements.

None of these methods can be used in isolation; a holistic approach is necessary to gain an overall assessment of each site and thereby build up a three dimensional picture of the regional hydrogeology and permeability. In any one area, as many factors as possible are considered together to try to make a balanced, defensible permeability decision. In order to extrapolate from point data to area assessments, the county is divided into permeability regions, usually on the basis of similar subsoil and/or bedrock characteristics. In parts of County Cavan, some till deposits had a similar parent material origin and indicators of permeability at the low to moderate boundary. These areas required detailed field-scale permeability mapping as there were slight variations in permeability over short distances.

It is intended that the assessments will allow a broad overview of relative permeability across the county, in order to help focus field investigations for future development projects on areas of interest. In mapping an area at County scale, the process cannot hope to be comprehensive at a site-specific level. Consequently, it is stressed that these permeability assessments are not a substitute for site investigations for specific projects. The vulnerability, which is partly based on the permeability mapping, is presented in Map 6. Details of the supporting data for each permeability decision can be found in Appendix III.

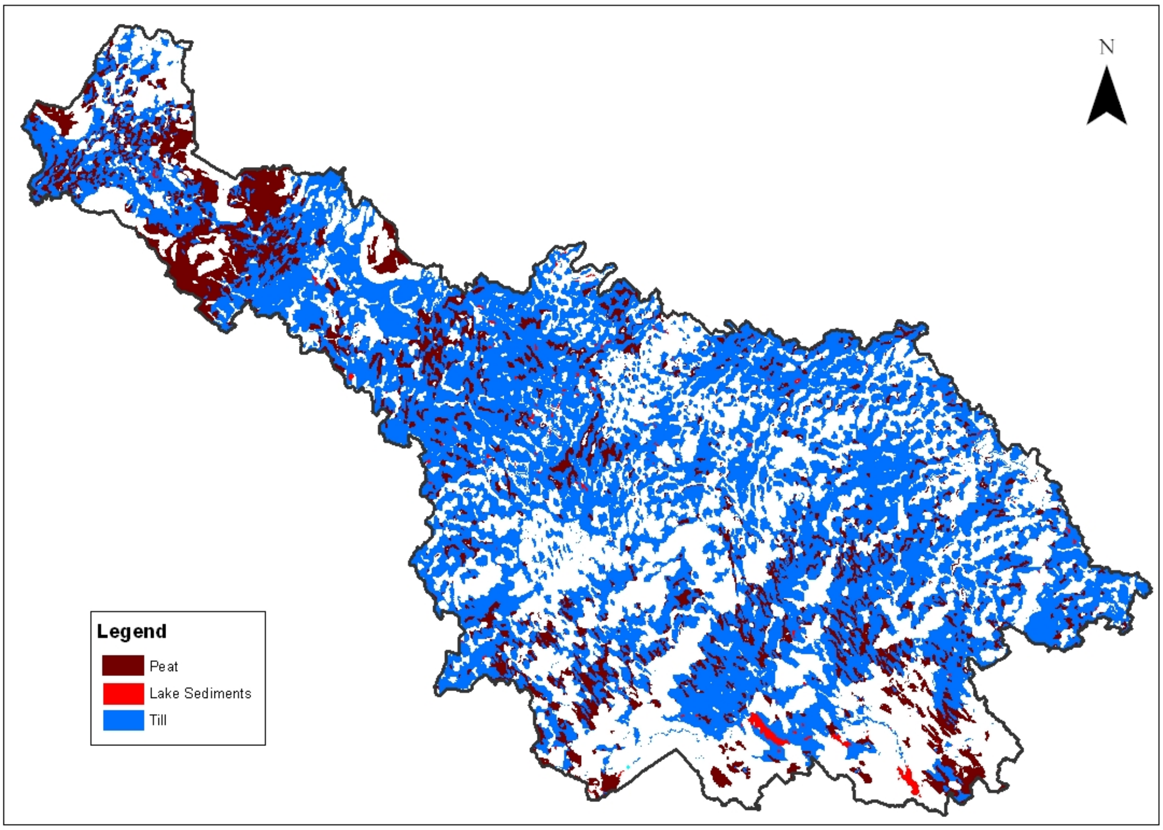
5.4 Permeability Regions

Seven broad permeability units have been defined for County Cavan using all the available data from existing site investigation work and project-specific drilling. These regions are likely to include smaller, discrete units of differing permeability which cannot be individually mapped at the scale of mapping. The presence of samples with contradicting data reflect this variability; where possible, these units have been delineated. Furthermore, mapping at a more detailed level was undertaken where such local variations are widespread. The permeability units are described in the following Section, under their 'low', 'moderate' and 'high' permeability categories.

5.4.1 Low Permeability Units

The greatest proportion of County Cavan constitutes low permeability material as most of the glacial tills have a high clay content. Peat and Lacustrine Clays are also included amongst the low permeability units. Extensive areas of peat are found in the northwest part of the county due to the increase in rainfall across Slieve Rushen and the Cuilcagh Mountains. Here, blanket peat is draped across the mountains and in the valley interdrumlin areas. Small areas of cutover peat are scattered throughout the remaining southeast and south part of the county. There are three relatively extensive areas of Lacustrine Clays to the west and south of Lough Ramor, which are likely to be thick enough to dictate the overall permeability at these locations. The low permeability areas are depicted in Figure 5.1.

Figure 5.1 Distribution of Low Permeability Subsoils in Cavan (>3m thick)



Permeability Unit 1: Central & East Cavan Till
This area comprises a large part of the county from Redhills, Butlers Bridge, Cavan Town and Arvagh, to Kilnaleck and Ballyjamesduff. The topography of the area is principally elevated hummocky land with drumlins and with low-lying drumlinised areas in the north (along Annalee River) and the south (around Lough Sheelin and Lough Ramor). The bedrock consists of Ordovician and Silurian metamorphics and volcanics, principally greywackes and shales, some sandstones, and with volcanics covering a minor aerial extent. The overlying till is a sandstone and shale till (Meehan, 2003), which was deposited by glaciers originating in the mountainous regions of Cavan and Fermanagh to the northwest. The till matrix reflects the clayey materials from which it originates. It includes a high proportion of crushed and broken shaly bedrock, particularly at the bedrock interface.

Artificial drainage is frequently seen at all elevations, though invariably around the base of drumlins. The vegetation in the area varies, partly due to intensive land management, from drumlins with rushes on the lower slopes to some completely rush covered slopes, supporting the low permeability assessment. Poaching of fields was occasionally seen, and marshy ground between elevated rocky gorse covered hills is evidence of a high water table in the area.

Of the samples collected, 78% are described as ‘CLAY’, and 18% as ‘SILT/CLAY’. Seven of the 19 available grain size analyses have greater than 12% clay content and 14 samples have more than 35% total fines. The grain size data does highlight the mixed nature of the till matrix however, when all indicators reflecting recharge are considered, a low permeability category is supported.

Permeability Unit 4: Cavan Panhandle Till
This area, referred to in this text as the "panhandle", describes the narrow strip in the northwest of the county. It includes the mountainous areas of Cuilcagh and Slieve Rushen, the low lying area to the south of Slieve Rushen and the low drumlinised area in the Erne Waterway basin. The bedrock is divided into three categories for the purposes of permeability potential: 1) the shales and shaly sandstones of the Namurian and the Lower Dinantian mountainous areas west of the Erne Waterway; 2) the Dinantian sandstones and limestones that occur in the centre of the Glenade valley and form Slieve Rushen; and 3) the pure bedded karstic limestone to the south and southeast of Slieve Rushen.

The characteristics of the overlying till matrix appear to have been influenced by the more clayey bedrock in the mountainous areas. The till overlying much of this unit, in the Glenade Valley, on the flanks of the mountainous areas and east of Ballyconnell, is described as a clayey shale and sandstone till, whilst above 200mOD to 250mOD it is mainly covered by blanket peat (see Permeability Unit 6). The till south of Slieve Rushen and Ballyconnell is described as a stony clayey chert and sandstone till. Two small area of Carboniferous Limestone till around Loughs Oughter and Gaffney, and Castlesaunderson Demesne are also included in this unit.

Both natural and artificial drainage density in the area is high. Vegetation includes a mixture of forestation, gorse and scrubland with some rushy fields used for grazing. The proportion of undeveloped scrubland and heath increases significantly in the Glenade Valley area, as does the extent of peat development due to high rainfall. The development of peat over moderately permeable bedrock (quartzitic sandstone) in the valley bottom suggests that the water table may be high in the area, which is confirmed by the gleyed nature of many samples.

Grain size analyses from this unit show that 6 out of 7 samples have greater than 12% clay content with over half having more than 14% clay content. The percentage of total fines for all of the samples is greater than 35%. Over 90% of the BS5930 field sample descriptions are 'CLAY'. Therefore all evidence (descriptions, grain size analyses and recharge indicators) supports a low permeability categorisation.

Permeability Unit 8: Lacustrine Sediments
Deposits of lacustrine sediments occur throughout the county, typically as small strips around the edges of the many lakes in Cavan. Most of these deposits are likely to be too thin to influence the overall permeability. The exceptions are some relatively small lake deposits of the Erne River (in the Belturbet area) mapped as "undifferentiated lake sediments", and three large areas of "clayey lacustrine sediments" in the southeast of the county.

The bedrock underlying the *lacustrine clays* is Silurian metasediments, whilst the Erne deposited lake sediments are on Dinantian rocks. The lacustrine clays were deposited by glacial lakes, which formed as the ice retreated and ultimately formed Lough Ramor and Lough Sheelin. These are typically very homogenous and very dense subsoils.

Rivers flowing into Lough Sheelin and out of Lough Ramor flow through the centre of these deposits. There is a distinct increase in the density of the arterial drainage network within each of the three areas, which is compatible with high density low permeability clays, and which also leaves the areas prone to flooding. Vegetation is generally marshy or wet grassland. Both drainage density and vegetation in the lacustrine clays indicate a low permeability material.

Only one BS5930 description is available for the *undifferentiated lake sediments* between Ballyconnell and Belturbet, which identified the subsoil type as CLAY. However, a strata of coarse gravel is logged under the clay (3m in thickness), which suggest that the lateral continuity of the gravels and the clay may vary in this deposit type. Therefore the undifferentiated lake sediments are categorised as moderate permeability, which concurs with the national categorisation of this material.

Permeability Unit 6: Blanket Peat, Cutover Peat and Fens

Deposits of blanket peat drape all the mountains in northwest County Cavan. There are four large areas of blanket peat; Slieve Rushen, the Cuilcagh Mountains, the toe of Bolebrack Mountain, and on The Playbank. As blanket peat frequently develops on rock, much of the blanket peat is categorised as 'Extremely Vulnerable' (<3m to bedrock), but it is likely to be up to 5m thick in places. Areas with deeper peat generally have intact, peat-associated vegetation, or occasionally have been cut for turf. These areas are assumed to have a greater than 3m thickness of peat and, apart from the less compacted upper layers, have a relatively low permeability.

Pockets of cutover (raised) peat are widespread throughout the county, occurring in the inter-drumlin areas and between rocky hillocks in the elevated terrain in the east of the county. Larger areas of cutover peat occur on the limestone tills, in the Mullagh area, and between Kilcolgy and Bellananagh.

These peat deposits are sufficiently thick at their centre to dominate the permeability of the area. However as Cutover Peat in Cavan is usually underlain by low permeability till, where it is thinner, the subsequent total thickness subsoil (peat plus till) has a low permeability categorisation. The exception is the Mullagh area, where the peat is considered to be greater than 3m thick (refer to section 5.4.2). Consequently, this has been classed as an area of low permeability.

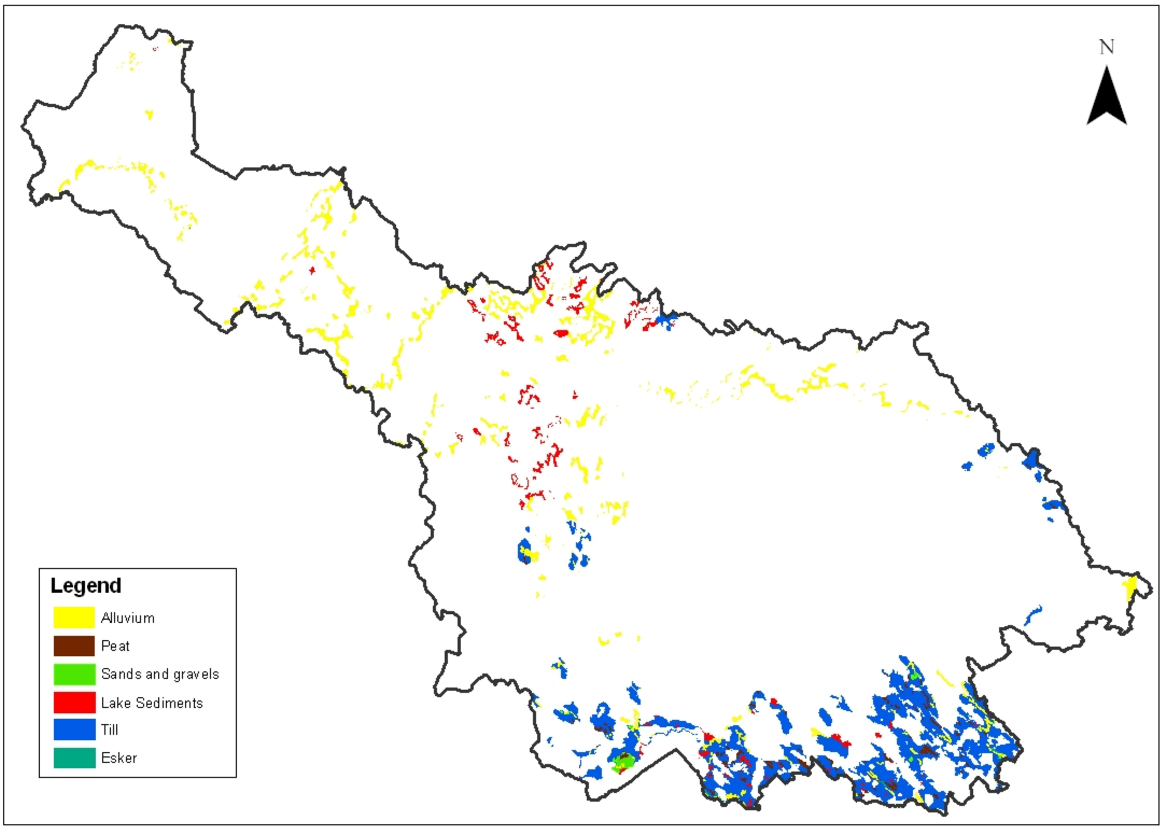
Fen peat occurs in two areas of County Cavan; at Annagh Lough east of Ballyconnell, and to the northwest of Belturbet. Fens comprise peat and mixed birch woodland, which are groundwater fed and dependent. They represent the early stages of a raised bog.

Generally, peat consists of a build-up of organic matter in water-logged conditions, and principally developed in the warmer and wetter post glacial period. The water-logged conditions generally results from a combination of low permeability rocks (metamorphics and limestones in County Cavan) and appropriate topographic setting that inhibits surface water drainage. The low permeability of peat is well known and therefore the collection of samples for these deposits was not undertaken.

5.4.2 Moderate Permeability Units

In Cavan, deposits that have moderate permeability comprise either silty, and/or sandy/gravely glacial till, or alluvium. Moderate permeability tills are divided into those within the Lower Palaeozoic Sandstone and Shale Till (Meehan, 2003), and till encompassing material from the Crossdoney Granite bedrock. The location of moderate permeability units are shown in Figure 5.2.

Figure 5.2 Distribution of Moderate Permeability Subsoils in Cavan (>3m thick)



Permeability Unit 3: Loughs Sheelin and Ramor, Mullagh, and Shercock Tills
Detailed field mapping undertaken indicated moderate permeability till from the Kilcolgy area, across the edge of Lough Sheelin and Lough Ramor, to the Mullagh-Virginia area. An isolated 'outlier' of moderate permeability material is also found around Shercock, in the northeast of Cavan. These areas comprise mainly low-lying, undulating land, becoming slightly more elevated to the east of Lough Ramor. Bedrock in the area is a mixture of metasediments and limestones around Lough Sheelin, with minor areas of pure limestones to the east of Lough Sheelin, adjacent to the county boundary. The overlying subsoil is a clayey sandstone and shale till.

The generally well drained land in this area differentiates it from Permeability Unit 1. Few rushes are seen and it has a low natural drainage density and limited development of arterial drainage. The land is principally used for grazing, (silage), and pig farming activities.

The grain size analyses illustrates the low clay content ~ all have less than 12% clay, whilst the total fines content is generally less than 35%. Nineteen out of forty-seven samples are described as either SAND or GRAVEL, although their silt content and the angular to sub-angular nature of the gravels is indication that they have not been fluvially sorted. As such, they are not considered to be sorted enough to fall into a high permeability category. Over 95% of the samples are described as either SAND, GRAVEL, SILT or SILT/CLAY, which are considered to have a moderate permeability.

Permeability Unit 2: Crossdoney Granite Till
This unit is located east of Crossdoney and north of Bellananagh, and also around Cornafean. The bedrock is typically Crossdoney Granite with overlying Granite Till. The Granite Till also extends to the south and southeast of the Granite bedrock, which corresponds with the direction of glacial movement that transported the till beyond the boundary of its granite parent material.

Granites typically weather to a sandy till, although in this instance the unit covers only a couple of drumlins north of Bellananagh and a small area around Cornafean. The surrounding clay-rich bedrock material has been incorporated into much of the till in the area and has influenced the permeability. Evidence of this was recorded at one section, which had two distinct CLAY horizons, with sandy till noted at a higher topographical elevation than the clay samples.

The land use in the area consists of grazing and tillage, and a golf course at Cornafean. Negligible arterial drainage was recorded and there were very few rushes. An understanding of the deposition and the recharge indicators are consistent with a moderately permeable material.

Permeability Unit 7: Alluvium

Alluvial deposits are found in narrow strips along streams and rivers throughout the county. They are underlain by a wide range of rock types, occur within all permeability regions, and are largely composed of differing proportions of water-sorted silt and sand, with thin clay lenses.

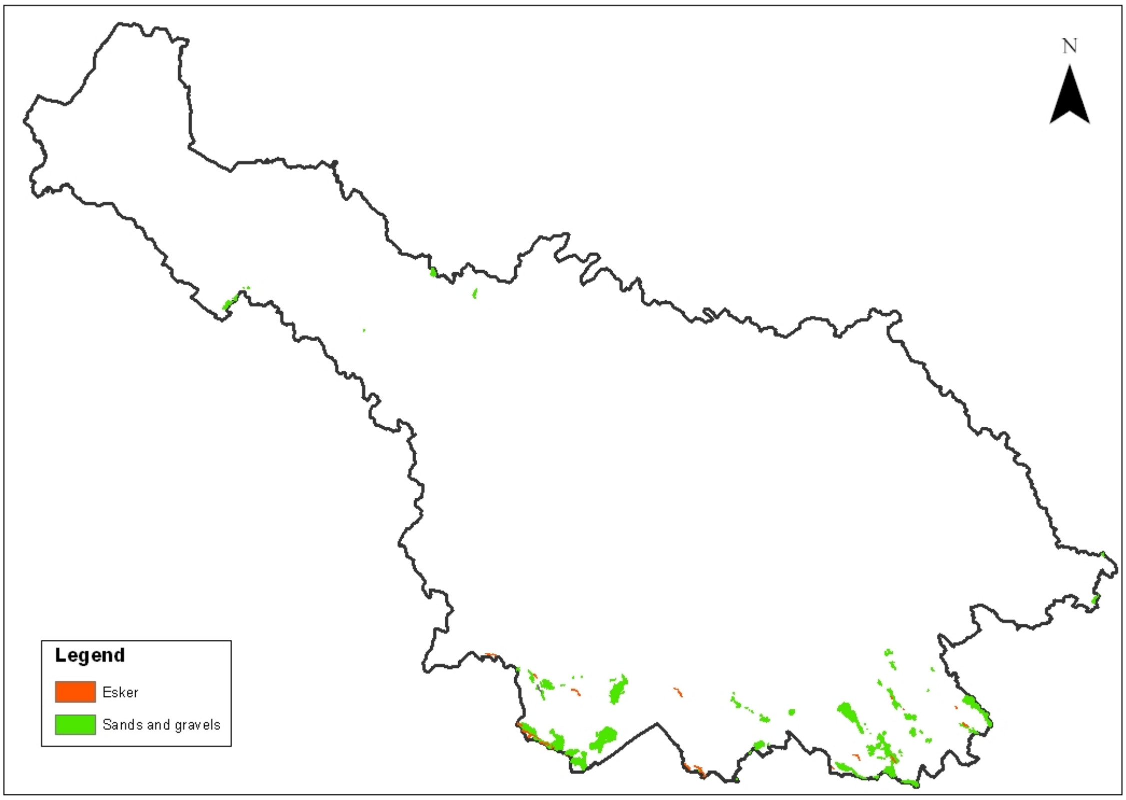
Thin alluvial deposits (<3m thick) are not thick enough to influence permeability classifications, which are then based on the thicker, underlying subsoil. However, the alluvial deposits along the larger rivers are more likely to be thicker than 3 m and therefore determine the permeability. Substantial alluvial deposits in County Cavan have developed around the Rivers Erne, Annalee, Woodford and Shannon. The bedrock type and subsoils, across which the depositing river flows, were also taken into consideration when identifying alluvial deposits which are expected to influence the permeability.

Nationally, alluvium deposits are dominated by SILT and therefore are categorised as moderate permeability. The Cavan "Undifferentiated Alluvium" samples generally reflected national data: 5 of the 7 samples are described as either SILT or SILT/CLAY, one is described as SAND/GRAVEL and the final sample is described as CLAY. Of the five samples with grain size data, only two had the percentage of clay analysed. Both of these have less than 9% clay. All 5 samples have less than 50% fines and three have <35% fines.

The data indicate that the deposits are predominantly moderate permeability although the spread of sample descriptions reflects the nature of the surrounding subsoils, which also contribute to lenses of more clayey material. However, the one alluvial deposit that was described as CLAY was categorised as low permeability.

5.4.3 High Permeability Units

Figure 5.3 Distribution of High Permeability Subsoils in Cavan (>3m thick)



Permeability Unit 5: Sand & Gravel Deposits
Deposits that have a high permeability are mapped as sand/gravel on the Forest Inventory Planning Subsoil Map (Meehan, 2004). They generally occur as patches around Loughs Sheelin and Ramor in the southeast of the county, and are associated with glacial melt-water, which formed deltaic deposits in these lakes. Sand/gravel deposits in northwest Cavan and in the Kingscourt area are river deposits that have formed more recently. The bedrock underlying the rivers that transported the sand/gravel is more relevant to their origin than the bedrock directly underlying the deposits themselves. The bedrock source of the sand and gravels in Cavan is variable.

The soils overlying the sand/gravels in the Kingscourt area are all shallow well drained acid soils, whilst basic soils overlie the sand/gravels in northwest Cavan. Sand and gravel in Cavan associated with naturally well drained land and negligible arterial drainage (nine sample sites).

Subsoils in this unit are distinguished from sand and gravel areas within till deposits by the degree of ‘washing’ and sorting of fines which occurred during their water borne deposition. Just over half the samples are described as SAND/GRAVEL according to BS5930, with the remainder being SILT. Seven of the nine samples display evidence of sorting (round or sub-round cobbles due to fluvial transportation). Typically the boundary between high and moderate permeability sands and gravels is around 8% total fines (O’Suilleabhain, 2000). One of the four available samples with grain sizes has less than 8% fines, with the remainder, which were categorised as SILT, having greater than 8%. From assessment of the mass characteristics of the sections from which these were obtained, and the evidence of sorting (rounded cobbles), it is believed that the silts are discrete lenses within a larger SAND/GRAVEL complex. The overall permeability is therefore, considered to be high, which is supported by other permeability indicators as discussed above.

5.4.4 Areas of 'Rock Close' to the Surface

'Rock close' describes areas where the depth to bedrock is generally less than 1m, and consequently where the subsoil deposits are too thin to be effective for groundwater protection. They most commonly occur in topographically elevated areas in the "Panhandle" area of east Cavan, and at elevation in the mountainous areas in northwest Cavan (see Map 2). A permeability classification is not attached to these regions, as the depth to bedrock results in an 'Extreme Vulnerability' rating.

Similarly, areas where the depth to bedrock is less than 3m from the surface are rated as 'Extreme Vulnerability', which means that permeability classifications are not assessed. The permeability of these areas may be higher than those where sediments are deeper due to greater weathering and glacial abrasion of the material over its bedrock parent material. For example, thin subsoil over the Lower Palaeozoic rocks, tend to consist of angular rock pieces, as opposed to the fine and medium grained matrix of tills deposited under thick ice sheets, but with the same parent material.

5.5 Depth to Bedrock

Along with permeability, the subsoil thickness (depth to bedrock) is a critical factor in determining groundwater vulnerability to contamination. A brief description of subsoil thicknesses is given in Section 3. The source data are shown in Map 3.

5.6 Recharge at Karst Features

Bypassing of the protecting layers of subsoil can occur where water flows rapidly underground, with minimal attenuation, at karst features such as swallow holes and dolines. Therefore, groundwater is classed as 'extremely' vulnerable within 30 m of karst landforms, including the area of loss of sinking streams, and within 10 m on either side of losing or sinking streams upstream of the area of loss. The distances can be varied depending on the circumstances, for instance, they can be increased where overland surface runoff is likely. The locations of karst features on GSI records are shown in Map 4.

5.7 Groundwater Vulnerability Distribution

The vulnerability map (Map 6) is derived by combining the contoured depth to bedrock data with the inferred subsoil permeabilities. Areas are assigned vulnerability classes of low, moderate, high or extreme. Appendix I provides an outline of the principles used.

It is emphasised that the boundaries on the vulnerability map are based on the available data and local details have been generalised to fit the map scale. Evaluation of specific sites and circumstances will normally require further and more detailed assessments, and will frequently require site investigations in order to assess the risk to groundwater. Detailed subsurface investigations and permeability measurements may reduce the area of high, or even extreme, vulnerability. However, the vulnerability map (Map 6) is considered to provide a good basis for decision-making.

Much of the county, in the 'panhandle' area and in the northwest corner, consists of extreme to high vulnerability areas, with a continuous area of low vulnerability between the Erne Waterway and Slieve Rushen. The 3m contour, which delineates the extreme and high vulnerability categories, is based on outcrop information, Quaternary mapping, borehole data and topographic interpretation. The 5m and 10m contours, which influence the moderate and low vulnerability categories, are more reliant on borehole data for their interpretation. The contours cannot be drawn without data from the boreholes. As more information becomes available, the maps should be up-dated.

The areas of extreme vulnerability where rock is generally at or close to the ground surface include upland areas which have little existing development and less potential for groundwater development as they are generally areas of poor aquifers. When these are excluded, the proportion of the county's groundwater that is extremely vulnerable is significantly reduced. Furthermore, many unrecorded, small pockets of deeper subsoil are likely to exist even within areas where rock outcrop is common. The areas of low vulnerability have been mapped where the subsoils (tills) have a low permeability and the depth to bedrock information indicates thicknesses of over 10 metres. Further confirmation by site investigation is essential to verify the vulnerability for specific developments. The distribution of vulnerability as a percentage of the total county is given in table 5.2 below.

Table 5.2 Percentage of different vulnerability classes in County Cavan

Vulnerability Class	Square Kilometres	% county
E(Rock near surface or karst)	138	7.4
E	416.7	22.4
H	533	28.6
M	537	28.8
L	239	12.8

6 Groundwater Protection Zones and Responses

6.1 Introduction

The general Groundwater Protection Scheme guidelines were outlined in Section 1, and in particular, the sub-division of the scheme into two components – land surface zoning and codes of practice (responses) for potentially polluting activities – was described (see also Appendix I). Subsequent sections described the different geological and hydrogeological land surface zoning elements as applied to County Cavan. This Section draws these together to give the ultimate elements of land surface zoning – the Groundwater Protection Scheme map and the source protection maps. It is emphasised that these maps are not intended as 'stand alone' elements, but must be considered and used in conjunction with the groundwater protection responses for potentially polluting activities. Five supplementary publications are currently available: **Groundwater Protection Responses for On-Site Systems for Single Houses ('septic tanks'), Groundwater Protection Responses for Landfills, Groundwater Protection Responses for Landspreading of Organic Wastes, Groundwater Protection Responses for Out Wintering Pads and Groundwater Protection Responses for Earth-Lined Slurry/Effluent Stores**.

6.2 Groundwater Protection Maps

The groundwater protection map (Map 7) was produced by combining the vulnerability map (Map 6) with the aquifer map (Map 5). Each protection zone on the map is defined by a code which represents both the vulnerability of the groundwater to contamination and the value of the groundwater resource (aquifer category). Most of the possible hydrogeological settings are present in County Cavan. Those which are present, and the percentage of the area they cover, are given in Table 6.1.

Table 6.1 Matrix of Groundwater Protection Zones

VULNERABILITY RATING	RESOURCE PROTECTION ZONES						
	Regionally Important Aquifers (R)		Locally Important Aquifers (L)			Poor Aquifers (P)	
	Rk(c/d)	Rf	Lk	Lm	Ll	Pl	Pu
Extreme (E)	1.8	0.1	Negligible	1.4	1.8	23.6	0.8
High (H)	1.7	0.5	Negligible	2.6	4.2	17.9	1.5
Moderate (M)	1.9	0.5	Negligible	1.8	3.8	20.7	Negligible
Low (L)	2.6	0.3	Negligible	0.8	4.3	4.8	Negligible

6.3 Groundwater Source Protection Reports and Maps

Source protection zones have been delineated around three group scheme (GWS) supplies, identified by Cavan County Council: Annagh Lough GWS, GWS Ballymachugh and Bawnboy GWS. These have been produced as separate sections in Volume II, and have been incorporated into Map 7 as well as separately delineated in Map 8.

6.4 Integration of Groundwater Protection Zones and Responses.

The integration of the groundwater protection zones and the groundwater protection responses is the final stage in the production of a Groundwater Protection Scheme. The level of response depends on the different elements of risk: the vulnerability, the value of the groundwater (with sources being more valuable than resources and regionally important aquifers more valuable than locally important, and so on) and the contaminant loading. By consulting a **Response Matrix**, it can be seen: (a) whether such a development is likely to be acceptable on that site; (b) what kind of further investigations may be necessary to reach a final decision; and (c) what planning or licensing conditions may be necessary for that development. The groundwater protection responses are a means of ensuring that good environmental practices are followed. Appendix I provides more information on the use of groundwater protection responses.

As the appropriate level of response takes aquifer category, proximity to public supply sources and vulnerability into account, concentration on the vulnerability map alone may result in the false impression that the acceptability of certain activities is quite limited. Table 6.2 provides a broad indication of the acceptability of certain activities in Cavan with respect to groundwater contamination.

Table 6.2 Site Suitability Response Levels in Cavan

Activity*	**Percentage of Cavan Occurring within Each Response Level**		
	Least restrictive response level (‘R1’)	Intermediate response levels: (‘R2’ and ‘R3’)	Most restrictive response level (‘R4’)
	Risk to groundwater can be managed using normal good practice guidelines.	Higher risk to groundwater. In order to manage the risk, additional requirements over and above normal good practice are recommended. Requirements can relate to site-specific ground conditions, construction, operation, and the number of existing developments in the area. If the required site-specific ground conditions do not occur at a particular site, or if the density of existing developments is too high, the activity would be regarded as ‘unacceptable’.	Additional requirements will not reduce the risk to groundwater to acceptable levels.
Landfill	11%	82%	7%
IPC Landspreading**	70%	30%	Negligible
On-site Treatment Systems	68%	32%	-
Out-Wintering Pads	63%	37%	Negligible
Earth-lined Slurry/Effluent Stores	63%	37%	Negligible

* Details on the precise response requirement for each activity can be found in (DOELG/EPA/GSI, 1999). Response levels for additional activities will be devised in the near future.
** Intensive farming, sewage sludges, poultry litter, industrial wastewater treatment plant sludges.

6.5 Conclusions

This Groundwater Protection Scheme will be a valuable tool for Cavan County Council in helping to achieve sustainable water quality management as required by national and EU policies. It will enable the County Council to take account of: (i) the potential risks to groundwater resources and sources; and (ii) geological and hydrogeological factors, when considering the location of potentially polluting developments. Consequently, it will be an important means of preventing groundwater contamination.

In considering the Groundwater Protection Scheme, it is important to remember that: (a) a scheme is intended to provide guidelines to assist decision-making in County Cavan on the location and nature of developments and activities with a view to ensuring the protection of groundwater; and (b) delineation of the groundwater protection zones is dependent on the available data. Cavan County Council will apply the scheme in decision-making on the basis that the best available data are being used. The maps have limitations because they generalise (according to availability of data) variable and complex geological and hydrogeological conditions. The scheme is therefore not prescriptive and needs to be qualified by site-specific considerations and investigations in certain instances. The investigation requirements depend mainly on the degree of hazard provided by the contaminant loading and, to a lesser extent, on the availability of hydrogeological data. The onus is on a developer to provide new information which would enable the zonation to be altered and improved and, in certain circumstances, the planning or regulatory response to be changed.

The scheme has the following uses for Cavan County Council:

- it provides a hierarchy of levels of risk and, in the process, assists in setting priorities for technical resources and investigations
- it contributes to the search for a balance of interests between groundwater protection issues and other social and economic factors
- it acts as a guide and provides a ‘first-off’ warning system before site visits and investigations are made
- it shows generally suitable and unsuitable areas for potentially hazardous developments such as landfill sites and piggeries
- it can be adapted to include risk to surface water
- it will assist in the control of developments and enable the location of certain potentially hazardous activities in lower risk areas
- it helps ensure that the pollution acts are not contravened.

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GLOSSARY OF TERMS

Alluvium: Sediments consisting of silt, sand, clay and gravel in varying proportions that are deposited by flowing water.

Aquifer: A saturated geological formation (rock or sediment) capable of storing, transmitting and yielding significant quantities of water to wells and springs.

Attenuation: The process of diminishing contaminant concentrations in groundwater, due to filtration, biodegradation, dilution, sorption, volatilisation and other processes. Breakdown or dilution of a contaminant in water.

Baseflow: That part of the flow in a stream which is not attributable to direct runoff from precipitation or snowmelt, usually sustained by groundwater discharge. That part of a stream discharge derived from groundwater seeping into the stream.

Borehole: A particular type of well, constructed by a drilling machine in order to gain access to the groundwater system.

Confined Aquifer: An aquifer in which the groundwater is overlain by impermeable geological strata. The confined groundwater is usually subject to pressure greater than atmospheric pressure.

Contaminant Loading: The amount (volume and concentration) of a contaminant discharged to soil or groundwater.

Cone of Depression: The cone of depression is where the potentiometric surface dips down forming a cone shape due to a pumping well. In an unconfined aquifer, it is the zone (usually around a well, but also around excavations such as quarries) that is normally saturated, but becomes unsaturated as a well is pumped.

Down Gradient: In the direction in which groundwater or surface water flows (also referred to as down-slope). Opposite of up-gradient.

Evapotranspiration: The sum of evaporation (the process where water changes to gas vapour and gets carried into the atmosphere) and transpiration (the process where plants take up water through their roots and give off vapour through their leaves).

Fissure: A natural crack in rock which allows rapid water movement.

Glacial Till: Deposits composed primarily of unsorted sand, silt, clay, and boulders laid down directly by melting ice.

Groundwater: The water below the water table contained in void spaces (pore spaces between rock and/or soil particles, or bedrock fractures)

Hazard: In this context, a potential source of pollution.

Hydraulic Gradient: In general, this describes the slope and direction of groundwater flow due to changes in the depth of the watertable.

Karst: Type of landscape that develops from underground solution of rocks and diversion of surface waters to underground routes. Karst areas are usually characterised by closed depressions or sink holes and an absence of surface drainage. It forms in areas underlain by soluble rock such as limestone, dolomite, gypsum and other soluble rock. The Burren is the best well-known karst area in Ireland.

Karstification: The process of dissolution of limestone bedrock, resulting in enlargement of fractures, fissures and bedding planes. Certain fractures usually get enlarged at the expense of others creating a focus for groundwater movement .

Karst Feature: Landscape feature which results from karstification, such as a enclosed depression, swallow hole, or cave, formed due to the presence of an underground drainage system.

Landfill: A site used for the deposit of waste on to or under land.

Percolation: The actual movement of subsurface water either horizontally or vertically. Lateral percolation usually occurs in the unconsolidated layers towards nearby surface drainage feature and vertical percolation usually occurs in the unsaturated zone, towards the groundwater zone.

Permeability: The ability of a medium to transmit fluids under a potential gradient (units = $L^3/t/L^2$ or L/t). Measure of a soil or rock's capacity to transmit water.

Point (Pollution) Source: Any discernible, confined, or discrete conveyance from which pollutants are or may be discharged, including (but not limited to) pipes, ditches, channels, tunnels, conduits, wells, containers, slatted sheds and animal rearing sheds.

Porosity: the ratio of the volume of void or air spaces in a rock or sediment to the total volume of rock or sediment.

Recharge: The addition of water to the zone of saturation; also, the amount of water added to the groundwater (groundwater recharge).

Runoff (surface): Precipitation that cannot be absorbed by the bedrock or overlying layers because they are already saturated with water. It occurs when precipitation exceeds the infiltration capacity of a layer. The excess water usually moves across the land (or top layers of soil as interflow) and enters a surface water body.

Saturated Zone: The zone below the water table in which all pores and fissures are full of water.

Source: A source of water supply. In this context all sources are groundwater fed (to some degree), and are usually a well (dug well or borehole) or a spring, or occasionally an infiltration gallery.

Specific Yield: The ratio of the volume of water a rock or soil will yield by gravity drainage to the volume of the rock or soil. Gravity drainage may take many months to occur.

Spring: A natural discharge of groundwater at the land's surface.

Storativity: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to the specific yield.

Subsoil: The material between the topsoil and the bedrock.

Swallow Hole: The point at which concentrated surface drainage becomes underground drainage.

Time of Travel (TOT): The time required for a contaminant to move in the saturated zone from a specific point to an outlet point (usually a spring or a well). It is the average linear velocity of flowing groundwater using Darcy's Law.

Topography: The contour of the land surface, the arrangement of the land surface, including its relief and the position of its natural features.

Unconfined aquifer: An aquifer that is not bounded above by low permeability layer. The upper boundary is defined by the water table. The water table is in connection with the atmosphere through openings in the overlying materials. Therefore, the water table surface is at atmospheric pressure.

Unsaturated Zone: The zone between the land surface and the water table, in which pores and fissures are only partially filled with water. Also known as the vadose zone.

Vulnerability: A term used to represent the intrinsic geological and hydrogeological characteristics that determine the ease with which groundwater may be contaminated by human activities.

Water Table: The uppermost level of saturation in an aquifer at which the pressure is atmospheric.

Zone of Contribution (ZOC): The area surrounding a pumped well that encompasses all areas or features that supply groundwater recharge to the well. It is defined as the area required to support an abstraction from long-term groundwater recharge.

Appendix I

Extract taken from Groundwater Protection Schemes (DELG, EPA, GSI, 1999)

The following text is taken from **Groundwater Protection Schemes**, which was jointly published in 1999 by the Department of Environment and Local Government (DELG), Environmental Protection Agency (EPA) and Geological Survey of Ireland (GSI). This Appendix gives details on the two main components of Groundwater Protection Schemes – land surface zoning and groundwater protection responses. It is included here so that this can be a stand alone report for the reader. However, it is recommended that for a full overview of the groundwater protection methodology, the publications **Groundwater Protection Responses for On-Site Systems for Single Houses (‘septic tanks’)**, **Groundwater Protection Responses for Landfills** and **Groundwater Protection Responses for Landspreading of Organic Wastes** should be consulted. These publications are available from the GSI, EPA and Government Publications Office.

Land Surface Zoning

Vulnerability Categories

Vulnerability is a term used to represent the intrinsic geological and hydrogeological characteristics that determine the ease with which groundwater may be contaminated by human activities.

The vulnerability of groundwater depends on: (i) the time of travel of infiltrating water (and contaminants); (ii) the relative quantity of contaminants that can reach the groundwater; and (iii) the contaminant attenuation capacity of the geological materials through which the water and contaminants infiltrate. As all groundwater is hydrologically connected to the land surface, it is the effectiveness of this connection that determines the relative vulnerability to contamination. Groundwater that readily and quickly receives water (and contaminants) from the land surface is considered to be more vulnerable than groundwater that receives water (and contaminants) more slowly and in lower quantities. The travel time, attenuation capacity and quantity of contaminants are a function of the following natural geological and hydrogeological attributes of any area:

(i) the subsoils that overlie the groundwater;
(ii) the type of recharge - whether point or diffuse; and
(iii) the thickness of the unsaturated zone through which the contaminant moves.

In general, little attenuation of contaminants occurs in the bedrock in Ireland because flow is almost wholly via fissures. Consequently, the subsoils (sands, gravels, glacial tills (or boulder clays), peat, lake and alluvial silts and clays), are the single most important natural feature influencing groundwater vulnerability and groundwater contamination prevention. Groundwater is most at risk where the subsoils are absent or thin and, in areas of karstic limestone, where surface streams sink underground at swallow holes.

The geological and hydrogeological characteristics can be examined and mapped, thereby providing a groundwater vulnerability assessment for any area or site. Four groundwater vulnerability categories are used in the scheme – **extreme (E)**, **high (H)**, **moderate (M)** and **low (L)**. The hydrogeological basis for these categories is summarised in Table A.1 and further details can be obtained from the GSI. The ratings are based on pragmatic judgements, experience and available technical and scientific information. However, provided the limitations are appreciated, vulnerability assessments are essential when considering the location of potentially polluting activities. As groundwater is considered to be present everywhere in Ireland, the vulnerability concept is applied to the entire land surface. The ranking of vulnerability does not take into consideration the biologically-active soil zone, as contaminants from point sources are usually discharged below this zone, often at depths of at least 1 m. However, the groundwater protection responses take account of the point of discharge for each activity.

Table A.1 Vulnerability Mapping Guidelines

Vulnerability Rating	**Hydrogeological Conditions**				
	Subsoil Permeability (Type) and Thickness			**Unsaturated Zone**	**Karst Features**
	high permeability (sand/gravel)	moderate permeability (e.g. sandy subsoil)	low permeability (e.g. clayey subsoil, clay, peat)	(sand/gravel aquifers only)	(<30 m radius)
Extreme (E)	0–3.0 m	0–3.0 m	0–3.0 m	0–3.0 m	–
High (H)	>3.0 m	3.0–10.0 m	3.0–5.0 m	>3.0 m	N/A
Moderate (M)	N/A	>10.0 m	5.0–10.0	N/A	N/A
Low (L)	N/A	N/A	>10.0 m	N/A	N/A

Notes: i) N/A = not applicable.
ii) Precise permeability values cannot be given at present.
iii) Release point of contaminants is assumed to be 1-2 m below ground surface.

Vulnerability maps are an important part of Groundwater Protection Schemes and are an essential element in the decision-making on the location of potentially polluting activities. Firstly, the vulnerability rating for an area indicates, and is a measure of, the likelihood of contamination. Secondly, the vulnerability map helps to ensure that a Groundwater Protection Scheme is not unnecessarily restrictive on human economic activity. Thirdly, the vulnerability map helps in the choice of preventative measures and enables developments, which have a significant potential to contaminate, to be located in areas of lower vulnerability.

In summary, the entire land surface is divided into four vulnerability categories – extreme (**E**), high (**H**), moderate (**M**) and low (**L**) – based on the geological and hydrogeological factors described above. This subdivision is shown on a groundwater vulnerability map. The map shows the vulnerability of the first groundwater encountered (in either sand/gravel aquifers or in bedrock) to contaminants released at depths of 1–2 m below the ground surface. Where contaminants are released at significantly different depths, there will be a need to determine groundwater vulnerability using site-specific data. The characteristics of individual contaminants are not taken into account.

Source Protection Zones

Groundwater sources, particularly public, group scheme and industrial supplies, are of critical importance in many regions. Consequently, the objective of source protection zones is to provide protection by placing tighter controls on activities within all or part of the zone of contribution (ZOC) of the source.

There are two main elements to source protection land surface zoning:
Areas surrounding individual groundwater sources; these are termed source protection areas (SPAs).
Division of the SPAs on the basis of the vulnerability of the underlying groundwater to contamination.

These elements are integrated to give the source protection zones.

Delineation of Source Protection Areas

Two source protection areas are recommended for delineation:
Inner Protection Area (SI);
Outer Protection Area (SO), encompassing the remainder of the source catchment area or ZOC.

In delineating the inner (SI) and outer (SO) protection areas, there are two broad approaches: first, using arbitrary fixed radii, which do not incorporate hydrogeological considerations; and secondly, a scientific approach using hydrogeological information and analysis, in particular the hydrogeological characteristics of the aquifer, the direction of groundwater flow, the pumping rate and the recharge.

Where the hydrogeological information is poor and/or where time and resources are limited, the simple zonation approach using the arbitrary fixed radius method is a good first step that requires little technical expertise. However, it can both over- and under-protect. It usually over-protects on the down gradient side of the source and may under-protect on the up gradient side, particularly in karst areas. It is particularly inappropriate in the case of springs where there is no part of the down gradient side in the ZOC. Also, the lack of a scientific basis reduces its defensibility as a method.

There are several hydrogeological methods for delineating SPAs. They vary in complexity, cost and the level of data and hydrogeological analysis required. Four methods, in order of increasing technical sophistication, are used by the GSI:

- (i) calculated fixed radius;
- (ii) analytical methods;
- (iii) hydrogeological mapping; and
- (iv) numerical modelling.

Each method has limitations. Even with relatively good hydrogeological data, the heterogeneity of Irish aquifers will generally prevent the delineation of definitive SPA boundaries. Consequently, the boundaries must be seen as a guide for decision-making, which can be re-appraised in the light of new knowledge or changed circumstances.

Inner Protection Area (SI)

This area is designed to protect against the effects of human activities that might have an immediate effect on the source and, in particular, against microbial pollution. The area is defined by a 100-day time of travel (ToT) from any point below the water table to the source. (The ToT varies significantly between regulatory agencies in different countries. The 100-day limit is chosen for Ireland as a relatively conservative limit to allow for the heterogeneous nature of Irish aquifers and to reduce the risk of pollution from bacteria and viruses, which in some circumstances can live longer than 50 days in groundwater.) In karst areas, it will not usually be feasible to delineate 100-day ToT boundaries, as there are large variations in permeability, high flow velocities and a low level of predictability. In these areas, the total catchment area of the source will frequently be classed as SI.

If it is necessary to use the arbitrary fixed radius method, a distance of 300 m is normally used. A semi-circular area is used for springs. The distance may be increased for sources in karst aquifers and reduced in granular aquifers and around low yielding sources.

Outer Protection Area (SO)

This area covers the remainder of the ZOC (or complete catchment area) of the groundwater source. It is defined as the area needed to support an abstraction from long-term groundwater recharge i.e. the proportion of effective rainfall that infiltrates to the water table. The abstraction rate used in delineating the zone will depend on the views and recommendations of the source owner. A factor of safety can be taken into account whereby the maximum daily abstraction rate is increased (typically by 50%) to allow for possible future increases in abstraction and for expansion of the ZOC in dry periods. In order to take account of the heterogeneity of many Irish aquifers and possible errors in estimating the groundwater flow direction, a variation in the flow direction (typically ±10–20°) is frequently included as a safety margin in delineating the ZOC.

A conceptual model of the ZOC and the 100-day ToT boundary is given in Fig. A.1.

If the arbitrary fixed radius method is used, a distance of 1000 m is recommended with, in some instances, variations in karst aquifers and around springs and low-yielding wells.

The boundaries of the SPAs are based on the horizontal flow of water to the source and, in the case particularly of the Inner Protection Area, on the time of travel in the aquifer. Consequently, the vertical movement of a water particle or contaminant from the land surface to the water table is not taken into account. This vertical movement is a critical factor in contaminant attenuation, contaminant flow velocities and in dictating the likelihood of contamination. It can be taken into account by mapping the groundwater vulnerability to contamination.

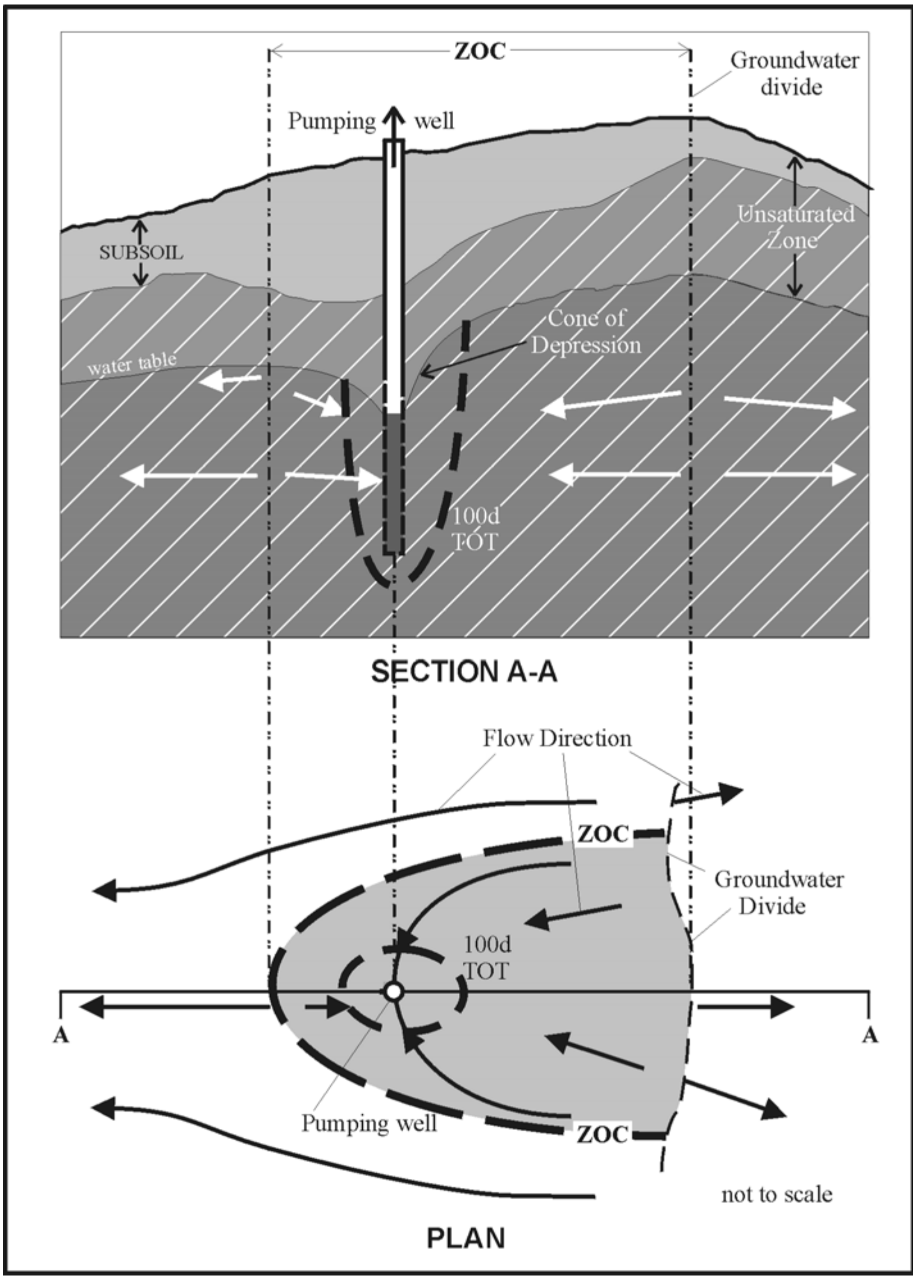

Fig. A.1 Conceptual model of the zone of contribution (ZOC) at a pumping well (adapted from US EPA, 1987)

Delineation of Source Protection Zones

The matrix in Table A.2 gives the result of integrating the two elements of land surface zoning (SPAs and vulnerability categories) – a possible total of eight source protection zones. In practice, the source protection zones are obtained by superimposing the vulnerability map on the source protection area map. Each zone is represented by a code e.g. SO/H, which represents an Outer Source Protection area where the groundwater is highly vulnerable to contamination. The recommended map scale is 1:10,560 (or 1:10,000 if available), though a smaller scale may be appropriate for large springs.

All of the hydrogeological settings represented by the zones may not be present around each groundwater source. The integration of the SPAs and the vulnerability ratings is illustrated in Fig. A.2.

Table A.2 Matrix of Source Protection Zones

VULNERABILITY RATING	SOURCE PROTECTION	
	Inner (SI)	Outer (SO)
Extreme (E)	SI/E	SO/E
High (H)	SI/H	SO/H
Moderate (M)	SI/M	SO/M
Low (L)	SI/L	SO/L

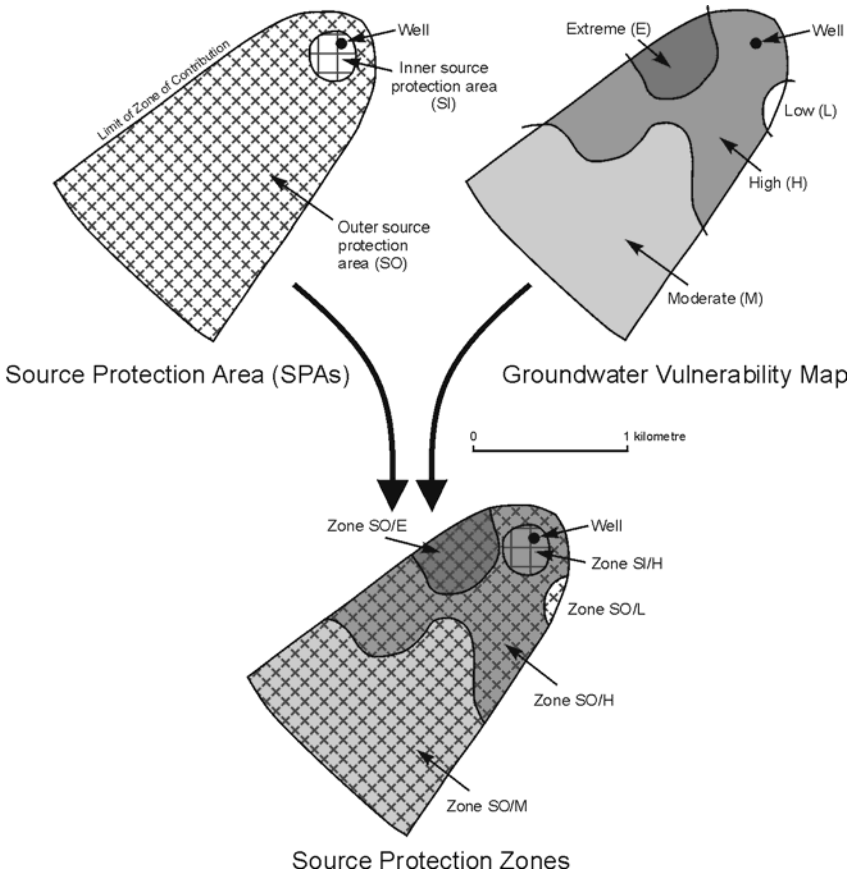

Fig. A.2 Delineation of Source Protection Zones Around a Public Supply Well from the Integration of the Source Protection Area Map and the Vulnerability Map

Resource Protection Zones

For any region, the area outside the SPAs can be subdivided, based on the value of the resource and the hydrogeological characteristics, into eight aquifer categories:

Regionally Important (R) Aquifers

(i) Karstified aquifers (**Rk**)
(ii) Fissured bedrock aquifers (**Rf**)
(iii) Extensive sand/gravel aquifers (**Rg**)

Locally Important (L) Aquifers
(i) Sand/gravel (**Lg**)
(ii) Bedrock which is Generally Moderately Productive (**Lm**)
(iii) Bedrock which is Moderately Productive only in Local Zones (**Ll**)

Poor (P) Aquifers
(i) Bedrock which is Generally Unproductive except for Local Zones (**Pl**)
(ii) Bedrock which is Generally Unproductive (**Pu**)

These aquifer categories are shown on an aquifer map, which can be used not only as an element of a Groundwater Protection Scheme but also for groundwater development purposes.

The matrix in Table A.3 gives the result of integrating the two regional elements of land surface zoning (vulnerability categories and resource protection areas) – a possible total of 24 resource protection zones. In practice this is achieved by superimposing the vulnerability map on the aquifer map. Each zone is represented by a code e.g. **Rf/M**, which represents areas of regionally important fissured aquifers where the groundwater is moderately vulnerable to contamination. In land surface zoning for groundwater protection purposes, regionally important sand/gravel (**Rg**) and fissured aquifers (**Rf**) are zoned together, as are locally important sand/gravel (**Lg**) and bedrock which is moderately productive (**Lm**). All of the hydrogeological settings represented by the zones may not be present in each local authority area.

Table A.3 Matrix of Groundwater Resource Protection Zones

VULNERABILITY RATING	RESOURCE PROTECTION ZONES					
	Regionally Important Aquifers (R)		Locally Important Aquifers (L)		Poor Aquifers (P)	
	Rk	Rf/Rg	Lm/Lg	Ll	Pl	Pu
Extreme (E)	Rk/E	Rf/E	Lm/E	Ll/E	Pl/E	Pu/E
High (H)	Rk/H	Rf/H	Lm/H	Ll/H	Pl/H	Pu/H
Moderate (M)	Rk/M	Rf/M	Lm/M	Ll/M	Pl/M	Pu/M
Low (L)	Rk/L	Rf/L	Lm/L	Ll/L	Pl/L	Pu/L

Flexibility, Limitations and Uncertainty
The land surface zoning is only as good as the information which is used in its compilation (geological mapping, hydrogeological assessment, etc.) and these are subject to revision as new information is produced. Therefore a scheme must be flexible and allow for regular revision.

Uncertainty is an inherent element in drawing geological boundaries and there is a degree of generalisation because of the map scales used. Therefore the scheme is not intended to give sufficient information for site-specific decisions. Also, where site specific data received by a regulatory body in the future are at variance with the maps, this does not undermine a scheme, but rather provides an opportunity to improve it.

Groundwater Protection Responses

Introduction

The location and management of potentially polluting activities in each groundwater protection zone is by means of a **groundwater protection response matrix** for each activity or group of activities. The level of response depends on the different elements of risk: the vulnerability, the value of the groundwater (with sources being more valuable than resources and regionally important aquifers more valuable than locally important and so on) and the contaminant loading. By consulting a **Response Matrix**, it can be seen: (a) whether such a development is likely to be acceptable on that site; (b) what kind of further investigations may be necessary to reach a final decision; and (c) what planning or licensing conditions may be necessary for that development. The groundwater protection responses are a means of ensuring that good environmental practices are followed.

Four levels of response (**R**) to the risk of a potentially polluting activity are proposed:

R1 Acceptable subject to normal good practice.

R2[a,b,c,...] Acceptable in principle, subject to conditions in note a,b,c, etc. (The number and content of the notes may vary depending on the zone and the activity).

R3[m,n,o,...] Not acceptable in principle; some exceptions may be allowed subject to the conditions in note m,n,o, etc.

R4 Not acceptable.

Integration of Groundwater Protection Zones and Response

The integration of the groundwater protection zones and the groundwater protection responses is the final stage in the production of a Groundwater Protection Scheme. The approach is illustrated for a hypothetical potentially polluting activity in the matrix in Table A.4.

The matrix encompasses both the geological/hydrogeological and the contaminant loading aspects of risk assessment. In general, the arrows (→↓) indicate directions of decreasing risk, with ↓ showing the decreasing likelihood of contamination and → showing the direction of decreasing consequence. The contaminant loading aspect of risk is indicated by the activity type in the table title.

The response to the risk of groundwater contamination is given by the response category allocated to each zone and by the site investigations and/or controls and/or protective measures described in notes a, b, c, d, m, n and o.

It is advisable to map existing hazards in the higher risk areas, particularly in zones of contribution of significant water supply sources. This would involve conducting a survey of the area and preparing an inventory of hazards. This may be followed by further site inspections, monitoring and a requirement for operational modifications, mitigation measures and perhaps even closure, as deemed necessary. New potential sources of contamination can be controlled at the planning or licensing stage, with monitoring required in some instances. In all cases the control measures and response category depend on the potential contaminant loading, the groundwater vulnerability and the groundwater value.

In considering a scheme, it is essential to remember that: (a) a scheme is intended to provide guidelines to assist decision-making on the location and nature of developments and activities with a view to ensuring the protection of groundwater; and (b) delineation of the groundwater protection zones is dependent on the data available and site specific data may be required to clarify requirements in some instances. It is intended that the statutory authorities should apply a scheme in decision-making on the basis that the best available data are being used. The onus is then on a developer to provide new information which would enable the zonation to be altered and improved and, in certain circumstances, the planning or regulatory response to be changed.

Table A.4 Groundwater Protection Response Matrix for a Hypothetical Activity

VULNERABILITY RATING	SOURCE PROTECTION		RESOURCE PROTECTION						
			Regionally Imp.		Locally Imp.		Poor Aquifers		
	Inner	Outer	Rk	Rf/Rg	Lm/Lg	Ll	Pl	Pu	
Extreme (E)	R4	R4	R4	R4	R3[m]	R2[d]	R2[c]	R2[b]	↓
High (H)	R4	R4	R4	R3[m]	R3[n]	R2[c]	R2[b]	R2[a]	↓
Moderate (M)	R4	R3[m]	R3[m]	R2[d]	R2[c]	R2[b]	R2[a]	R1	↓
Low (L)	R3[m]	R3[o]	R2[d]	R2[c]	R2[b]	R2[a]	R1	R1	↓
	→	→	→	→	→	→	→	→	→

(Arrows (→ ↓) indicate directions of decreasing risk)

Use of a Scheme

The use of a scheme is dependent on the availability of the groundwater protection responses for different activities. Currently, responses have been developed for three potentially polluting activities: IPC-licensable landspreading of organic wastes (primarily piggeries and poultry waste), domestic wastewater treatment systems, and landfills. Additional responses for other potentially polluting activities will be developed in the future.

Appendix II, Explanation of Borehole Productivity concept

QSC graphs: an aid to classification of data-poor aquifers in Ireland

G.R. Wright

From*:* Robins, N.S. and Misstear, B.D.R. (eds.) *Groundwater in the Celtic Regions: Studies in Hard Rock and Quaternary Hydrogeology.* Geological Society, London, Special Publications, **182**. The Geological Society of London.

QSC graphs: an aid to classification of data-poor aquifers in Ireland

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Abstract: The Geological Survey of Ireland's aquifer classification system recognizes three main categories: Regionally Important, Locally Important and Poor Aquifers. This system is increasingly used to assist local authorities and state agencies to make decisions on planning applications and integrated pollution control licences, by prioritizing areas according to the value of their underlying groundwater resources. Most aquifers in Ireland are unconfined fractured hard rock aquifers, often of limited extent, which can exhibit a wide range of properties. Pumping test data are scarce, patchy and often of uncertain quality, and reliable transmissivity or permeability values are unavailable for many aquifers. Under these circumstances, the classification of a given geological formation in a given region can be difficult. The 'QSC Graph' compares the specific capacity (SC) for a borehole, determined by a pumping test, with the abstraction rate during the test (Q), and indicates a 'borehole productivity index', in five classes (I, II, III, IV and V from highest to lowest). From the relative frequency of productivity classes for a given aquifer, the appropriate aquifer category can be inferred. However, other types of information for the aquifer should also be considered. The current QSC data set comprises about 1100 boreholes, and for individual formations up to 150 boreholes. The minimum data set required for an aquifer, depending on the diversity or compactness of the data, is between 20 and 50. Examples are given of the application of the approach to a number of Irish aquifers.

The Geological Survey of Ireland (GSI) has created a system of aquifer classification for use in groundwater protection schemes (Daly & Warren 1998; Department of Environment and Local Government *et al.* 1999). Three basic aquifer categories are recognized – Regionally Important Aquifers (R), Locally Important Aquifers (L) and Poor Aquifers (P), further subdivided as follows:

- Regionally Important Sand/Gravel Aquifers (Rg)
- Regionally Important Fractured Bedrock Aquifers (Rf)
- Regionally Important Karstified Aquifers (Rk)
- Locally Important Sand/Gravel Aquifers (Lg)
- Locally Important Bedrock Aquifers which are generally moderately productive (Lm)
- Locally Important Bedrock Aquifers which are moderately productive only in local zones (Ll)
- Poor Bedrock Aquifers which are unproductive except in local zones (Pl)
- Poor Bedrock Aquifers which are generally unproductive (Pu)

This classification acknowledges that wells in almost any type of rock in Ireland can yield sufficient water to supply at least a single household, and therefore no bedrock type is termed a 'non-aquifer'. The Republic of Ireland lacks any thick clay or shale lithologies (cf. the Oxford Clay of England) which are sufficiently unproductive to be unequivocally 'non-water-bearing'. The GSI classification also avoids the use of such terms as 'aquitard', 'aquiclude' or 'aquifuge', which are largely unknown to the wide range of people who are involved in water supply and protection in Ireland.

Because hydrogeological data are often scarce and patchy, various criteria are used in aquifer classification, including lithology, karstification, structural setting, occurrence/size of springs, baseflow estimation, and drainage density. However, where data are available on borehole yields and specific capacities, these are normally the main evidence whereby an aquifer is classified. While transmissivity (T) estimates from pumping tests would be desirable, there are currently too few of these for any given aquifer, and they are particularly scarce for the poorer aquifers. Even where pumping test data are available, they often fail to yield unambiguous T values, and often only a range can be suggested.

GSI's initial efforts to use borehole yield data for aquifer classification were based on the relative occurrence of 'excellent', 'good', 'moderate'

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and 'poor' yields (>400, <400 > 100, <100 > 40, and <40 m^3/d). However, it was known that the reported yield of a well could be quite different from its maximum sustainable yield. Specific capacities were also taken into account, where available, but there was no simple or consistent way to do this. There was a need for a means of integrating borehole yield data with specific capacity data in a consistent manner (Wright 1997).

Methodology

All available specific capacity data for Irish boreholes (currently almost 1100) have been compiled. The data come from four main sources: (1) local authority public supply boreholes, mostly with relatively high yields (>100 m^3/d), and mainly from counties where specific studies have been carried out; (2) boreholes drilled by the Irish Land Commission, mainly for single farms or small group schemes between 1950 and 1980, typically 30–60 m deep, with generally low test rates (<100 m^3/d); (3) consultants' well records, normally for deeper boreholes (60–120 m) with higher yields (often over 400 m^3/d); and (4) GSI records, including boreholes drilled for GSI projects.

Two important features of Irish aquifers need to be borne in mind when reviewing the data:

(a) Most Irish aquifers are unconfined.
(b) Except for Quaternary gravel/sand deposits, Irish aquifers depend almost entirely on fracture permeability, and well losses are very significant. Since fracture frequency and openness tend to decrease with depth, permeability also tends to decrease with depth, and transmissivity and specific capacity can vary substantially according to the water table level. Thus a given borehole can show very different specific capacities at different times of year, due to water table changes, and may also show sharp decreases in specific capacity at higher drawdowns.

From the data set, graphs were prepared for the commonest geological formations, plotting well 'yield' (Q) against specific capacity (SC), hence the graphs are termed 'QSC Graphs'. The QSC graphs allow the available yield and specific capacity data to be viewed simultaneously and in the context of similar data from other aquifers.

Results

The QSC graph for all boreholes (Fig. 1) covers a range of several orders of magnitude for both parameters, showing an obvious general trend within a broad 'envelope' of data points. The upper boundary of the envelope is very 'fuzzy', but the lower boundary is sharper and can be seen as controlled by two main factors, one artificial and one natural: (a) borehole depths limit the available drawdown, and (b) permeability tends to decrease with depth.

In general, a data point close to the lower boundary indicates a deep borehole which is being

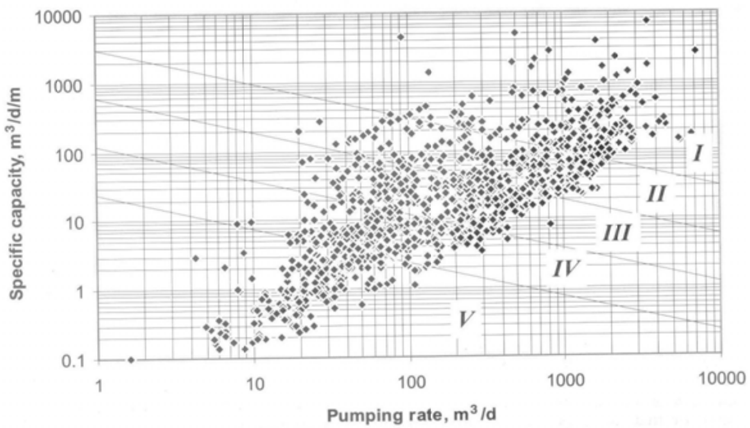

Fig. 1. QSC graph for full data set (c. 1100 boreholes), showing productivity classes I II, III, IV & V.

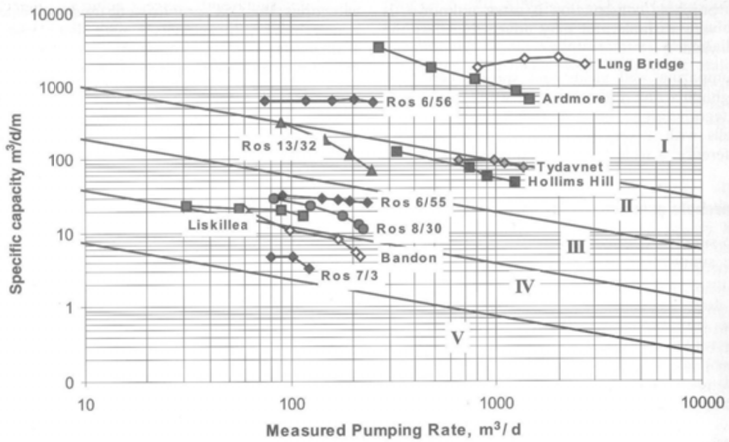

Fig. 2. QSC data for selected step tests in Ireland.

pumped near its maximum sustainable rate (i.e. most available drawdown has been used). Conversely, a data point in the upper part of the envelope indicates a borehole which could be pumped at a much higher rate than indicated, or a shallow borehole with little available drawdown.

The QSC axes can also be used to plot data from multiple tests (e.g. step tests) from the same borehole, in which case the points normally plot along a line which falls from left to right, i.e. as the pumping rate increases the specific capacity decreases (Fig. 2). The gradient will normally be quite gentle until a critical point is reached, after which it may become much steeper as well losses increase. This critical point may indicate the maximum sustainable yield of the borehole, due to increasing well losses and/or decreasing permeability down the hole.

If the general slope of such curves from individual boreholes in a given aquifer can be estimated, it is possible to extrapolate from a single data point on a QSC graph in order to predict the approximate maximum yield of a given borehole. However, it should be borne in mind that step tests may give different curves at different times of year.

By plotting QSC data from a number of boreholes in a given geological formation or aquifer unit, a classification of the aquifer can be attempted. In some cases, the graph indicates that the formation is too variable for a single classification, or that no single classification applies in all regions. In such cases the data must be examined to see if a regional or stratigraphical–lithological sub-division is valid (or both), i.e. is the wide spread of the data due to lithological variations within the formation or due to regional (perhaps structural) variations, or both?

In considering the data, too much attention must not be paid to any single data point, because the data quality may be suspect. The validity of any conclusions depends on the totality of the data, and therefore depends on having enough data points, so that occasional extreme values can be discounted. A number of factors may detract from the data quality:

- data collection by untrained personnel, low accuracy of measurements;
- pumping tests of variable length, sometimes too short: in some cases it is possible to extrapolate drawdown to, say, one week, in order to derive a realistic specific capacity value;
- in many cases, pumping rates were not constant;
- often, drawdown may not have stabilized;
- pumping tests may have been carried out at a time of relatively high water table, thus giving an unduly high SC; this may be particularly important in the poorer aquifers;
- the geological formation/lithology may not have been identified/inferred correctly;
- borehole depths are very variable (graphs plotting depth against yield show virtually no correlation, but in an individual borehole the depth will often be significant);

- borehole construction is often unknown, is very variable and may adversely affect the yield.

Comparing well yields and specific capacities highlights the difficulties of using well yield categories alone, because each category includes wells with a very wide range of SC and, by inference, a wide range of transmissivities.

Borehole productivity index

To simplify comparisons between aquifers, and to supplement the four existing well yield categories, the QSC graphs were used to create a new index ('Productivity'), with five classes: I (highest), II, III, IV and V (lowest), with boundaries as shown on Fig. 1. The boundary lines have a gradient of 1:10 (corresponding to the approximate gradient given by step tests in unconfined Irish aquifers) and are half an order of magnitude apart on the y-axis. The boundaries were set so that each class contained approximately equal numbers of data points: in practice, this worked out as follows: (I) 19%, (II) 21%, (III) 22%, (IV) 19% and (V) 19%. A five-class system seems to offer a suitable balance between simplicity and discrimination.

Fig. 3. Map of Ireland, showing counties.

For any given formation or aquifer unit, the numbers of wells in each productivity class are plotted as bar charts, to provide a productivity 'profile' which should be attributable to a particular aquifer category. Boreholes in a Regionally Important Aquifer should plot largely within classes I & II, and those in a Poor Aquifer should plot predominantly within classes IV & V. Locally Important Aquifers will plot largely in classes II to IV. However, boreholes in limestone aquifers in particular may plot across all classes because of the extreme variability produced by karstification.

Figure 3 shows a map of Ireland, with counties identified for reference. The relative frequency of occurrence of productivity classes are shown by means of bar charts for each aquifer (Figs 4–8). To illustrate the usefulness of these charts, the data are discussed below, beginning with aquifers already known to be either very good or very poor.

Regionally Important Aquifers

Quaternary Deposits (Sands & Gravels) (Fig. 4a). Well-sorted sand/gravel deposits, if sufficiently thick and saturated, are good aquifers. There are 98 data points from Quaternary deposits, mainly known sand/gravel aquifers. As expected, both Q and SC are generally high, and many data points indicate higher ultimate well yields. Lower values are probably from very thin aquifers, glacial tills, or poorly constructed wells. The great majority of data points fall into productivity classes I or II. These aquifers, if sufficiently extensive, are categorized as Regionally Important (Rg), or if too small, as Locally Important (Lg).

Wexford Formation (Limestone) (Fig. 4b). This is a small dolomitized limestone formation in County Wexford in SE Ireland, which has been quite intensively developed. Only 17 data points exist, but the data are of good quality. This is the most compact data set, with a relatively small logarithmic range of both Q (600–3000 m^3/d) and SC (15–350 m^3/d/m), and the aquifer is classed as a Regionally Important Aquifer (Rk). Most wells plot near the lower boundary of the QSC envelope, indicating that they have been tested near their maximum yield.

Campile Formation (Ordovician volcanics) (Fig. 4c). This is a highly fractured aquifer in the SE corner of Ireland (Counties Wexford and Waterford), providing 39 data points. The data set is fairly compact, and even the few lower yielding wells have rather high SCs, indicating much higher ultimate yields.

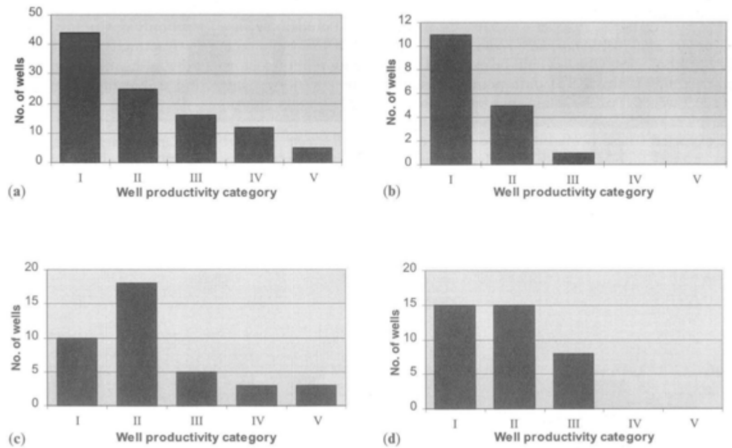

Fig. 4. Productivity bar charts for Regionally Important Aquifers (**a**) Quaternary deposits, (**b**) Wexford Limestone Formation, (**c**) Campile Formation, (**d**) Kiltorcan Sandstone Formation.

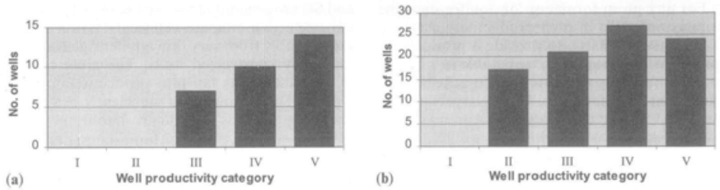

Fig. 5. Productivity bar charts for Poor Aquifers **(a)** Granites and metamorphic rocks, **(b)** Lower Palaeozoic rocks (excluding Campile Formation).

Kiltorcan Formation (Sandstone) (Fig. 4d). This Upper Devonian–Lower Carboniferous sandstone formation provides 37 data points, almost all in the upper half of the envelope, and mostly in the upper third. This aquifer is often confined. Step test results from confined aquifers show that the SC values decline only slightly with increases in discharge, so the use of the 'standard' QSC graphs tends to underestimate their productivity index. However, most values still fall into productivity classes I or II. Ideally, a different set of productivity classes should be created for confined aquifers.

Poor Aquifers

Granites and Metamorphic rocks (Fig. 5a). These lithologies, which would be expected to be poor aquifers, provide 31 data points, clustered in the lower half of the total range, and mostly in the lower third. Some SCs are higher than might be expected (these probably derive from pumping tests at high water tables). Median yield is about 33 m^3/d. These data can be taken as characteristic of a Poor Aquifer.

Lower Paleozoic rocks (excluding Campile Formation) (Fig. 5b). These fine-grained sedimentary rocks, mainly slates and greywackes, provide 89 data points. The spread of data is surprising: Q ranges up to 1000 m^3/d and more, but most values are under 100 m^3/d, and the median is about 55 m^3/d. Median SC is about 7 $m^3/d/m$. The data need further examination for regional or lithological factors, but a general classification of Poor Aquifer (Pu or Pl) is supported, with some Locally Important (Ll).

Locally Important Aquifers

Cork Group (Fig. 6a). These Lower Carboniferous rocks, mainly fine sandstones, siltstones and mudstones, are found only in County Cork, and are quite intensely fractured. Twenty five data points exist, generally in the middle third of the envelope, suggesting a Locally Important (Ll) classification.

Ballysteen Formation (Limestone) (Fig. 6b). This Lower Carboniferous argillaceous bioclastic limestone formation provides 75 data points over a wide range, but with few yields over 400 m^3/d.

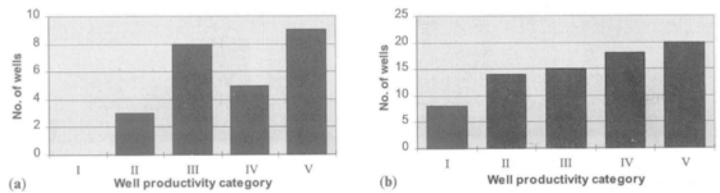

Fig. 6. Productivity bar charts for Locally Important Aquifers **(a)** Cork Group, **(b)** Ballysteen Limestone.

Median Q is about 60 m^3/d, and median SC about 8 $m^3/d/m$. The data need further study to distinguish regional (structural) and lithological (clean/muddy/dolomitized) variations. Higher yields (e.g. in counties Kilkenny and Tipperary) are probably from cleaner oolitic and/or dolomitized members. In general, a classification of Locally Important (Ll) is supported.

Variable aquifers

Devonian 'Old Red Sandstone' (excluding Kiltorcan Sandstone) (Fig. 7a). This provides 61 data points spread widely through the range, except at the very top and bottom. Median Q is 70–80 m^3/d and median SC is about 13 $m^3/d/m$. A general classification of Locally Important (Ll) is supported, but there is evidence that the coarser formations (conglomerates/coarse sandstones) are more productive, whereas finer-grained formations (siltstones, etc.) may be Poor Aquifers (Pl).

Calp Formation (Limestone) (Figs 7b–d). The Calp is a Lower Carboniferous argillaceous limestone sequence occurring widely across central Ireland from Dublin in the east to Galway in the west. The 122 data points cover a very wide range. Median Q is about 100 m^3/d, and median SC about 12 $m^3/d/m$. The data show substantial regional variations. In County Galway, in the west of Ireland, values are almost invariably low (Poor) (Fig. 7b). In County Meath in the east, Q and SC are fairly high, justifying a Locally Important (Lm) rating (Fig. 7d). Values in the intervening counties (Offaly, Westmeath, Dublin, and Kildare) are intermediate, justifying a Locally Important (Ll) rating (Fig. 7c).

Waulsortian Formation (Limestone) (Figs 8a–b). The Waulsortian Formation is a clean, fine-grained, massive Lower Carboniferous limestone which was deposited as large mud-mounds. Ninety data points exist, covering a very wide range, but mostly in the upper half of the envelope. A marked regional contrast is evident. In the south (Counties Cork, Kilkenny, Limerick, Tipperary and Waterford), where it was intensively fractured by the Variscan orogeny, and is extensively karstified and often dolomitized, a classification of Regionally Important (Rk) is amply justified (Fig. 8a). Elsewhere it is no better than Locally Important (Ll) (Fig. 8b). Further investigation may extend the Regionally Important area.

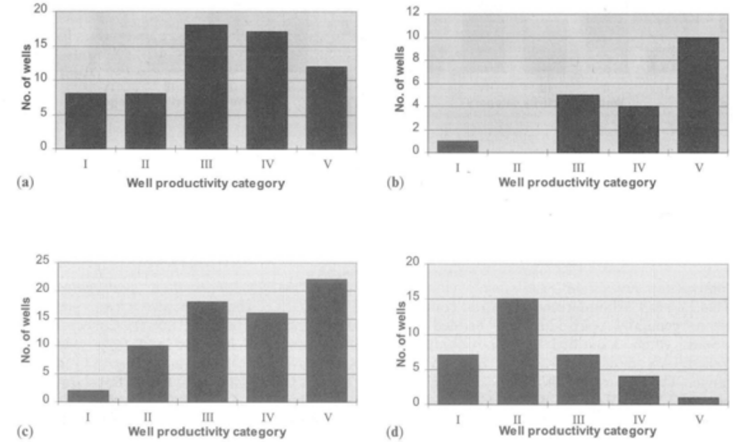

Fig. 7. Productivity bar charts for Variable Aquifers (sandstones and muddy limestones) **(a)** Old Red Sandstone (excluding Kiltorcan Formation), **(b)** Calp Limestone (Galway), **(c)** Calp Limestone (Midlands–Dublin), **(d)** Calp Limestone (Meath–North Dublin).

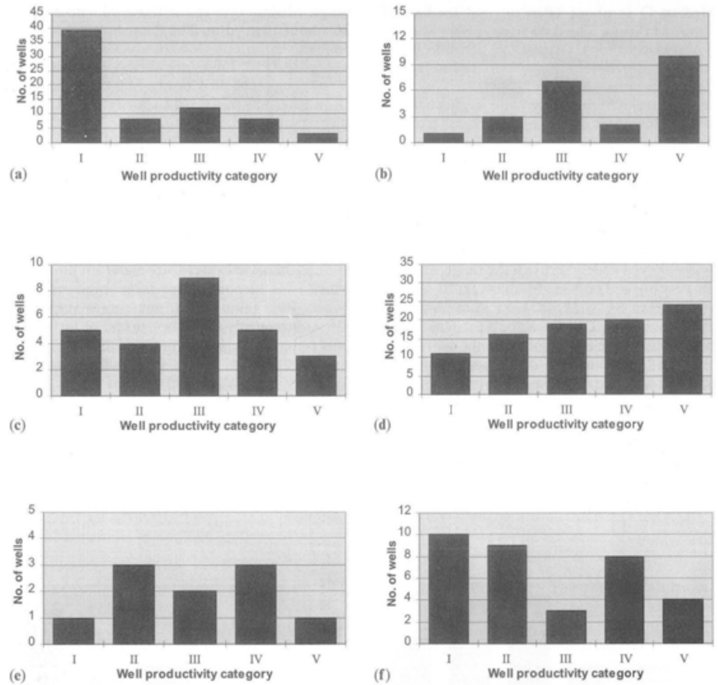

Fig. 8. Productivity bar charts for Variable Aquifers (clean limestones) (**a**) Waulsortian Limestone (South), (**b**) Waulsortian Limestone (North), (**c**) Ballyadams Limestone, (**d**) Burren Limestone (Galway–Mayo), (**e**) Burren Limestone (Laois–Offaly), (**f**) Burren Limestone (north-central region).

Ballyadams Formation (Limestone) (Fig. 8c). This Lower Carboniferous formation comprises clean, generally coarse-grained, bedded limestones, often karstified and/or dolomitized. Twenty six data points cover quite a wide range. The occurrence is limited to the southern and SE midlands (Counties Carlow, Laois, Kilkenny, and South Tipperary), so further regional analysis is difficult. Generally it is regarded as Regionally Important (Rk), but the QSC data throw some doubt on this, and in places Locally Important (Ll) may be more appropriate.

Burren Limestone Formation (and equivalents) (Figs 8d–f). These are also clean, generally coarse-grained, bedded Lower Carboniferous limestones. One hundred and forty one data points cover almost the whole range of Q and SC. Counties Galway and Mayo (Fig. 8d) show lower values than the Laois–Offaly region (Fig. 8e) and the 'north-central' region (counties Cavan, Leitrim, Longford, Meath and Roscommon, Fig. 8f). Classification is currently Regionally Important (Rk), but to some extent this derives from the high aquifer throughput rather than the QSC data.

Conclusions

QSC graphs and bar charts offer a useful semi-quantitative method of using limited pumping test data to evaluate the appropriate aquifer categories in Ireland. It is envisaged that their principal use will be to support aquifer categorization which may come under challenge where important planning decisions are involved.

A similar approach may be applicable in other countries where groundwater mainly occurs in unconfined fractured formations and where good hydrogeological data are scarce. However, the boundaries between productivity classes used in Ireland are essentially arbitrary and would probably require adjustment in other environments.

The size of the data set and its distribution are important. A total data set of at least 500 is probably needed for an area of the size and complexity of Ireland, and (depending on variability) a data set of at least 20 to 40 data points is probably needed for a defensible aquifer categorization.

The method demonstrates the need for regional discrimination: virtually identical rocks can have quite different aquifer characteristics in different areas, owing to differing geological and geomorphological histories.

Past and present colleagues in GSI are thanked for useful discussions. I am also grateful to many hydrogeologists, engineers and well drillers who contributed data, and to two anonymous reviewers for suggestions. The paper is published by permission of the Director of the Geological Survey of Ireland, Dr. Peadar McArdle.

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Appendix III, Permeability Regions in County Cavan

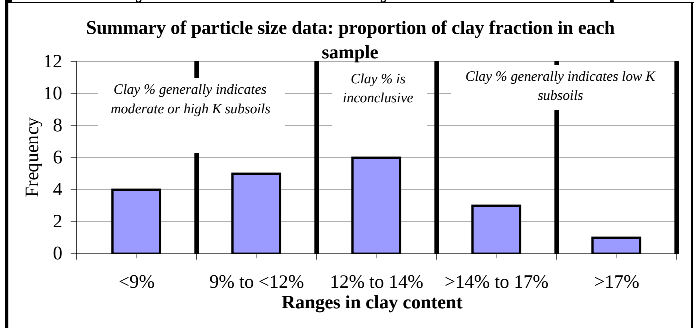
Summary of Permeability Data and Analyses for Permeability Region 1: Central East Cavan Till

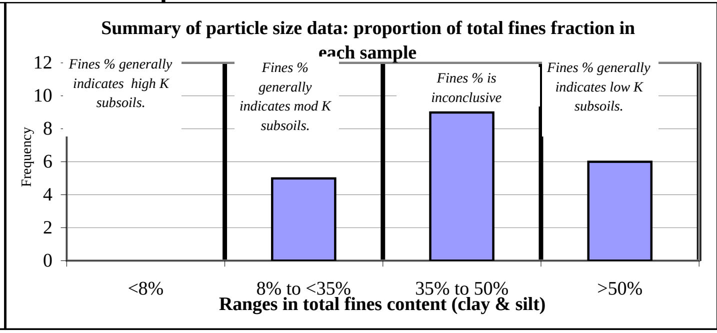
Description of unit location:	Extends across much of east Cavan (from the Erne Waterway east to Virginia and Kingscourt areas, and north to the Cavan border.
Why is this a single K unit?	Similar rock types and subsoils over areas of generally elevated topography

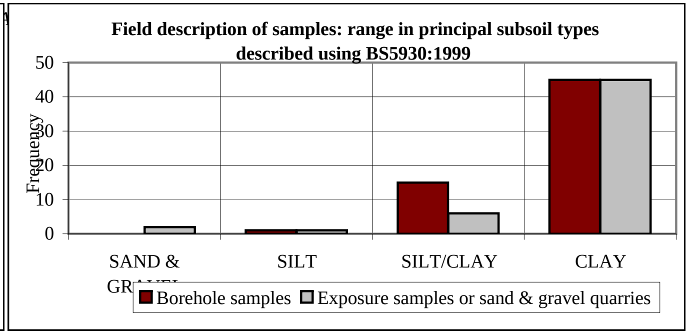
1. General Permeability Indicators and Region Characteristics

Rock type	Silurain and Ordovician Metasediments
Depth to bedrock	Highly variable, thin cover on elevated bedrock controlled areas to >10m thickness won the edges of the upland areas, moving into drumlinised areas. Drumlins generally till cored, with the exception of the Redhills area in which they are rock cored,and some crag and tail features in the lower elevations at the edge of the area.
Subsoil type	Mainly tills derived from sandtones and shales of Palaeozoic origin
Soil type	Principally acid mineral soils, deep on lower ground and shallow on elevated topography, usually well drained, with patches of poorly drained soil in places.
Vegetation and land use	Grazing and silage land, which is frequently heavily artificially drained and managed with fertilizer.
Artificial drainage density	Typically high, occasionally moderate
Natural drainage density	Moderate
Topography and altitude	Most of the area is elevated rocky hills with elevated drumlins between, an area of low lying drumlins stretches across the north around the Annalee River, and an area of relatively flat lo
Ave. effective rainfall (mm)	100 to 120mm/yr

2. Summary of Particle Size Analysis and Field Descriptions of Subsoil Samples.







3. Data from Permeability Tests.

T' tests: min/25mm # Results	# Tests T<1	# Tests T>50	**Variable head tests (m/sec):** # Results	Range Values	Typical value	**Pump tests (m/sec):** # Results	Range Values	Typical value	**Lab tests (m/sec):** # Results	Range Values	Typical value

4. Summary and Analysis

Criteria	Comments		Implications of each criterion for assessment of subsoil permeabilit
Quaternary / subsoil origin	Till with a clay rich matrix and often high gravel content, from shales and minor sandstones.	>>>	Low
Particle size data	Highest proportion of samples have borderline clay content, but high total fines content	>>>	Low
Field description data	Borehole samples	>>>	Low
	Exposure samples	>>>	Low
Soil type	AminDW	>>>	Moderate
Artificial drainage density	Generally High	>>>	Low
Natural drainage density	Moderate	>>>	Moderate
Permeability test data	No data	>>>	-
Rock type	Mainly low permeability Metamorphics (shales and greywackes) and minor Volcanics.	>>>	Low
Land use	Grazing on well managed and artificially drained land	>>>	Low
	Overall conclusion	>>>	**LOW**

5. COMMENTS: The majority of the data points to a low permeability area, which corresponds with the bedrock type (mainly shales and greywackes) and source of the overlying till. Variation in the sedimetary origin of the metamorphics results in localised variabilities in the clay content of the till (such as where sandstones occur), and permeabilities which are close to the Moderate-Low boundary in some areas. Hence, the area is used for grazing with good land management.

Summary of Permeability Data and Analyses for Permeability Region 2: Crossadoney Area Till

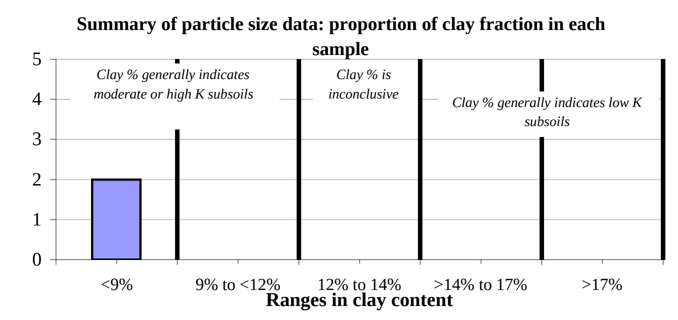
Description of unit location:	Corlismore to west of Crossadoney, and south 2km past Bellananagh
Why is this a single K unit?	Presence of Granite till subsoil and the Crossadoney Granite have resulted in patches of localised higher permeability where the gı

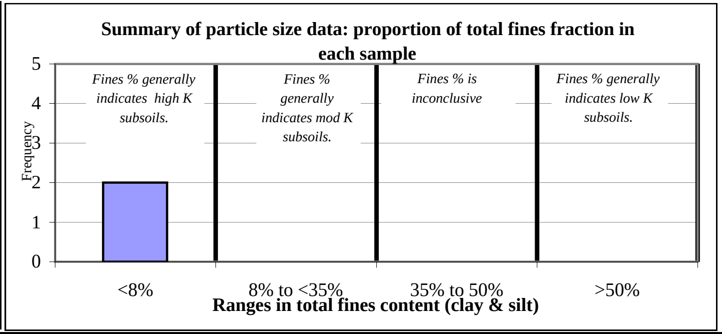
1. General Permeability Indicators and Region Characteristics

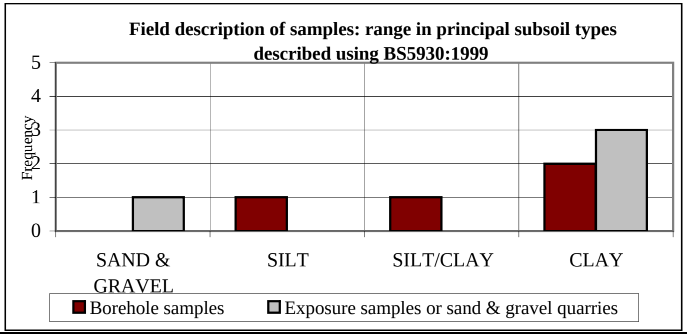
Rock type	Crossodoney Granite
Depth to bedrock	Much "rock close" in the area, generally <10m elsewhere.
Subsoil type	Granite till
Soil type	Acid mineral well drained soils (with very minor patches of acid mineral poolry drained soil).
Vegetation and land use	Grazing and tillage crops. The till areas are reasonably free draining due to a thin (upper horizon ~2m) of free draining topsoil/subsoil, and more dense low permeability dark subsoil belo
Artificial drainage density	Moderate to Low
Natural drainage density	Moderate to Low
Topography and altitude	Central Cavan with low lying NW SE trending drumlins
Ave. effective rainfall (mm)	variable; 100 to 600mm/yr

2. Summary of Particle Size Analysis and Field Descriptions of Subsoil Samples.

NB Particle distributions adjusted to discount particles greater than 20mm. Graphs only depict samples taken from 1) a known depth exceeding 1.5m in boreholes or 1m in exposures, AND 2) locations not at permeability boundaries.







3. Data from Permeability Tests.

T' tests: min/25mm	# Results	# Tests T<1	# Tests T>50	Variable head tests (m/sec):	# Results	Range Values	Typical value	Pump tests (m/sec):	# Results	Range Values	Typical value	Lab tests (m/sec):	# Results	Range Values	Typical value

4. Summary and Analysis

Criteria	Comments		Implications of each criterion for assessment of subsoil permeability
Quaternary / subsoil origin	Till with a sand/silt matrix - probably derived locally from coarse-grained grainitic rocks.	>>>	Moderate
Particle size data	<12% clay in the only PSDs available.	>>>	Moderate
Field description data	Borehole samples	>>>	Moderate-Low
	Exposure samples	>>>	Moderate-Low
Soil type	AminDW	>>>	Moderate-Low
Artificial drainage density	Low	>>>	High
Natural drainage density	Moderate to Low	>>>	Moderate-High
Permeability test data	No data	>>>	-
Rock type	Crossodoney Granite	>>>	Moderate-low
Land use	Grazing and tillage.	>>>	Moderate-High
	Overall conclusion	>>>	**MODERATE**

5. COMMENTS: Limited areas of the granite tills displayed this moderate permeability (rushes and arterial drains mapped) probably due to mixing in of material from the surrounding metasediments during iceflow. Some quite large tracts of alluvium have formed between the drumlins on the granite which is to be expected for alluvial sediments formed on granites/granite till.

Summary of Permeability Data and Analyses for Permeability Region 3: Loughs Sheelin Ramonr, Mullagh Shercock Tills

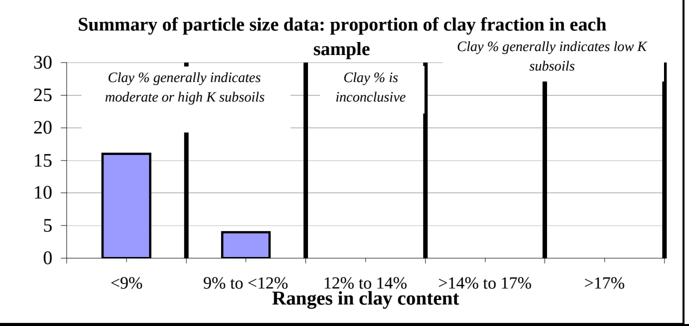
Description of unit location:	This permeability Unit is locate in the southeast of Cavan, around Loughs Sheelin and Ramor, and stretches up through the Mullagh area. There is also a small area of similar permeability around Lough Silian to north of Shercock.
Why is this a single K unit?	Uniform till which frequently has a high fines, but borderline low to mod, or low CLAY content. The area also has similar topsoil and land use and relatively uniform topography.

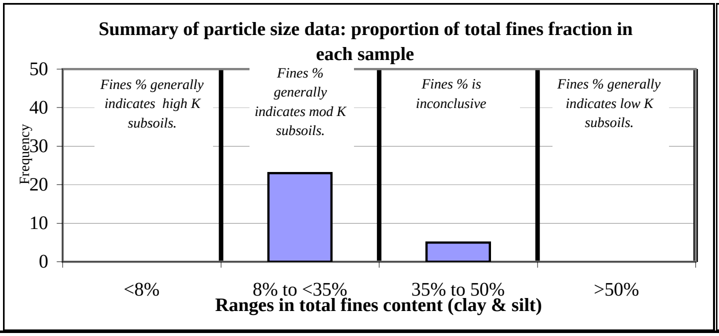
1. General Permeability Indicators and Region Characteristics

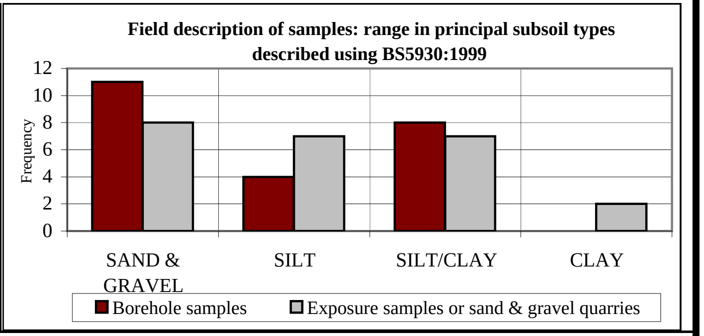
Rock type	Principally Silurian Metasediments and Volcanics, with some impure and pure Dinantian Limestones (sandstones and shales) around Lough Sheelin.
Depth to bedrock	The range in depth to bedrock is between 2m and 9.3m, the southern part is generally shallower including the limestone tills to the east of Lough Sheelin.
Subsoil type	Palaeozoic tills with an area of limestone tills to the east of Lough Sheelin.
Soil type	Principally acid mineral soils, deep on lower ground and shallow on elevated topography, usually well drained, with patches of poorly drained soil in places.
Vegetation and land use	The area in the south of the county is generally free draining and used for grazing cattle and occasionally sheep. Piggery's and coillte land also take up a portion of the land, the former pa
Artificial drainage density	Generally low
Natural drainage density	Moderate to low
Topography and altitude	The topography is mainly low lying undulating land, and some small areas of elevated land, with the exception of the Shercock area which is an elevated drumlinised area.
Ave. effective rainfall (mm)	Principally 400 to 500mm/yr, 500 to 600mm/yr in places

2. Summary of Particle Size Analysis and Field Descriptions of Subsoil Samples.

NB Particle distributions adjusted to discount particles greater than 20mm. Graphs only depict samples taken from 1) a known depth exceeding 1.5m in boreholes or 1m in exposures, AND 2) locations not at permeability boundaries.







3. Data from Permeability Tests.

T' tests: min/25mm	# Results	# Tests T<1	# Tests T>50	Variable head tests (m/sec):	# Results	Range Values	Typical value	Pump tests (m/sec):	# Results	Range Values	Typical value	Lab tests (m/sec):	# Results	Range Values	Typical value

4. Summary and Analysis

Criteria	Comments		Implications of each criterion for assessment of subsoil permeab
Quaternary / subsoil origin	Till with a clay rich matrix and often high gravel content, from shales and minor sandstones.	>>>	low
Particle size data	All PSD samples have <12% clay, fines generally<35%	>>>	moderate
Field description data	Borehole samples	>>>	high-moderate
	Exposure samples	>>>	high-moderate
Soil type	AminDW and AminSW	>>>	moderate
Artificial drainage density	low	>>>	high
Natural drainage density	moderate to low	>>>	moderate-high
Permeability test data	No data	>>>	-
Rock type	Mainly low permeability metasediments and impure limestones	>>>	moderate-low
Land use	Grazing land, generally with few rushes.	>>>	moderate-high
	Overall conclusion	>>>	**MODERATE**

5. COMMENTS: The presence of clean sand an gravel patches within this permeabiltiy unit will affects the overall drainage patterns and vegetation. A significant proportion of sand & gravels ave been recorded in this unit, although they still contain sufficient fines to result in a moderate permeability.

Summary of Permeability Data and Analyses for Permeability Region 4: Cavan Panhandle Till

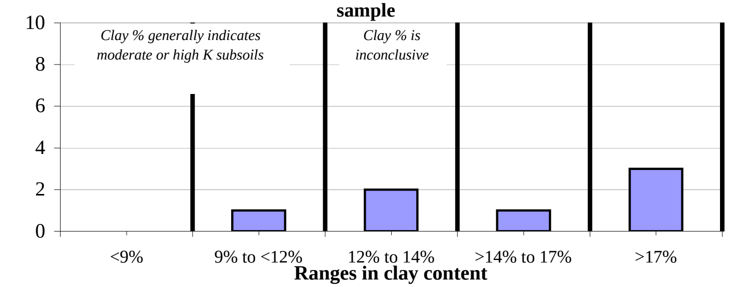
1. General Permeability Indicators and Region Characteristics

Rock type	Namurian Shales and sandstones, and Dinantian shales, sandstones and limestones in the mountaineous areas, Dinantian sandstones and Pure Bedded Limestones in the centre of Glengevlin and to the southwest, south and east of Slieve Rushen. Impure Dinantian Limestones underly the southeast of the area.
Depth to bedrock	Formation of thick tills of >10m depth between mountaineous areas.
Subsoil type	Namurian shale and sandstone till in Glangevlin, Carboniferous chert and sandstone till south and east of Slieve Rushen, patches of limestone till in the east.
Soil type	Mixture of deep well drained and poorly drained acid mineral soils in the mountaineous areas, principally the former in the remainder of this area.
Vegetation and land use	Much forested land, scrub/unused land and bog, with occasional areas for grazing.
Artificial drainage density	Very high where land has been used for forestry or grazing.
Natural drainage density	Very high draining off upland peat and in valley areas, moderate in southeast of area.
Topography and altitude	Mountainous areas up to ca. 300mOD, valleys and lowland areas generally 60 to 100m OD
Ave. effective rainfall (mm)	120 up to 160mm/yr on elevated areas, to 100 to 120 in low lying areas of the valleys and southeast.

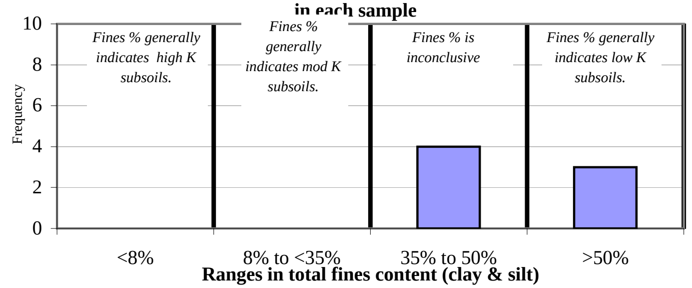
2. Summary of Particle Size Analysis and Field Descriptions of Subsoil Samples.

NB Particle distributions adjusted to discount particles greater than 20mm. Graphs only depict samples taken from 1) a known depth exceeding 1.5m in boreholes or 1m in exposures, AND 2) locations not at permeability boundaries.

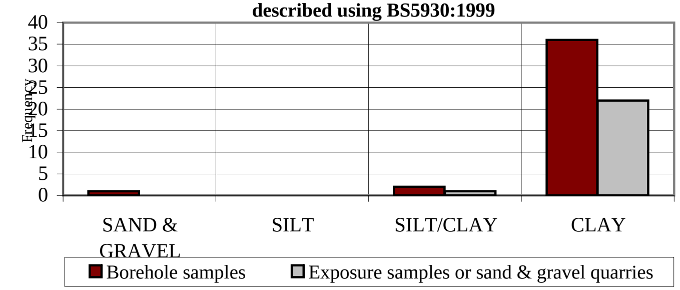
Summary of particle size data: proportion of clay fraction in each sample



Summary of particle size data: proportion of total fines fraction in each sample



Field description of samples: range in principal subsoil types described using BS5930:1999



3. Data from Permeability Tests.

T' tests: min/25mm # Results	# Tests T<1	# Tests T>50	**Variable head tests (m/sec):** # Results	Range Values	Typical value	**Pump tests (m/sec):** # Results	Range Values	Typical value	**Lab tests (m/sec):** # Results	Range Values	Typical value

4. Summary and Analysis

Criteria	**Comments**		**Implications of each criterion for assessment of subsoil permeability**
Quaternary / subsoil origin	Till derived from very sandstones and shales, from carboniferous sandstone, and from carboniferous limestone.	>>>	Low to Moderate
Particle size data	Majority have >12% Clay and all have >35%fines	>>>	Low
Field description data	Borehole samples	>>>	Low
	Exposure samples	>>>	Low
Soil type	Mainly AminDW, some Amin PD	>>>	Low to Moderate
Artificial drainage density	Very High	>>>	Low
Natural drainage density	Very High	>>>	Low
Permeability test data	No data	>>>	
Rock type	Low permeability shales, sandstones, and muddy limestones, karst limestones and moderately permeably sandstones.	>>>	Low top Moderate
Land use	Forestry, scrub, and occasional sheep grazing	>>>	Low
	Overall conclusion	>>>	**LOW**

5. COMMENTS: Argillaceous shales, sandstones and limestones at head of the glaciaers has resulted in high % clay content, and a till matrix which is particularly stiff may result from the weight of particularly thick glaciers overhead in the mountaineous area at the head of the glacier formation. The limestone tills were included in this unit as they display similar till densities and % clay content. High annual precippitation is a further reason for differences in land use between this area and the rest of Cavan.

Summary of Permeability Data and Analyses for Permeability Region 5: Sand and Gravel.

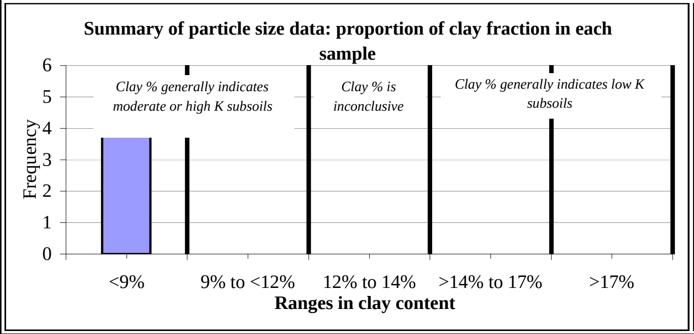
Description of unit location:	Sand and Gravel Areas
Why is this a single K unit?	Delineated as sand and gravel. Similar topsoil land use and topography.

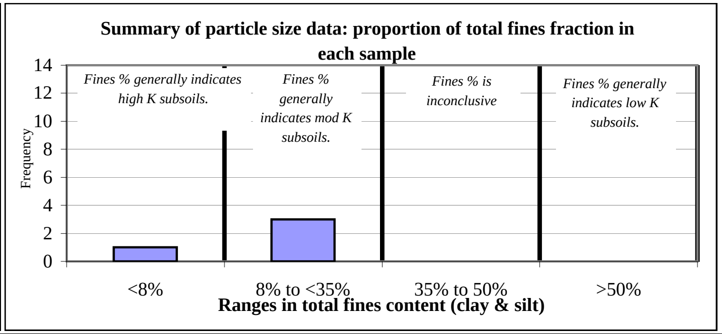
1. General Permeability Indicators and Region Characteristics

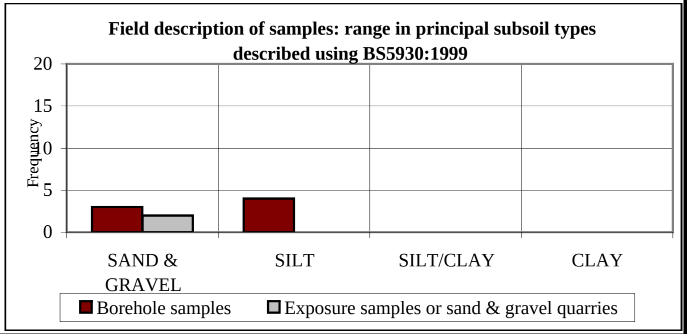
Rock type	Various. Generally low permeability rocks.
Depth to bedrock	Generally >5m and sometimes >10m.
Subsoil type	Glaciofluvially deposited sand and gravel of various rock type origins; metamorphics, limestones and sandstones.
Soil type	Mainly well drained acid mineral soils.
Vegetation and land use	Grazing. Very free draining land.
Artificial drainage density	Very low.
Natural drainage density	Low, although areas are quite small. Sometimes has streams because located in low lying discharge areas.
Topography and altitude	Generally in undulating low lying areas, less than 100m OD, frequently near or at the edges of Loughs Ramor or Sheelin.
Ave. effective rainfall (mm)	Typically 500-800

2. Summary of Particle Size Analysis and Field Descriptions of Subsoil Samples.

NB Particle distributions adjusted to discount particles greater than 20mm. Graphs only depict samples taken from 1) a known depth exceeding 1.5m in boreholes or 1m in exposures, AND 2) locations not at permeability boundaries.







3. Data from Permeability Tests.

T' tests: min/25mm	# Results	# Tests T<1	# Tests T>50	Variable head tests (m/sec):	# Results	Range Values	Typical value	Pump tests (m/sec):	# Results	Range Values	Typical value	Lab tests (m/sec):	# Results	Range Values	Typical value

4. Summary and Analysis

Criteria	Comments		Implications of each criterion for assessment of subsoil permeability
Quaternary / subsoil origin	Sand and/or gravels from glacial melt-water	>>>	high
Particle size data	<9% clay in 2 of 4 PSDs. <8% fines in 8 of 12 PSDs.	>>>	high - moderate
Field description data	Borehole samples	>>>	high
	Exposure samples	>>>	-
Soil type	Mainly acid brown earths	>>>	high - moderate
Artificial drainage density	Very low - negligible	>>>	high - moderate
Natural drainage density	Generally low, although is influenced by topographic positions (discharge zones) over larger areas.	>>>	high - moderate
Permeability test data	No data.	>>>	-
Rock type	Mainly low permeabilities Precambrian Quartzites, Gneisses & Schists .	>>>	low
Land use	Grazing, very free draining, occasional small quarries.	>>>	high - moderate
	Overall conclusion	>>>	**HIGH**

5. COMMENTS: Most areas are well sorted sand and gravel are characteristicly flat, adjacent to the coast. The limited PSD reflect a high to moderate permeability although it is anticipated that some of the larger deposits to grade to, or include 'channels' of, finer-grained material. Generally, the BS descriptions, vegetation, land use, artificial and natural drainage, soil and occasional gravel pits all support a decision of high permeability.

Summary of Permeability Data and Analyses for Permeability Region 6: Peat.

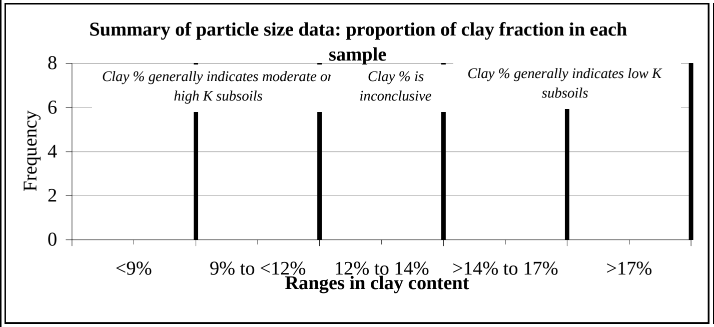
Description of unit location:	Peat areas
Why is this a single K unit?	Delineated as peat. Uniform subsoil and topsoil. Similar topography and land use.

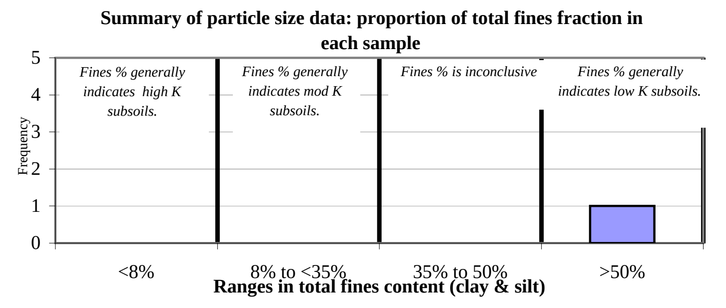
1. General Permeability Indicators and Region Characteristics

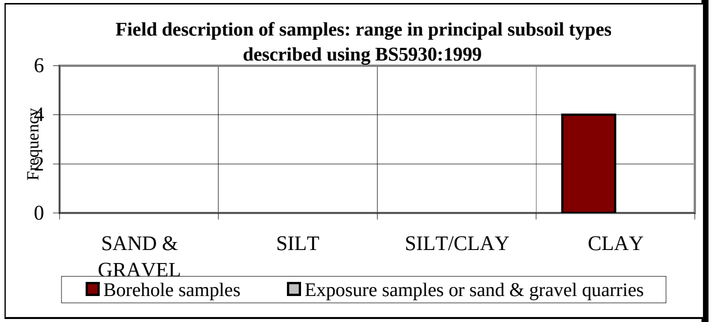
Rock type	Various, but more extensively on Namurian sandstones and shales, and Dinantian sandstones, shales and limestones.
Depth to bedrock	Generally less than 5m in low lying areas,(expected to be 5m or less in mountaineous areas also)
Subsoil type	Predominantly Blanket Peat over the higher areas. Some areas of 'Cutover Peat' that are likely to be sitting on top of lake clays and silts.
Soil type	Frequently recorded as blanket peat and cutover peat
Vegetation and land use	Much of the area is covered with coniferous forest plantations, partcularly mountaineous areas, otherwise heather, moss and rushes dominate, with occassional areas of sheep grazing.
Artificial drainage density	High on worked or aforested areas of peat, drainage is extensive to allow entry for machinery.
Natural drainage density	Moderate. The bog can store a great deal of the recharge.
Topography and altitude	Generally the higher upland areas - frequently mountainous. Also lower, shallow rock areas. Altittudes variable from 70m to 700m.
Ave. effective rainfall (mm)	Variable (80 - 160) upland to low lying areas, 160 to 180 in areas of mountaineous blanket peat.

2. Summary of Particle Size Analysis and Field Descriptions of Subsoil Samples.

NB Particle distributions adjusted to discount particles greater than 20mm. Graphs only depict samples taken from 1) a known depth exceeding 1.5m in boreholes or 1m in exposures, AND 2) locations not at permeability boundaries.







3. Data from Permeability Tests.

T' tests: min/25mm	# Results	# Tests T<1	# Tests T>50	Variable head tests (m/sec):	# Results	Range Values	Typical value	Pump tests (m/sec):	# Results	Range Values	Typical value	Lab tests (m/sec):	# Results	Range Values	Typical value

4. Summary and Analysis

Criteria	Comments		Implications of each criterion for assessment of subsoil permeability
Quaternary / subsoil origin	Peat	>>>	Low
Particle size data	only one data set available	>>>	Low
Field description data	Borehole samples	>>>	Low
	No Exposures	>>>	n/a
Soil type	Blanket Peat, peaty podzols, gleys.	>>>	Low
Artificial drainage density	High where developed	>>>	Low
Natural drainage density	Moderate to High	>>>	Moderate to low
Permeability test data	-	>>>	-
Rock type	Variable but mostly low permeability bedrock	>>>	Low
Land use	Sheep grazing, turf-cutting, if any	>>>	Low
	Overall conclusion	>>>	**LOW**

5. COMMENTS: Blanket bogs consist of a build-up of organic matter in water-logged conditions where there is high precippitation. They developed in the warmer and wetter post glacial period. Cutover peat (raised bogs) developed in depressions in the bedrock which were originally lakes, until the lakes became colonised by plants which filled in the lake as they died. Apart from the less compacted upper layers, peat has a relatively low permeability. Data are sparse but it seems likely that the overall depth to bedrock is 5-10m. Extensive cutting and draining effects the depth and permeability of the material.

Summary of Permeability Data and Analyses for Permeability Region 7: Alluvium.

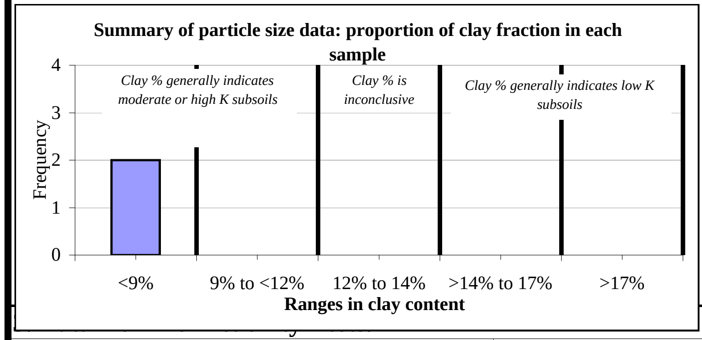
Description of unit location:	Alluvium strips mainly along Rivers Owenmore, Claddagh, Blackwater, Woodford and Annalee
Why is this a single K unit?	They are primarily fine-grained water-lain deposits found on the banks and flood-plains of rivers.

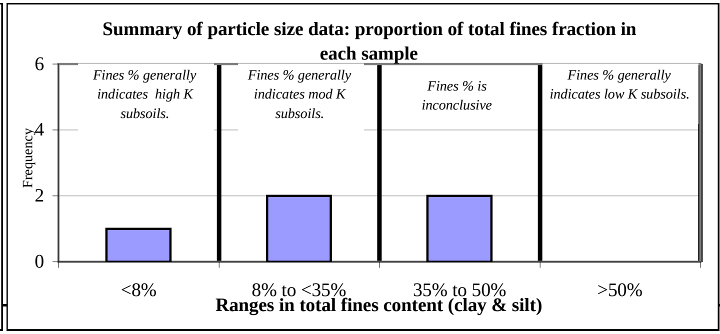
1. General Permeability Indicators and Region Characteristics

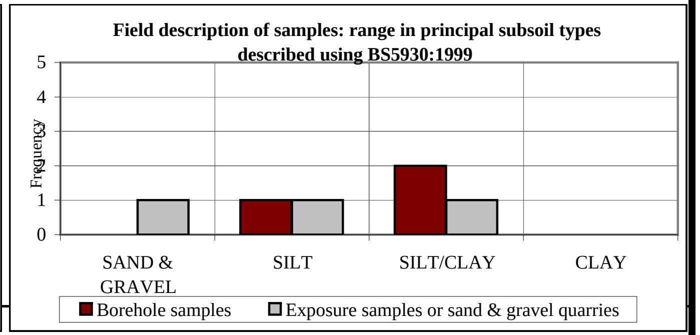
Rock type	Variable
Depth to bedrock	Typically greater than 5m. The alluvium generally overlies till or gravel deposits.
Subsoil type	Interbedded, predominantly fine-grained and sorted: sandy, silty and clayey water-lain alluvial deposits.
Soil type	Various. Not differentiated from surrounding till. Locally, groundwater gleys expected due to high water table.
Vegetation and land use	Immediately next to the rivers, the land is commonly water-logged and rushy. Where the alluvium is extensive, it may be grazed.
Artificial drainage density	High, reflecting the proximity of the watertable to the surface.
Natural drainage density	High.
Topography and altitude	Typically in valley flats throughout the county.
Ave. effective rainfall (mm)	Variable (500 - 700)

2. Summary of Particle Size Analysis and Field Descriptions of Subsoil Samples.

NB Particle distributions adjusted to discount particles greater than 20mm. Graphs only depict samples taken from 1) a known depth exceeding 1.5m in boreholes or 1m in exposures, AND 2) locations not at permeability boundaries.







T' tests: min/25mm	# Results	# Tests T<1	# Tests T>50	Variable head tests (m/sec):	# Results	Range Values	Typical value	Pump tests (m/sec):	# Results	Range Values	Typical value	Lab tests (m/sec):	# Results	Range Values	Typical value

4. Summary and Analysis

Criteria	Comments		Implications of each criterion for assessment of subsoil permeability
Quaternary / subsoil origin	Water-lain, bedded, sands, silts and clays.	>>>	high - low
Particle size data	High percentage of fines but SILT is likely to be dominant fraction	>>>	moderate
Field description data	Borehole samples	>>>	moderate - high
	Exposure samples - only one sample	>>>	Low
Soil type	Varied.	>>>	-
Artificial drainage density	High	>>>	low
Natural drainage density	High	>>>	low
Permeability test data	No data.	>>>	-
Rock type	Variable.	>>>	-
Land use	Some grazing where land is not water-logged.	>>>	moderate - low
	Overall conclusion	>>>	**MODERATE**

5. COMMENTS: The alluvial deposits all share a common origin and the BS descriptions highlight a mix of sands, silts and clays. This makes it most likely that they will have a moderate permeability. One PSD has very high clay but the fines are extremely high and thus the silts dominate the behaviour (i.e. sample dilates). This is likely to be the case for the other high fines samples. Alluvium is a quite recent deposit that is likely to be underlain by the subsoil types surrounding it. Deposits are likey to be thicker along the larger rivers although are likely to have an influence on the overall permeability in most instances.

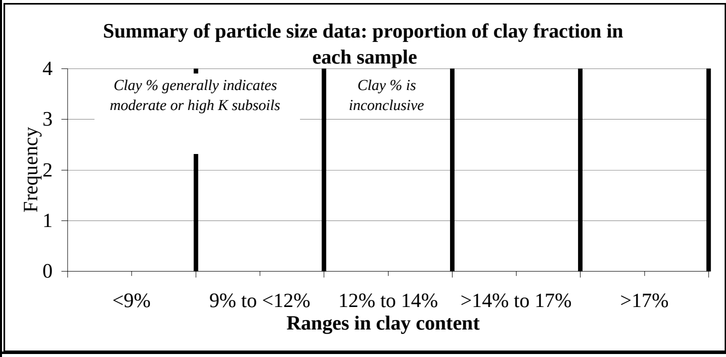
Summary of Permeability Data and Analyses for Permeability Unit 8: Lacustrine Clays

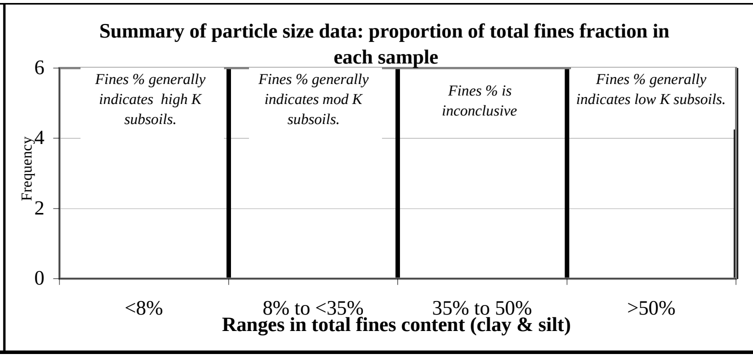
1. General Permeability Indicators and Region Characteristics

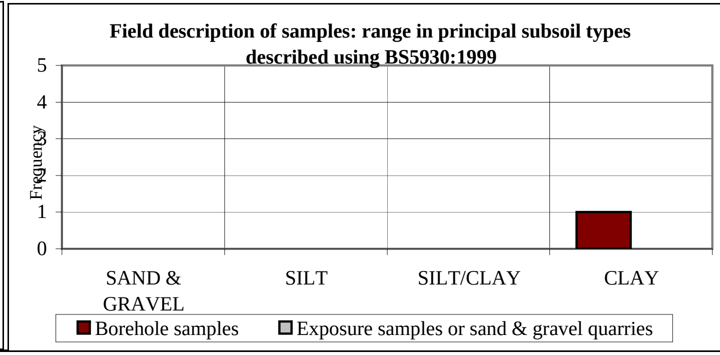
Rock type	Variable; Silurian Metasediments under lacustrine clays, Dinantian shales, sandstones and limestones under undifferentiated lacustrine deposits.
Depth to bedrock	Typically greater than 3m. Lacustrine clays generally overly tills.
Subsoil type	Fine grained, very homogenous, high density water-lain clays, whilst undifferentiated lacustrine clays can be less homogenous and more interbedded.
Soil type	Various. Not differentiated from surrounding till. Locally, groundwater gleys expected due to high water table.
Vegetation and land use	Marshy and often water-logged.
Artificial drainage density	Very high, reflecting the proximity of the watertable to the surface, and the dense low permeability material.
Natural drainage density	High.
Topography and altitude	Typically in low lying areas adjacent to lakes throughout the county.
Ave. effective rainfall (mm)	Variable (500 - 700)

2. Summary of Particle Size Analysis and Field Descriptions of Subsoil Samples.

NB Particle distributions adjusted to discount particles greater than 20mm. Graphs only depict samples taken from 1) a known depth exceeding 1.5m in boreholes or 1m in exposures, AND 2) locations not at permeability boundaries.







3. Data from Permeability Tests.

T' tests: min/25mm	# Results	# Tests T<1	# Tests T>50	Variable head tests (m/sec):	# Results	Range Values	Typical value	Pump tests (m/sec):	# Results	Range Values	Typical value	Lab tests (m/sec):	# Results	Range Values	Typical value

4. Summary and Analysis

Criteria	Comments		Implications of each criterion for assessment of subsoil permeability
Quaternary / subsoil origin	Water-lain (quiescent), homogenous clays.	>>>	Low
Particle size data	n/a	>>>	-
Field description data	Borehole samples - only one sample	>>>	Low
	Exposure samples - none available	>>>	-
Soil type	Varied.	>>>	-
Artificial drainage density	High	>>>	Low
Natural drainage density	High	>>>	Low
Permeability test data	No data.	>>>	-
Rock type	Variable.	>>>	-
Land use	Some grazing, generally marshy and water-logged.	>>>	Low
	Overall conclusion	>>>	**LOW**

5. COMMENTS: Deposits of lacustrine sediments occur throughout the county, typically as small strips around the edges of the many lakes in Cavan, but most of these deposits are considered too small and therefore likely to be too thin to influence the overall permeability, but rather reflect the permeability of the underlying till