County Donegal
Groundwater Protection Scheme

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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 are posing increasing risks to groundwater quality as there is widespread disposal of domestic, agricultural and industrial effluents to the ground and the 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, in low flow periods in summer, more than 90% is from groundwater. 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:

- a 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 is occurring;
- there is widespread application of domestic, agricultural and industrial effluents to the ground;
- the quantities of domestic, agricultural and industrial wastes are increasing;
- a significant increase in the application of inorganic fertilisers to agricultural land, and usage of pesticides in recent years;
- there are greater volumes of road traffic and more storage of fuels/chemicals; and
- manufacture and distribution of chemicals of increasing diversity and often high toxicity, used for a wide range of purposes.

The main threats to groundwater in Ireland are posed by both point and diffuse contamination sources. There are various potential point contamination sources, such as farmyard wastes (mainly silage effluent and soiled water), effluent from on-site wastewater treatment systems, sinking streams where contamination of surface water has occurred, leakages, spillages, pesticides used for non-agricultural purposes and leachate from waste disposal sites. Diffuse sources include the spreading of 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 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 by integrating hydrogeological factors into land-use policy and planning by means of groundwater protection schemes.

Land-use planning (including environmental impact assessments), 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 Groundwater Pollution Prevention

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 et al., 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 were also launched, namely, **Groundwater Protection Responses for Landfills**, **Groundwater Protection Responses for Landspreading of Organic Wastes** and **Groundwater Protection Responses for On-Site Systems for Single Houses**. Similar 'response' publications will be prepared in the future for other potentially polluting activities and developments.

There are two main components of a groundwater protection scheme, which are shown schematically in Figure 1.1:

- **Land surface zoning**;
- **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.

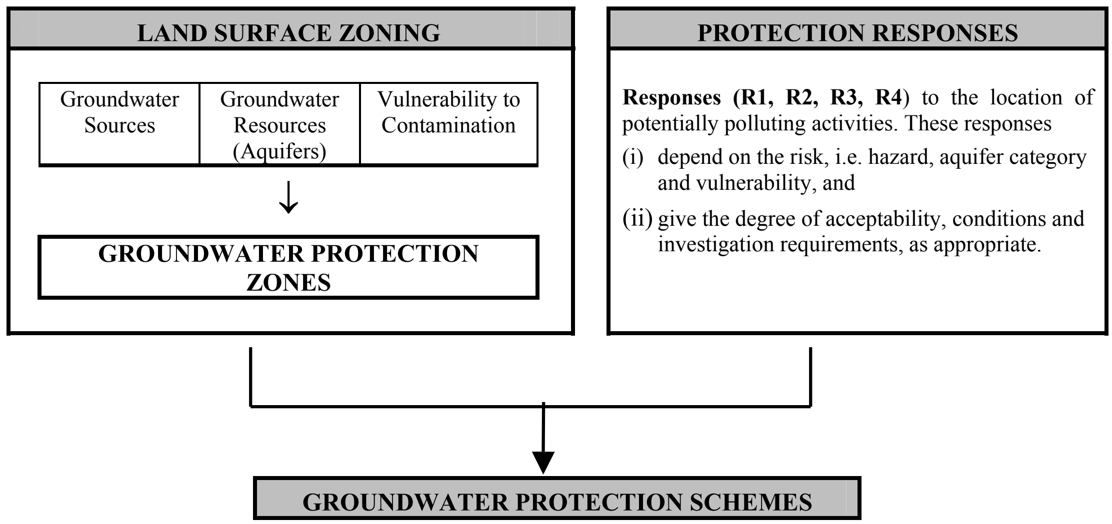

Figure 1.1 Summary of Components of Groundwater Protection Schemes

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 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.

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 interlinked in a protection scheme.

Two of the main chapters 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 et al., 1999) should be consulted.

1.5 Objectives of the County Donegal Groundwater Protection Scheme

The overall aim of the groundwater protection scheme is to preserve the quality of groundwater in County Donegal for drinking purposes and other beneficial uses, and 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; rather it will 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 needs to be qualified by site-specific considerations.

1.6 Scope of County Donegal Groundwater Protection Scheme

The groundwater protection scheme is the result of co-operation between Donegal County Council and the Geological Survey of Ireland.

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

- delineation of aquifers;
- assessment of the groundwaters' vulnerability to contamination;
- delineation of protection areas around seven public supply wells and springs identified by Donegal County Council: Ballyshannon PWS, Carndonagh PWS, Culdaff PWS, Fanad North (Tri-a-Lough Borehole) PWS, Letterkenny PWS, Magherabeg/Veagh PWS, Pettigo PWS;
- production of a groundwater protection scheme which relates the data to possible land uses in the county and to codes of practice for potentially polluting developments.

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. In addition, this information has become part of a database within the Geological Survey of Ireland (GSI) that can be accessed by the local authority and others, and which can be up-dated as new information becomes available.

Accompanying this report is a suite of environmental geology maps. These are as follows:

Primary Data or Basic Maps

- Bedrock Geology Map (Map 1)
- Forest Inventory and Planning System – Integrated Forestry Information System (FIPS-IFS) Draft Soils Parent Material Map (Map 2)
- Outcrop and Depth to Bedrock Map (Map 3)
- Hydrogeological Data Map (Map 4)

Derived or Interpretative Maps

- Aquifer Map (Map 5)
- Groundwater Vulnerability Map (Map 6)

Land-use Planning Map

- Groundwater Protection Scheme Map (Map 7)

The protection scheme deliverable has recently been enhanced by the incorporation of these outputs into 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 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 of most interest to the Local Authorities, as they have direct relevance 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.

Detailed regional hydrogeological investigations in County Donegal have included work undertaken by the GSI at present and in previous decades, as well as feasibility studies for the development of public supply sources, Environmental Impact Statements and research publications. Despite this, it is not possible to provide a fully comprehensive scientific assessment of the hydrogeology of the county, but this report provides a good basis for strategic decision-making and for site specific investigations.

1.7 Donegal County Development Plan

It is envisaged that this Groundwater Protection Scheme should be incorporated into the County Development Plan, by whatever means the Council deems suitable.

1.8 Structure of Report

The structure of this report is based on the information and mapping requirements for land surface zoning. The groundwater resource protection zone map (Map 7) is a land-use planning map and is the ultimate or final map as it is obtained by combining the aquifer (Map 5) and vulnerability maps (Map 6). The aquifer map boundaries, in turn, are based on the bedrock map (Map 1) boundaries, and the aquifer categories are obtained from an assessment of the available hydrogeological data (Map 4). The vulnerability map is based on the subsoil map (Map 2), the depth to rock map (Map 3) and an assessment of specifically relevant permeability and karstification information. This is illustrated in Figure 1.2.

Similarly, the source protection zone maps result from combining vulnerability and source protection area maps. The source protection areas are based largely on assessments of hydrogeological data. This relationship is illustrated in Figure 1.3.

Chapters 2 and 3 provide brief summaries of the bedrock and subsoil geology, respectively. Chapter 4 summarises and assesses the hydrogeological data for the different rock units, and gives the basis behind each of the aquifer categories. Chapter 5 describes the county with respect to mapped permeability regions and gives the basis behind the vulnerability categories. Finally, Chapter 6 draws all of this information together and summarises the groundwater protection zones present in County Donegal. The hydrochemistry and water quality in Donegal is presented in a separate report. Similarly, the reports outlining the protection of the public supplies are provided separately.

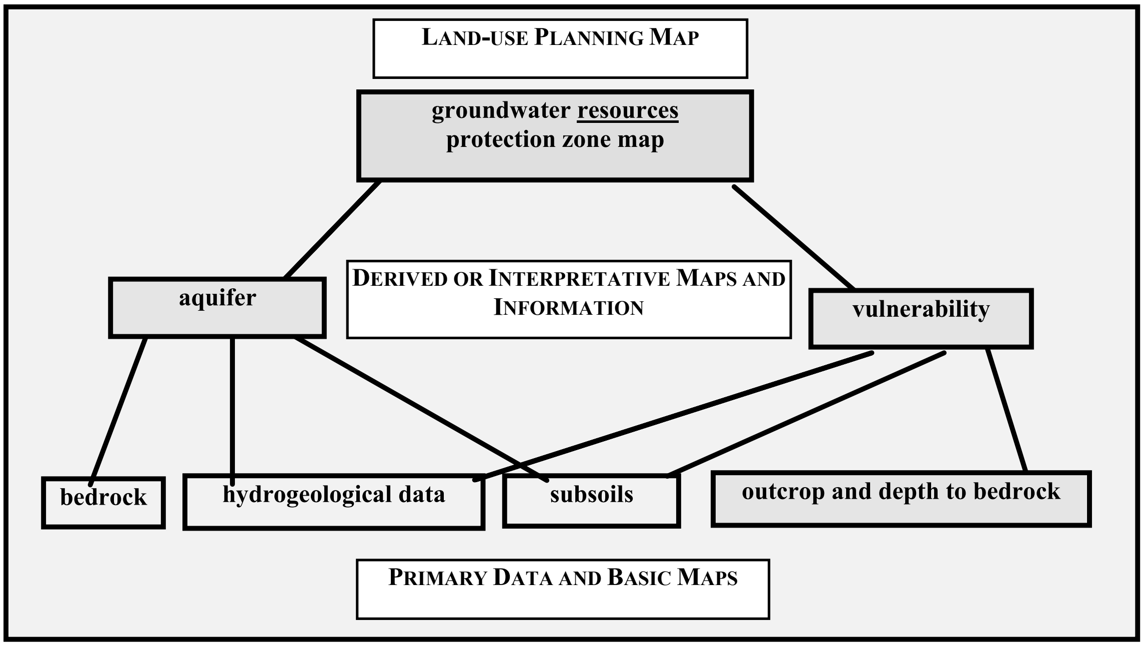

Figure 1.2 Conceptual Framework for Production of Groundwater Resource Protection Zones, Indicating Information Needs and Links

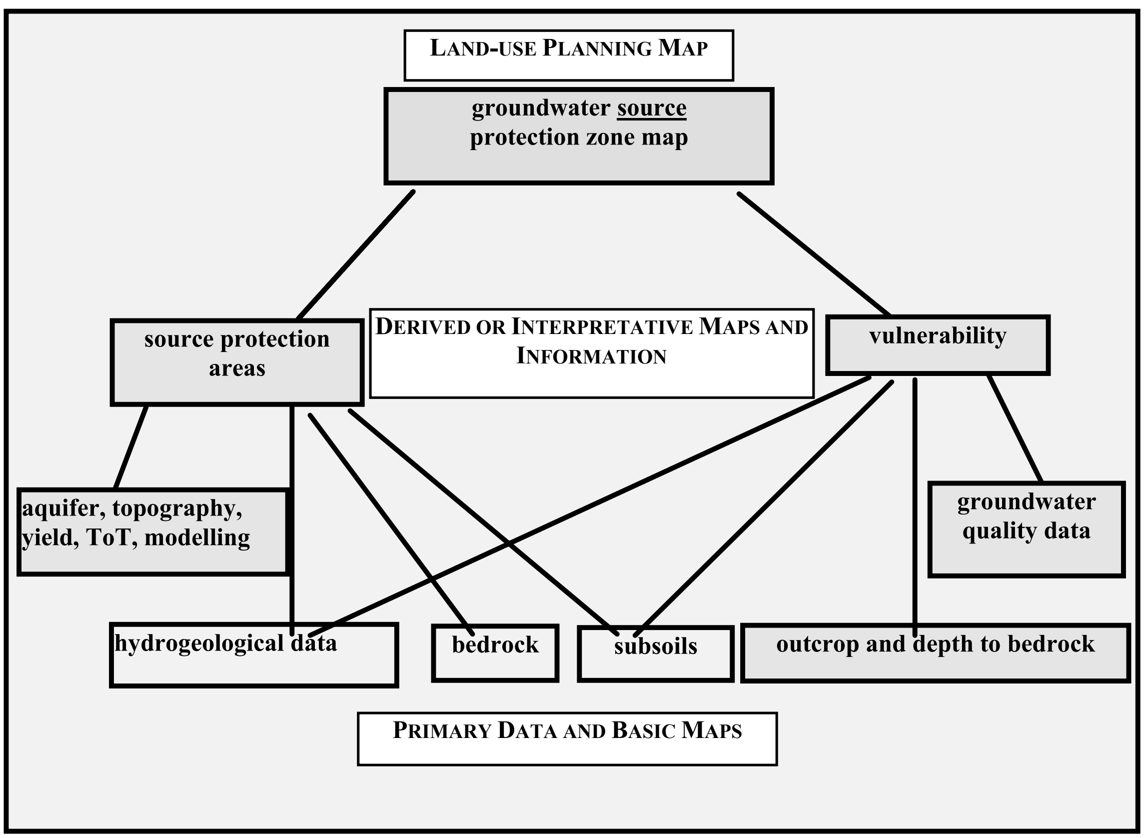

Figure 1.3 Conceptual Framework for Production of Groundwater Source Protection Zones, Indicating Information Needs and Links.

1.9 Acknowledgements

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2 Bedrock Geology

2.1 Introduction

This chapter presents a brief description of the elements of the bedrock geology of County Donegal 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.

The rocks in Donegal range in age from Precambrian to Tertiary (c.1780 to c.60 million years old). The older rocks are highly complex in origin consisting predominantly of metamorphic rocks with igneous rocks intruding them. Younger, sedimentary rocks cover only a small proportion of the county (see Table 2.1). The oldest rocks consist of coarsely crystalline metamorphic rocks and are found on Inishtrahull, northeast of Malin Head, and between Lough Derg and Ballyshannon. The youngest rocks were intruded as igneous dykes during the opening of the north Atlantic, and are particularly abundant in the Derryveagh Mountains.

All the rocks of Donegal have been folded and faulted in response to various deformation events, the latest being the opening of the north Atlantic Ocean some 65 million years ago. The most major event was during the closure of the Iapetus Ocean, when they were initially metamorphosed i.e. altered by deformation, burial and heating.

The fundamental controls on the Donegal landscape are the interactions of rock structure and glaciation (Long and McConnell, 1999). The upland areas in the north-western half of the county are underlain by hard erosion-resistant quartzites and granites, while the valleys in the south-eastern half are underlain by softer schists, shales, sandstones, and, in the extreme south of the county, limestones. Major faults and fractures running through the rocks have been enlarged and scoured by the glaciers of the last Ice Age to produce long, straight valleys, such as the dramatic Glenveagh valley.

A brief description of the different rock units and their inter-relationships is given in this report (see Table 2.1) with more detailed descriptions in Long and McConnell (1997 and 1999). In describing the rock units the emphasis is placed on the rock composition because this is the feature of most relevance to groundwater flow. The formal rock formation name and letter code is also given to enable hydrogeologists to link the brief descriptions in this report to the more detailed descriptions in the literature. The rocks are described in groups according to their age, starting with the oldest:

(i) Precambrian Rocks;
(ii) Lower Palaeozoic Rocks: Cambrian, Ordovician and Silurian;
(iii) Caledonian Intrusions (Granite);
(iv) Devonian Old Red Sandstones;
(v) Lower Carboniferous Rocks;
(vi) Tertiary Intrusions (Dolerite Dykes).

The bedrock geology of the area is shown in Map 1. This map was compiled from the Bedrock Geology 1:100,000 scale GSI map series, Sheets 1, 2, 3 and 4 (Long and McConnell 1997 and 1999).

Table 2.1 Bedrock Succession in County Donegal

Age		Succession	Main Succession		South East Donegal		South Donegal		North Donegal	
Tertiary	(65 Million yrs.)		**Dolerite, Basalt & Gabbro (D)**	Thin, silica-poor dykes						
Lower Carboniferous	Dinantian		**Mullaghmore Sandstone (MU)**	Sandstone, siltstone and shale			**Muckros Sandstone (MK)**	Calcareous sandstone and sandy oolite	**Culmore Sandstone CM)**	Sandstone, with quartz pebbles, mudstone
			Bundoran Shale (BN)	Dark shale, minor fine-grained limestone	**Bundoran Shale (BN)**	See main succession				
			Killin (KG)	Coarse feldspathic sandstone and conglomerate						
	(355 Million yrs.)		**Ballyshannon Limestone (BS)**	Pale grey calcarenite limestone	**Ballyshannon Limestone (BS)**	See main succession	**Rinn Point Limestone (RP)**	Dark fine calcarenite and calcareous shale		
			Banagher Sandstone (BG)	Feldspathic sandstone and conglomerate	**Claragh Sandstone (GH)**	Coarse to pebbly sandstone, conglomerate	**Basal Deposit Member (RPbc)**	Dark fine calcarenite and calcareous shale		
			Argillaceous Member (BSag)	Thin bedded argillaceous limestones and calcitic shales						
			Basal Deposit Member (BSbc)	Basal sandstones, limestones and shales						
Devonian sediments			**Edergole (ED)**	Conglomerate, sandstone and siltstone						
	(410 Million yrs.)		**Ballymastocker (BA)**	Red conglomerate and arkosic sandstone						
Silurian and Devonian magmatism			**Granites (various)**	Pale, coarsely crystalline intrusive igneous rock, comprising mainly quartz and feldspar						
			Appinite (Ap, Ab, H)	Diverse intrusive rocks, commonly rich in hornblende						
	(438 Million yrs.)		**Lamphrophric dykes (L)**	Hornblende-rich dykes						
Cambrian and Ordovician			**Metadolerite (Md)**	Hornblendic and sometimes schistose						
	(545 Million yrs.)		**Metabasite (bas)**	Fine-grained metabasite pods						

Cont'd …

Table 2.1 Bedrock Succession in County Donegal

Age		Succession	Main Succession (NW Donegal)		South East Donegal		South Donegal
Pre-Cambrian	Neoproterozoic (Dalradian) (700 Million yrs.)	Lough Foyle	**Greencastle Green Beds (GR)**	Green epidotic grit and green schist			
			Inishowen Head Grits & Phyllites (IH)	Psammitic and pelitic schists with grit			
			Fahan Grit (FG)	Pale grey grit with psammitic schist			
			Cloghan Green Beds (FGgc)	Graded grit with green epidotic grit			
			Fahan Slate (FS)	Dark pelitic and psammitic schist	**Claudy (CY)**	Psammite, pebbly grit, quartzite, marble	
			Undifferentiated Lough Foyle (LFS)	Schist and grit with thin marble units	**Undifferentiated Lough Foyle (LFS)**	Schist and grit with thin marble units	
		Ballybofey			**Mullyfa and Deele (MF)**	Psammite, pebble beds, marble, schist	
					Lifford Volcanics (DGlv)	Volcaniclastic green beds	
					Marble unit (DGmb)	Marble-rich unit	
					Aghyaran & Killygordon Lst. (DG)	Graphitic marble, quartzite, psammite	
					Killeter Quartzite (KT)	Slightly impure quartzite (equiv to LC and UC)	
					Lough Eske Psammite (LE)	Feldspathic psammite, quartzite, marble	
					Lough Mourne (LM)	Quartz and feldspar pebbles, green matrix	
					Boultypatrick (BO)	Psammite, graphitic clasts/beds, pebbles	
					Croaghubbrid Pelite (CH)	Graphitic pelite, thin psammite, marble	
		Finn			**Reelan (RE)**	Calcitic schist, marble and quartzite	
					Gaugin Quartzite (GA)	Pale quartzite, pebble beds, rare schist (equiv to ST)	
					Port Askaig (PA)	Diamictite, schist and quartzite	
					Croveenanta (CV)	Schist, quartzite, marble	

Cont'd …

Table 2.1 Bedrock Succession in County Donegal

Age	Succession	Main Succession (NW Donegal)		South East Donegal		South Donegal	
	Kilmacrenan	**Culdaff/Dungiven Limestone (CU/DG)**	Grey graphitic marble and pelitic schists				
		Upper Crana Quartzite (UC)	Psammitic schist with pebbly grit beds	**Upper Crana Quartzite (UC)**	Psammitic schist with pebbly grit beds		
		Lower Crana Quartzite (LC)	Psammitic schist, some marble beds	**Lower Crana Quartzite (LC)**	Psammitic schist, some marble beds		
		Termon (TE)	Banded semi-pelitic and psammitic schist	**Termon (TE)**	Banded semi-pelitic and psammitic schist	**Croaghgarrow (CW)**	Schist and aluminous schist
				Knockletteragh (TEkg)	Pebbly grits		
		Cranford Limestone (CR)	Quartzite breccia and marble	**Slieve League Quartzite (SL)**	Flaggy quarzite and dark schist		
		Slieve Tooey Quartzite (ST)	Whitish quartzite with pebble beds	**Slieve Tooey Quartzite (ST)**	Whitish quartzite with pebble beds		
		Port Askaig (PA)	Diamictite, schist and quartzite	**Port Askaig (PA)**	Diamictite, schist and quartzite		
		Glencolumbkille Limestone (GL)	Dolomitic marble and semi-pelitic schist	**Glencolumbkille Limestone (GL)**	Dolomitic marble and semi-pelitic schist		
		Glencolumbkille Pelite (GP)	Black graphitic pelitic schist	**Malin Schist (MS)**	Quartzofeldspathic and micaceous psammite		
	Creeslough	**Sessiagh-Clonmass (SC)**	Quartzite, dolomitic marble and schist	**Sessiagh-Clonmass (SC)**	Quartzite, dolomitic marble and schist		
		Clonmass Limestone (SCcl)	Dolomitic marble, calcitic and pelitic schist	**Clonmass Limestone SCcl)**	Dolomitic marble, calcitic and pelitic schist		
		Port Limestone (SCpl)	Blue-grey dolomitic marble with flags	**Port Limestone (SCpl)**	Blue-grey dolomitic marble with flags		
		Ards Quartzite (AQ)	Whitish quartzite with pebble beds	**Ards Quartzite (AQ)**	Whitish quartzite with pebble beds		
		Ards Pelite (AP)	Black pelitic schist	**Ards Pelite (AP)**	Black pelitic schist		
		Altan Limestone (AL)	White calcitic marble, some graphite	**Altan Limestone (AL)**	White calcitic marble, some graphite		
		Creeslough (CS)	Clay-rich schist with marble				
Mesoproterozoic (1700 Million yrs.)		**Metabasite (bas)** **Semi-pelitic biotite schist (SWB)** **Calc-silicate paragneiss (SWbc)** **Psammitic paragneiss (SWQ)**					
Palaeoproterozoic (1780 Million yrs.)		**The Rhinns Complex (RHC)**	Coarse-grained metasyenites, with minor metagabbro and assorted dykes				

There are a number of frequently used geological terms in the following sections. Each of these are briefly defined below:

Calcarenite	A limestone composed of greater than 50% sand-sized calcium carbonate particles.
Diamictite	A type of conglomerate in which the larger clasts are suspended in a fine-grained matrix; it is a matrix-supported conglomerate. Such conglomerates are commonly associated with glacial deposits.
Dyke	Sheet-like body of igneous rock that cross-cuts the bedding or fabric of the host rock.
Gneiss	Metamorphic rocks characterised by coarse grains and banding. The bands are predominantly comprised of quartz and feldspar.
Pelite/ pelitic	Metamorphosed clays, mudstones and siltstones/ clayey.
Psammite	Metamorphosed sandstone.
Quartzite	Metamorphosed and recrystallised sandstone.
Schist	Metamorphic rocks characterised by undulating foliation. Clay minerals (i.e., micas) give rise to schistosity.
Sill	Sheet-like body of igneous rock that conforms with the bedding or fabric of the host rock.

2.2 Precambrian Rocks

Much of Donegal is underlain by Precambrian rocks, which due to their age, have become metamorphosed. The upper part of the Precambrian is subdivided into the Palaeoproterozoic, the Mesoproterozoic and the Neoproterozoic, which in total, can be several kilometres in thickness.

2.2.1 Palaeoproterozoic Rocks: The Rhinns Complex (RHC)

Found on Inshitrahull, these are the oldest rocks in Donegal. They are thought to have been igneous rocks originally, which crystallised within the earth's crust c.1780 million years ago. Since then, these rocks have undergone several deformation events. They are predominantly coarse-grained intrusive igneous rocks.

2.2.2 Mesoproterozoic or Neoproterozoic Rocks: The Slishwood Division

The rocks of the Slishwood Division are metamorphic rocks found in the south of the county, around Lough Derg and are therefore also known as the 'Lough Derg Inlier'. They are thought to have originally been sedimentary rocks, deposited c.1700 million years ago, although their age is not certain. The initial period of metamorphosis is considered to have occurred c.1100-900 million years ago, during the Grenville Orogeny, or mountain building event. The second took place during the Brazildide Orogeny, some 600 million years ago. The rock units in this division are briefly described below, beginning with the oldest:

Psammitic paragneiss (SWQ) — Metamorphosed quartz and feldspar-rich sandstone, with an equigranular texture (Granoblastic quartzo-feldspathic psammite).

Semi-pelitic biotite schist (SWB) — Foliated rock containing platy clay minerals, quartz and feldspar (Biotite-muscovite-quartz-feldspar schist).

Calc-silicate paragneiss (SWBc) — Metamorphosed calcite and silica-rich sedimentary rocks (Calc-silicate assemblages composed of various combinations of minerals).

Metabasite (bas) — Metamorphosed feldspar-rich igneous intrusions (Garnet-clinopyroxenite or amphibolite metabasite pods).

2.2.3 Neoproterozoic Rocks: The Dalradian Supergroup

The Dalradian Supergroup contains metamorphic rocks, recorded only in Ireland and Scotland. These rocks are thought to have sedimentary origins, being laid down 700-600 million years ago, and to have first been metamorphosed c.475 million years ago (Grampian Orogeny). They are believed to have been subsequently affected by four other mountain building events (orogenies).

Due to the range of rocks within this group and the correlation with rocks in Scotland[1], subdivisions are complex, with differing rock types and successions (stratigraphic sequence of rocks) in different parts of the county. For the purposes of this report, the Dalradian rocks in Donegal are divided into three regions; northwest Donegal, southeast Donegal, and south Donegal. Within these regions, the individual rock units are grouped into local successions. Most of these successions are tectonically isolated from each other by major faults and slides.

Northwest Donegal:

1) The Creeslough Succession

Creeslough Formation (CS)	Calcareous pelitic (clay-rich) schist (foliated rock) with marble.
Altan Limestone Formation (AL)	White calcitic marble, some graphite (carbon).
Ards Pelite Formation (AP)	Black pelitic (clay-rich) schist (foliated rock); transition at top.
Ards Quartzite Formation (AQ)	Whitish quartzite with pebble beds.
Sessiagh-Clonmass Formation (SC)	Quartzite, dolomitic marble and schist.
Clonmass Limestone Member (SCcl)	*Dolomitic marble, calcitic and pelitic schist.*
Port Limestone Member (SCpl)	*Blue-grey dolomitic marble with flags.*
Lower Falcarragh Pelite Formation (LF)	Grey carbonaceous pelitic schist.
Falcarragh Limestone Formation (FL)	Blue-grey banded marble, pelite (clay) partings.
Upper Falcarragh Pelite Formation (UF)	Pelitic, semi-pelitic, psammitic (sandy) schist.
Loughros Formation (LO)	Quartzite with semi-pelitic schist.

2) The Kilmacrenan Succession

Glencolumbkille Pelite Formation (GP)	Black graphitic pelitic schist.
Glencolumbkille Limestone Fmn. (GL)	Dolomitic marble and semi-pelitic schist.
Port Askaig Formation (PA)	Diamictite (lithified boulder clay), schist and quartzite.
Slieve Tooey Quartzite Formation (ST)	Whitish quartzite with pebble beds.
Cranford Limestone Formation (CR)	Quartzite breccia and marble.
Termon Formation (TE)	Banded semi-pelitic and psammitic (sandy) schists.
Lower Crana Quartzite Formation (LC)	Psammitic (sandy) schist, some marble beds.
Upper Crana Quartzite Formation (UC)	Psammitic schist with pebbly grit beds.
Culdaff/Dungiven Limestone Fmn (CU/DG)	Grey graphitic marble and pelitic schists (both equivalent).

[1] See Long and McConnell (1997) and Long and McConnell (1999) for correlations.

3) The Lough Foyle Succession

Undifferentiated Lough Foyle Succession (LFS)	Schist and grit with thin marble units.
Fahan Slate Formation (FS)	Dark pelitic and psammitic schist.
Fahan Grit Formation (FG)	Pale grey grit with psammitic schist.
Cloghan Green Beds Member (FGcg)	*Graded grit with green epidotic grit.*
Inishowen Head Grits & Phyllites Formation (IH)	Psammitic and pelitic schists with grit.
Greencastle Green Beds Formation (GR)	Green epidotic grit and green schist.

Southeast Donegal:

1) The Creeslough Succession

The succession is the same as in north-west Donegal, except that the Creeslough Formation is absent.

2) The Kilmacrenan Succession

Malin Schist Formation (MS)	Quartzofeldspathic and micaceous psammite (equivalent to the Glencolumbkille Pelite Formation in the north-west).
Glencolumbkille Pelite Formation (GP)	Black graphitic pelitic schist.
Glencolumbkille Limestone Fmn. (GL)	Dolomitic marble and semi-pelitic schist.
Port Askaig Formation (PA)	Diamictite (lithified boulder clay), schist and quartzite.
Slieve Tooey Quartzite Formation (ST)	Whitish quartzite with pebble beds.
Slieve League Quartzite Formation (SL)	Flaggy quartzite and dark schist (equivalent to the Cranford Limestone Formation).
Cranford Limestone Formation (CR)	Quartzite breccia and marble.
Termon Formation (TE)	Banded semi-pelitic and psammitic schists.
Knockletteragh Member (TEkg)	Pebbly grits.
Lower Crana Quartzite Formation (LC)	Psammitic schist, some marble beds.
Upper Crana Quartzite Formation (UC)	Psammitic schist with pebbly grit beds.

3) The Finn Succession

Croveenanta Formation (CV)	Schist, calcitic schist, quartzite and marble.
Port Askaig Formation (PA)	Diamictite, schist and quartzite.
Gaugin Quartzite Formation (GA)	Pale quartzite, pebble beds, rare schist.
Reelan Formation (RE)	Calcitic schist, pale marble and quartzite.

4) The Ballybofey Succession

Croaghubbrid Pelite Formation (CH)	Graphitic pelite, thin psammite, marble.
Boultypatrick Formation (BO)	Psammite, graphitic clasts/beds, pebbles.
Lough Mourne Formation (LM)	Quartz and feldspar pebbles, green matrix.
Lough Eske Psammite Formation (LE)	Feldspathic psammite, quartzite, marble.
Killeter Quartzite Formation (KT)	Slightly impure quartzite.
Aghyaran & Killygordon Limestone (DG)	Graphitic marble, quartzite, psammite.
Lifford Volcanic Member (DGlv)	Volcaniclastic green beds.
Marble Unit (DGmb)	Marble-rich unit.
Mullyfa and Deele Formations (MF)	Psammite, pebble beds, marble, schist.

5) The Lough Foyle Succession

Undifferentiated Lough Foyle Succession (LFS)	Schist and grit with thin marble units.
Claudy Formation (CY)	Psammite, pebbly grit, quartzite, marble.

South Donegal:

Croaghgarrow Formation (CW)	Schist and aluminous schist.

2.3 Late Neoproterozoic, Cambrian and Ordovician Rocks

During late Neoproterozoic to Cambrian times, continental rifting is believed to have occurred, forming the Iapetus Ocean. Further south in Ireland, thick successions of schist (metamorphosed oceanic muds) are found from this period. Through the following Ordovician times, the Iapetus Ocean began to close, which yielded schists, siltstones and volcanics. The rocks of Cambrian and Ordovician age in Donegal are igneous, representing the volcanic activity associated with the formation and destruction of the Iapetus Ocean. They are found throughout the county and consist of generally thin, intrusive sills, although they can be up to 200 m in thickness. Subsequent metamorphism has altered their originally crystalline form.

Metabasite (bas)	Fine-grained metamorphosed igneous intrusions (metabasite pods, garnet-clinopyroxenite or -amphibolite).
Metadolerite (Md)	Metamorphosed igneous intrusions (Hornblend, sometimes schistose).

2.4 Late Silurian and Early Devonian Igneous Rocks

The final closure of the Iapetus Ocean was accompanied by large-scale emplacement of granite, which occurred in several different areas of Donegal although is most apparent in the Rosses, Ardara and Barnesmore. Long and McConnell (1997 and 1999) assign the granites different names according to their location and composition (Map 1). This report simplifies their description to:

Granites: • ***Ardara Granite (ArG1; ArG2; ArG3)*** • ***Barnesmore Granite (BaG1; BaG3)*** • ***Fanad Granite (FA)*** • ***Main Donegal Granite (MdGr)*** • ***Rathilin Obirne Granite (RaGr)*** • ***Rosses Granite (RsG4; mGr)*** • ***Thorr Granite (Th; spTh; ThMi)*** • ***Toories Granite (To)*** • ***Trawenagh Bay Granite (TrG1; TrG2; TrG3; TrAg; TrTr)*** • ***Tullagh Point Granite (Tu)***	Pale, coarsely-crystalline intrusive igneous rock, comprising mainly quartz and feldspar.
Appinite (Ap, Ab, H)	Diverse intrusive rocks, commonly rich in hornblende.
Lamprophyric dykes (L)	Hornblende-rich dykes found in most abundance near Ardara.

Some of the Dalradian rocks were broken off, forming rafts within the granite body. Their original units have been deformed and are named according to their lithologies (see Map 1).

2.5 Devonian Sedimentary Rocks

Deposition of the Old Red Sandstone (ORS) rocks took place 410 million years ago, in a desert-like environment. Periodic, torrential rainfall gave rise to intense erosion and then deposition of gravel, sand, silt and some clay in the flood plains of meandering rivers. The resulting 'sandstones' are reddish-brown in colour, reflecting the arid sub-aerial oxidising conditions under which these rocks were formed. They exhibit layers of fine and coarse material that reflects the varying speed of river flow during their deposition. Coarser material is common, sometimes concentrated into distinct conglomerate beds.

In Donegal, Devonian rocks are not extensive. Instead small patches are found on the eastern side of Fanad Head, north of Lough Eske, and northeast of Killybegs. The Devonian sandstones unconformably overlie the Dalradian rocks, and their base is marked by the presence of conglomerates. The two main units identified in Donegal are:

Ballymastocker Formation (BA)	Red conglomerate and feldspar-rich sandstone. Approximately 250 m thick.
Edergole Formation (ED)	Conglomerate, sandstone, siltstone. Up to 275 m thick.

2.6 Lower Carboniferous Rocks

The Lower Carboniferous was a period of marine deposition as warm tropical seas transgressed northwards, from present day County Cork, over the Devonian Old Red Sandstone continent. Consequently, the first 15 million years of the Carboniferous Period remained a time of sandstone deposition in Donegal, until the seas had reached that far north to allow marine deposition to occur.
The first marine sediments of the Lower Carboniferous in Donegal are the limestones and shales of the Ballyshannon Limestone Formation. However, uplift towards the north is believed to have resulted in the development of a southward-spreading deltaic environment, depositing muds, sandstones and conglomerates, such as the Bundoran Shale Formation, found around Donegal Bay. By late Lower Carboniferous times, these deltas began to retreat, and marine carbonates were

deposited once more. These later carbonates are not found in Donegal, where they have presumably been eroded away, but do occur to the south in Sligo. Carboniferous rocks in Donegal are mainly restricted to the south of the county, with only a small area of Lower Carboniferous sandstone (the Culmore Formation) found along the shores of Lough Foyle.

Claragh Sandstone Formation (GH)	Coarse to pebbly sandstone, conglomerate. Found east of Lough Derg. It is equivalent in age to the lower part of the Ballyshannon Limestone Formation.
Ballyshannon Limestone Formation (BS)	Pale grey calcarenite (coarse-grained) limestone. Dolomitised in places. Up to 330 m thick. Found extensively in south Donegal, particularly between Ballintra and Ballyshannon. It is equivalent in age to both the Claragh Sandstone Formation, and the Banagher Sandstone Formation.
Basal deposit Member (BSbc)	Basal sandstones, limestones and shales. Ranges in thickness from 10-70 m. Found outcropping from Lough Eske to Lough Golagh.
Argillaceous Member (BSag)	Thin bedded argillaceous (clayey) limestones and calcareous shales. Found overlying the Basal deposit Member from Lough Eske to Lough Golagh.
Banagher Sandstone Formation (BG)	Feldspar-rich sandstone and conglomerate. It is found outcropping just west of Lough Eske, and also north of Dunkineely. It is laterally continuous with the Ballyshannon Limestone Formation.
Rinn Point Limestone Formation (RP)	Dark fine calcarenite (coarse-grained limestone) and calcareous shale. Typically 130 m thick. Equivalent in age to the Ballyshannon Limestone Formation.
Basal deposit Member (RPbc)	*Basal sandstones, limestones and shales.* Typically 120 m thick. Outcrop close to Largy.
Bundoran Shale Formation (BN)	Dark shale, minor fine-grained limestone. Typically 200 m thick. Found at the surface around Bundoran and also along Doorin Point.
Killin Formation (KG)	Coarse feldspar-rich sandstone and conglomerate. Typically 260 m thick. Laterally continuous with the Bundoran Shale Formation, and found north of Doorin Point.
Muckros Sandstone Formation (MK)	Calcareous sandstone and sandy oolitic limestone. Typically 40 m thick. Found in one small area near Largy. Partially equivalent in age to the Bundoran shale and the Mullaghmore sandstone.
Mullaghmore Sandstone Formation (MU)	Sandstone, siltstone and shale. Typically 200 m thick. Found along the coast near Bundoran and Mountcharles. Conformably overlies the Bundoran Shale. Partially equivalent in age to the Muckros Sandstone.
Culmore Formation (CM)	Pebbly and calcareous sandstones and mudstones. May be equivalent in age to the top of the Mullaghmore Sandstone. Found only in north Donegal, along the eastern shore of Lough Foyle.

2.7 Upper Carboniferous Rocks

Throughout Ireland, the boundary between the Lower Carboniferous Limestones and the non-limestone Namurian and Westphalian rocks above is marked by an unconformity; this abrupt break in deposition is clearly visible as a scarp. It records a change from shallow tropical seas to first a quiet deep water environment. By the end of the Namurian, the marine basin had filled to become a coastal plain with extensive mudflats and river deltas. During Westphalian times, silty swamps were formed which spread between the sand-filled channels of large rivers in a deltaic environment. No Namurian or Westphalian rocks are present in Donegal.

2.8 Post-Carboniferous Rocks

In Donegal, no rocks are recorded for the period between 325 to 65 million years ago. This is a common occurrence across Ireland, with much ongoing debate as to what happened to the rocks laid down in this period. The Carboniferous rocks do however, show signs of having been buried and subjected to low grade metamorphism, which indicates considerable deposition.

2.9 Tertiary Rocks

The youngest rocks in Donegal are igneous, which were intruded into the older rocks during the Tertiary period, 65 million years ago. This igneous activity was related to the development of the Atlantic Ocean. The rocks of this period in Donegal are:

Dolerite, Basalt and Gabbro (D)	Thin dykes, commonly 1 m thick, and rarely substantially thicker. Silica poor, with analcime and olivine.

2.10 Structural History

The regional structure of the area is influenced by three major structural events known as the Brazildide, the Caledonian and the Variscan Orogenies (mountain-building events).

The earliest orogeny (Brazildide) occurred around 600 million years ago, and resulted in the high pressure metamorphism of the oldest rocks in Donegal, the Slishwood Division. The main deformation of the Dalradian rocks occurred during the Caledonian orogeny. This 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 Shannon Estuary to Silvermines, Navan and Clogher Head. The collision caused the intrusion of the granites, the western-most exposure of which is seen in the Inistioge area.

The Variscan Orogeny was a north-south compression event which occurred towards the end of the Carboniferous Period. The effects of this deformation are evident across Donegal as east-west trending folds (anticlines and synclines) and numerous north-south faults. In the north, these folds are quite gentle. In the south, around Mooncoin and Piltown, folding and faulting are much more intense. Rocks will have reacted differently to these pressures, depending on, amongst other factors, their strength. More competent, cleaner limestones and sandstones will generally have deformed in a more brittle manner than shales and muddy limestones.

3 Subsoil Geology

3.1 Introduction

This chapter deals primarily with the geological materials that lie above the bedrock and beneath the topsoil. Subsoil deposition occurred 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 Ice Age the glaciers and ice sheets laid down a wide range of deposits that differ in thickness, extent and lithology. Material for these deposits largely originated from bedrock or previously lain glacial deposits, 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. As ice moves, pieces of rock and soil over which it flows become attached to its base, and may become incorporated into the lower layers of the ice, making the base of the ice very abrasive. This allows the ice to rapidly erode the underlying material. In this way the substrate is eroded, picked up and transported by the ice. When the ice melts, the material is deposited as one of the many landforms caused by glacial ice. For example, water from melting glaciers tends to wash away the finer particles, leaving behind well sorted gravel deposits.

For Donegal, the subsoil mapping was undertaken by Dr. R. Meehan, in Teagasc, Kinsealy. This was part of the Forest Inventory and Planning System – Integrated Forestry Information System (FIPS-IFS) project and comprised initial compilation of all available Quaternary data, and then photogrammetric modelling of aerial photographs to infer Quaternary geological (subsoil) boundaries. Field mapping was undertaken to check these boundaries. The end product was the Soils Parent Material Map. This product was further developed as part of the Aggregate Potential Mapping (APM) Programme, undertaken by Dr. S. McCarron (2002), in the Minerals Section, GSI. The Soils Parent Material Map with the additional information provided by the APM Programme forms the foundation of subsequent subsoil permeability assessments (described in Chapter 5). Subsoil distribution is presented in the FIPS-IFS Soils Parent Material Map (Map 2), and discussed briefly in Section 3.2. An overview of evidence for ice flow directions has been provided in Section 3.4.

3.2 Subsoil Types

Much of the subsoil in County Donegal were laid down during the last glaciation affecting Ireland. The deposits remaining from this glaciation are varied in their sedimentology and their landforms. Six subsoil types are identified in Donegal, as shown on Map 2:

- Till
- Sands and Gravel
- Peat
- Alluvium
- Estuarine and Lake Deposits
- Outcrop and Shallow Rock (i.e. where bedrock comes within about 1 m of the surface).

3.2.1 Till

Till (often referred to as boulder clay or drift) occurs throughout County Donegal, covering a third of the total area. Due to the glacial history of this county, it is more prevalent in the east and southeast of the county and less common in the higher mountainous regions. Till is a diverse material that is largely deposited sub-glacially and 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. Some of the tills in Donegal have been formed into elongated hills, or drumlins. This landscape is particularly evident in the south of the county. These land features are thought to 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 (Map 2). A number of particle size analyses (PSA) were carried out during the permeability mapping and these results are discussed in the context of subsoil permeability and groundwater vulnerability in Chapter 5.

3.2.2 Sand and Gravel

Apart from beach and raised beach material, sands and gravel deposition takes place mainly when the glaciers are melting, which gives rise to large volumes of melt-water with great erosive and transporting power. Subsoil deposited in this environment are primarily well rounded gravel and 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.

Donegal has a number of reasonably large sand and gravel deposits (>1 km^2). They generally comprise either glacial or beach (possibly raised) deposits, frequently situated in the lower-lying, flatter areas around the coastline. There are a smaller number of inland glacial deposits, some of which are quarried. Although esker deposits occur, they are less frequent in this part of the country. The larger areas of mapped sand and gravel include:

- metamorphic sand and gravel at Carndonagh (glacial melt-water deposition);
- marine gravel at Doagh Isle, around Melmore Head and Falcarragh;
- wind blown sand, sometimes deposited as dunes, around Carrickart, Fanad Head, Bunbeg, Dunfanaghy, Rossnowlagh and Ballyshannon;
- beach and raised beach around Loughros More/Beg Bay, Gweebarra Bay and Inishfree Bay.

Frequently, the sand and gravel is reflected in the topography as large fan shaped deposits (outwash, deltas), or hummocks, or occasional ridges (eskers).

3.2.3 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 that 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 Donegal: blanket bog, which are characteristic of upland areas with high rainfall, and raised (cutover) bogs, which are associated with lowland areas with impeded drainage.

Mapped over 40% of the county, blanket bog is the most widespread subsoil unit in Donegal. It generally occurs on the upland, more mountainous areas and therefore dominates the west, northwest and north of the county. It is likely to be between 1-3 m thick, although develops to greater thickness where the conditions are favourable. Raised (cutover) bog occupies less than 1% of the county and is limited to the inter-drumlin areas in the south and southwest. In some areas, the bogs are worked for turf/peat, although this is not particularly common in Donegal.

3.2.4 Alluvium

Alluvial sediments are deposited by rivers and include unconsolidated materials of all grain sizes, from coarse gravel down to finer silts and clays, and may contain organic detritus. These deposits are usually bedded, consisting of many complex strata of water-lain material. Most of the alluvial deposits in Donegal comprise sand, silt and clay, and occasionally gravel. The largest area of mapped alluvium are in the east of the county along the Rivers Swilly, Foyle, Deele, Finn and Swilly Burn, and the reclaimed land to the north and northeast of Newtown Cunningham.

3.2.5 Estuarine and Lake Deposits

The estuarine and lake deposits are considered together as they comprise similar material; predominantly fines-dominated 'mud', or silty/clayey material, similar to the finer type of alluvium.

The estuarine deposits in Donegal are deposited in a tidal environment by the actions of the Lough Swilly Estuary and Gweebarra Bay. Lake deposits were formed in the quiet waters of lakes formed by melting glacier waters. Only a few small areas of lake deposits are mapped in Donegal, mainly in the southwest.

3.3 Depth to Bedrock

The depth to bedrock (i.e. subsoil thickness) is a critical factor in determining groundwater vulnerability. Subsoil thickness varies considerably over the county, from very thin cover where the rock is close to the surface, to depths of more than 30 m.

Broad, regional-scale variations in depth to bedrock have been interpreted across the county by using information from the Teagasc FIPS-IFS mapping programme, GSI databases and field mapping. Depth to rock data (Map 3) highlights areas where rock crops out at, or is close to, the surface, and depth to rock data from borehole records. The borehole records are colour-coded according to the degree of their location accuracy e.g. 'red' data points are plotted to within an accuracy of 50 m. In addition to these data, some general assumptions are made in order to extrapolate to areas where data are not available.

Complex glacial processes and a variable landscape have given rise to different amounts of erosion and deposition throughout the county. The direction of ice movement and the height and competency of the bedrock, for example, have spatially influenced the thickness of the deposits. In general, there has been removal of eroded material from Donegal, with recent data indicating that there has been a high degree of deposition of this eroded material further out on the continental shelf i.e. on the seabed (Dr. R. Meehan, *pers.comm.* 2004). Consequently, a large proportion of the county is considered to have only a thin covering of subsoil material, which is particularly evident on the higher, more mountainous regions.

The thickest till deposits in Donegal are mainly found on the lower-lying valley areas to the east of the county (east and southeast of Letterkenny), and the drumlin area in the south and southwest of the county. Sand/gravel deposit around the lower-lying coastal areas are also thought to be relatively thick e.g. the Carndonagh sand and gravel body. The thickness of alluvial, estuarine and lake deposits are usually unknown but it is unlikely that they are more than 10 m thick. Blanket peat on higher ground is typically 3 m, or less, in thickness.

3.4 Ice Flow Direction

Since the Tertiary period, the landscape in Donegal has undergone significant erosion, principally during the Quaternary ice ages (last 2 million years). During this period, ice extended outwards from an ice shed centred on the Derryveagh Mountains, which reach as far as the Bluestack Mountains. In the north of the county, all available evidence (e.g. striae on Lough Salt Mountain, roches moutonnées on the Glegesh Plateau, granite erratics on Errigal) indicate that ice moved to the northeast and the northwest from the ice shed. The northeast moving ice was forced to move northwards along Inishowen, Lough Swilly, Mulroy Bay and Sheep Haven (Long and McConnell, 1997).

The south of the county was also subjected to ice moving southwards from the Derryveagh/Bluestack Mountains ice shed, but was also influenced by ice flowing from an ice-divide stretching from Carrick-on-Shannon to Lough Neagh (Long and McConnell, 1999). The ice from these two centres met in Donegal Bay and deflected, to flow towards the east and southeast, which is also indicated by the drumlin orientation around Donegal Bay.

During the final stages of glaciation, the ice grew thinner and the topography provided a much stronger control on ice flow direction. Ice was channelled around the highest mountains and along the well developed glaciated ('U' shaped) valleys e.g. Barnesmore Gap and Poisoned Glen.

The rock material that was incorporated into the ice was eventually deposited, either directly by the ice as till, or by melt-water as sorted gravel, sand, silt or clay. Overall, there has been removal of accumulated weathering products by the moving ice in the upland areas, which has resulted in few areas of deeper sediment cover and extensive areas of exposed, relatively un-weathered bedrock (McCarron, 2002). On the lowlands, however, till is often over 30 m thick, especially in the areas dominated by drumlins.

4 Hydrogeology and Aquifer Classification

4.1 Introduction

This chapter summarises the relevant and available hydrogeological and groundwater information for County Donegal. A brief description of the hydrogeology of each rock unit 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 aquifer classifications are shown on Map 5.

4.2 Data Availability

All the groundwater data in the GSI and from County Council files, consultants and drillers (c.1000 wells and springs in total) were compiled and entered into a computer database in the GSI.

The assessment of the hydrogeology of County Donegal is based on the following data:

- Abstraction data for Public Water Supply Schemes, Group Water Supply Scheme, and for a limited number of other high yielding private wells.
- Information from the Well Improvement Grant Scheme.
- Specific capacity[2] and discharge data for some 100 wells in Donegal. These parameters are used to derive the 'productivity category', which can be related to the aquifer category (Wright, 2000).
- Information on large springs.
- The GSI karst database.
- Hydrochemical data from County Council/GSI and EPA sampling rounds of the main Public and Group Water Schemes.
- Reports by engineering and hydrogeological consultants.
- Relevant academic research papers.
- General hydrogeological experience of the GSI, including work carried out in delineating the Draft National Aquifer Map (2004).

4.3 Rainfall, Evapotranspiration and Recharge

Mean annual rainfall in County Donegal for the period 1961-1990 varied from just over 1010 mm in Newtown Cunningham, to some 2800 mm in the Bluestack Mountains (Fitzgerald and Forrestal, 1996). Recharge has been estimated for more localised areas around Public Water Supply Schemes using Met Eireann rainfall and potential evapotranspiration data (Volume II).

The long term mean annual potential evapotranspiration (PE) has been calculated from the data collected at the Malin Head synoptic weather station; 570 mm for the period 1961 to 1990 (Met Eireann data). Actual evapotranspiration (AE) is estimated at about 90-95% of the PE, giving an approximate value 530 mm.

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[2] Specific capacity is the rate of abstraction per unit drawdown. The unit used is $m^3/d/m$.

The mean annual effective rainfall (rainfall minus AE) is therefore estimated to be in the range of 480-2270 mm, with the lowest levels in the low-lying southern and north-eastern areas, and the highest in the central and north-western uplands. The annual recharge to groundwater (effective rainfall less surface water runoff) depends on the relative rates of infiltration, which are influenced by subsoil permeability and saturation. In low permeability or waterlogged areas, actual recharge may be as low as 5% of the effective rainfall.

4.4 Groundwater Usage

In comparison to the national average of 25% groundwater usage, County Donegal has a low groundwater consumption – only 5%, some 3000 m^3/d, of publicly supplied water is from groundwater. The publicly supplied water constitutes 95% of all water provided in this county. From the available information, significant quantities of groundwater are abstracted from some 25 Public and Group Water Supply Schemes. Areas not served by these or surface water schemes generally rely on individual private wells as their source of water.

4.5 Background to Aquifer Classification

4.5.1 Introduction

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 or three classes:

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

(i) Karstified Bedrock (**Rk**)
(ii) Fissured Bedrock (**Rf**)
(iii) Extensive Sand and Gravel (**Rg**)

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

(i) Karstified Bedrock (**Lk**)
(ii) Bedrock which is Generally Moderately Productive **(Lm)**
(iii) Bedrock which is Moderately Productive only in Local Zones **(Ll)**
(iv) Sand and Gravel (**Lg**)

Poor (**P**) **Aquifers**

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

4.5.2 Bedrock Aquifers

Irish bedrock aquifers are not generally considered to have significant pore-space permeability. Consequently, flow is thought to depend on the development of a network of secondary permeability within fractures. As a result, 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 give enough water for domestic supplies and therefore all are called ‘aquifers’.

Karstification and dolomitisation are two processes that strongly influence the development of secondary permeability and aquifer potential in Irish bedrock units. Each are explained briefly below. The terms will occur in several of the classifications provided in Sections 4.6 to 4.10.

Karstification

Karstification is the process whereby limestones are slowly dissolved away by acidic waters moving through them. This most often occurs 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 enclosed depressions ('dolines'), 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 in Ireland from slight to intensive. In order to assist in the understanding and development of regionally important (**R**) limestone aquifers, the GSI has compartmentalised the broad range of karst regimes into three categories. Where karstification is slight, the limestones are similar to fissured rocks and are classed as **Rf**, although some karst features may occur. Aquifers in which karst features are more significant are classed as **Rk**. Within the range represented by **Rk**, two sub-types are distinguished, termed $\mathbf{Rk^c}$ and $\mathbf{Rk^d}$.

$\mathbf{Rk^c}$ are those aquifers in which the degree of karstification limits the potential to develop groundwater. They have a high 'flashy' groundwater throughput, but 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.

$\mathbf{Rk^d}$ 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.

Dolomitisation

Dolomitisation is a weathering process where magnesium ions have replaced calcium ions in the crystal lattice, to form 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 purer the original limestone, the greater the degree of dolomitisation.

4.5.3 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 area. 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 thick. This is not the case where deposits have a high relief (for example eskers or deposits in high topographic areas) as these gravel bodies are often dry.

Table 4.1 Sand and Gravel Aquifer Classification

	Regionally important	***Locally important***
Area	> 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, extent, and the thickness of the unsaturated zone (see Table 4.1). In the absence of permeability test data, gravel 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 area of *at least* 10 km^2. This is to ensure that, assuming an average annual rainfall of 650 mm, there will be enough recharge to provide a supply of one million cubic metres per year from the whole aquifer.

4.5.4 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 4.5:

- 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 'low' 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 data from formal pumping tests, where discharge and water levels 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). A 'productivity index' is assigned to a well from one of five classes: I (highest), II, III, IV, and V, using a graphical comparison of well discharge with specific capacity (discharge divided by drawdown).
- Occurrence of springs with 'high' flows (greater than 2160 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 strata are thin, and baseflows or flows in rivers (better aquifers will support higher baseflows and summer flows).
- Lithological and/or structural characteristics of geological formations which indicate an ability to store and transmit water. Washed and sorted sands and gravel for example, are more permeable than poorly sorted glacial tills. Pure limestones are also more permeable than impure limestones. Areas where folding and faulting has produced extensive joint systems tend to have higher permeabilities than areas where this has not occurred.
- Aquifer assessments from the draft National Aquifer Map (2004) and from existing reports.

All of these 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 and of sand and gravel deposits in County Donegal is presented in Sections 4.6 to 4.11. A summary can be found in Table 4.6, 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 Section 2 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 with 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.

4.6 Classification of the Precambrian Aquifers

In County Donegal, there are in the region of 60 different Precambrian rock units, which are all briefly described in Section 2.2. Generally, the Precambrian rocks are characterised by the absence of an inter-granular permeability, and low fissure permeability. They have been subjected to a lengthy history of deformation, undergoing at least eight phases of major structural folding and faulting. The repeated folding and faulting, combined with the metamorphism, have eradicated original sedimentary structures. The most permeable zones are at the top of the rock with the permeability significantly decreasing with depth, although groundwater flow may be slightly enhanced along large faults and axes of folds.

In comparison to other bedrock types, the Precambrian rocks frequently form steep and rugged terrain, from which there is a large amount of rapid runoff. Accordingly, the drainage density across these rocks is generally very high and small streams and lakes are common. These conditions often favour the development of peat vegetation. All of these indicators suggest that the Precambrian rocks have a low permeability with poor storage capacity.

For the purposes of aquifer classification, the Precambrian units are divided into two broad groups of similar characteristics:

- Precambrian Marbles, and
- Precambrian Quartzites Gneisses and Schists.

The aquifer properties of these groups are discussed in the following sections.

4.6.1 Precambrian Marbles Aquifer

This aquifer comprises ten rock units (AL, CR, CU, DG, DGmb, FL, GL, mb, SCcl and SCpl) that cover just over 5% (c.250 km^2) of the county. Aghyaran and Killygordon Limestone (DG) is the most extensive unit (4% coverage), mainly occurring in the lower lying area between Manorcunningham and Castlefinn. The remaining marble rocks form discrete units, no more than a few tens of meters thick, predominantly in the north of the county.

Whilst Precambrian marble originated as limestone, it is more compacted and coarsely crystalline than other Carboniferous Limestone, making it less susceptible to dissolution i.e. fracture enlargement, over time. It will, however, break more cleanly and dissolve more readily than most other metamorphic rocks. Large fractures are recorded in Public Water Supply boreholes in two of these units – Aghyaran and Killygordon Limestone marble unit (DGmb) and Culdaff Limestone (CU) – the latter of which is possibly solutionally enlarged (Section 3.5.2, Volume II).

Some Precambrian marble units have been dolomitised and/or karstified. The dolomitisation generally occurred after deposition and any resulting increase in void space is likely to have been compacted during the deformation and metamorphism that followed. Karstification has been recorded in some locations e.g. Pollnapaste Cave in the Falcarragh Limestone (FL), at the mouth of the Gweebarra River (Parkes *et al*., 1999). Current data on karstification in these rocks are limited and the causes and controls on the karst development are poorly understood. Not all marble units appear to be susceptible to karstification (Faulkner, 2000).

Although hydrochemical data are limited, information from the Public Water Supplies suggests that the groundwater in the DGmb unit is generally hard (250-350 mg/l $CaCO_3$) whilst the CU groundwater is bordering on very hard (>350 mg/l $CaCO_3$). The increased hardness in the CU further supports a potentially higher degree of solution in these rocks.

Well productivity data for the Precambrian marbles are available for three units: Aghyaran and Killygordon Limestone (DG) and its marble unit (DGmb), and the Culdaff Limestone (CU). Although over 50% of these data are within class V, nearly 30% are in classes I and II, and three of these wells have 'excellent' yields (Figure 4.1). Transmissivities of 11 m^2/d and 110 m^2/d have been estimated for the DGmb and CU units respectively.

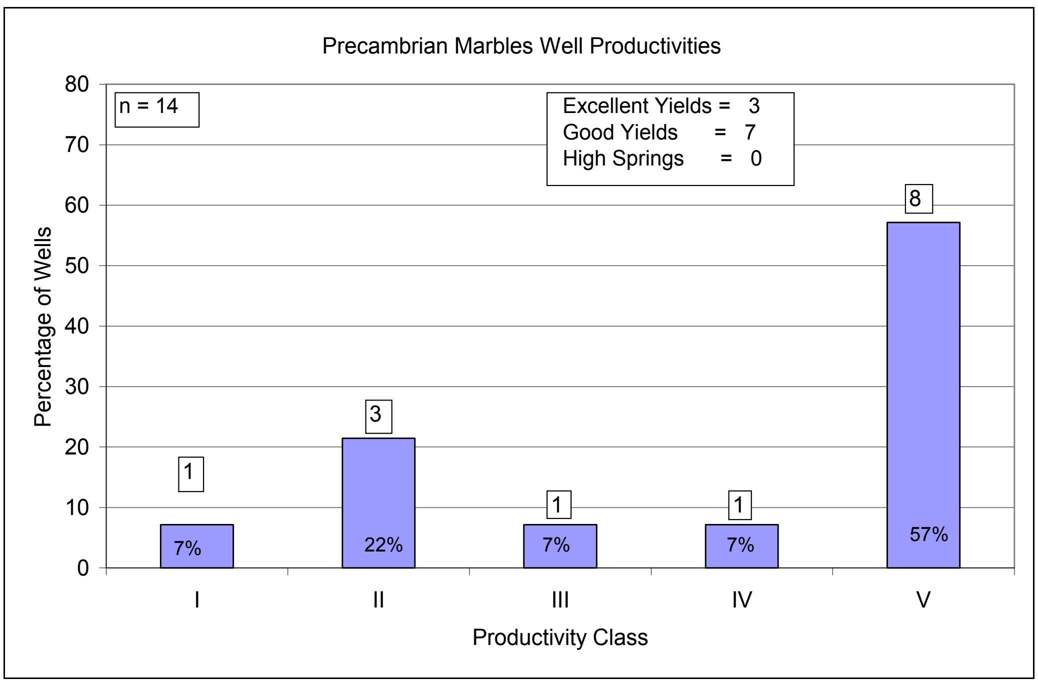

Figure 4.1 Well Productivities in the Precambrian Marbles

The lithological characteristics and available data (productivity, well yield and transmissivity) indicate that the Precambrian marbles contains some locally productive zones. In some instances, the permeability of these zones may have been further enhanced by possible karstification. The more productive units are thought to be the Culdaff Limestone Formation (CU), the main northern area of Aghyaran & Killygordon Limestone (DG) and its marble-rich member (DGmb), and the Falcarragh Limestone Formation (FL). These units have therefore been classified as **Locally Important Aquifers, which are Moderately Productive only in Local Zones (Ll).** It is recognised that in a national context these rocks are likely to occur at the less productive end of the Ll scale.

The remaining Precambrian marble units (Altan Limestone (AL), Cranford Limestone (CR), Glencolumbkille Limestone (GL), undifferentiated marble (mb), Clonmass Limestone (SCcl), Port Limestone (SCpl) and the southern outcrop of the Aghyaran & Killygordon Limestone (DG)) are classified as **Poor Aquifers, which are Generally Unproductive except for Local Zones (Pl)**.

4.6.2 Precambrian Quartzites, Gneisses and Schists Aquifer

This group of Precambrian rocks underlie the majority of the county; c.3300 km^2 or 70%, and comprises some 50 individual units, which are shown in Table 4.2. These rocks dominate the eastern half of the county, north of the Derryveagh Mountains, and sweep across the centre of the county in a northeast-southwest trending band to Malin Bay, south of Glencolumbkille. Due to the resistant nature of the more competent quartzites and gneisses, they are widespread across the upland areas of Donegal, forming the crests of mountains such as Muckish, the Urris Hills, Slieve Snaght and Carnaween. Shists and more variable (layered) units underlie both upland and lowland landscapes.

Table 4.2 Precambrian Quartzite, Gneiss and Schist Rock Units

Rock Unit	Area (km^2)	Rock Unit	Area (km^2)	Rock Unit	Area (km^2)
Appinite suite intrusive breccia (Ab)	1	Inishowen Head Grits and Phyllites (IH)	111	Mullyfa and Deele Units (MF)	83
Ards Pelite (AP)	35	Knockletteragh Unit (TEkg)	9	Pelite (pe)	1
Ards Quartzite (AQ)	156	Lifford Volcanic Unit (DGlv)	4	Port Askaig Unit (PA)	11
Boultypatrick (Grit) Unit (BO)	42	Lithologically diverse (mx)	1	Psammitic paragneiss (SWQ)	162
Claudy Unit (CY)	12	Lough Eske Psammite (LE)	140	Quartzite (qz)	<1
Cloghan Green Beds (FGcg)	21	Lough Foyle Succession (undifferentiated) (LFS)	220	Reelan Unit (RE)	6
Creeslough Unit (CS)	52			Rhinns Complex (RHC)	<1
Croaghgarrow Unit (CW)	44	Lough Mourne Unit (LM)	143	Semi-pelite (sp)	1
Croaghubbrid Pelite (CH)	39	Loughros Unit (LO)	12	Semi-pelitic biotite schist (SWB)	3
Croveenananta Unit (CV)	4	Lower Crana Quartzite (LC)	148	Sessiagh-Clonmass & Marble (mbSC)	<1
Fahan Grit (FG)	103	Lower Falcarragh Pelite (LF)	55		
Fahan Slate (FS)	86	Upper Falcarragh Pelite (UF)	79	Sessiagh-Clonmass Unit (SC)	75
Gaugin Quartzite (GA)	29	Malin Schist (MS)	3	Slieve League Unit (SL)	100
Glencolumbkille Pelite (GP)	14	Metadolerite (Md)	78	Slieve Tooey Quartzite (ST)	296
Greencastle Green Beds (GR)	5	Metadolerite & Lithologically diverse (mxMd)	<1	Tectonic schist (ts)	4
Hornblende diorite (H)	<1			Termon Unit (TE)	693
Killeter Quartzite (KT)	30	Metavolcanic green bed (vg)	<1	Upper Crana Quartzite (UC)	170

Precambrian quartzites (metamorphosed sandstones) and gneisses (quartz and feldspar metamorphic rocks) are commonly coarse grained, with only a small clay component. Accordingly, fissures resulting from faulting and folding are less likely to be infilled by weathered, fine grained material. Fissures in more fine grained Precambrian rocks such as the schists and pelites, which were once mudstone and shale, are likely to be infilled with weathered material. Fissure permeability is therefore likely to be very low in these rocks, and slightly higher in the coarse grained quartzites and gneisses.

Generally, groundwater in basement rocks, such as the Precambrian, is soft with a total hardness of less than 150mg/l $CaCO_3$ (Long & McConnell, 1997). The sparse hydrochemistry data for these units in Donegal concur with this generalisation, with most of the samples having a soft (<50 mg/l $CaCo_3$) to moderately soft (50-100 mg/l $CaCo_3$) hardness classification. Potential issues associated with the 'natural' water quality include high iron and manganese, particularly as these rocks are extensively overlain by peat, which increase the likelihood of metals being leaching from the rock. The data show that these issues are founded, as a number of the samples have levels of iron and/or manganese that are elevated above the maximum admissible concentration (MAC).

The available dry weather flows (Table 4.3), ranging from 0.41-1.11 l/s/km^2. The flow for the Precambrian quartzites is 1.11 l/s/km^2, which is low in comparison to typical un-metamorphosed sandstone (e.g. 2.80 l/sec/km^2). It is, however, double that of the schists (0.41 l/s/km^2), suggesting that the quartzite is slightly better than the schists at storing groundwater through to the summer months. The inefficient storage in the shists suggest that the majority of the water will flow along the surface of the rock, or follow short flowpaths in the upper, weathered zone of the aquifer. The dry weather flows associated with the psammites, which are also metamorphosed sandstone, are more comparable the quartzites.

Table 4.3 Summary of Selected Dry Weather Flow Data from Rivers in County Donegal

Catchment/ Gauge	DWF* (l/sec)	Total Gauge Area (km^2)	Adjusted DWF (l/sec)	Adjusted Gauge Area (l/sec/km^2)	Specific DWF (l/sec/km^2)	Main Rock Type within Adjusted Gauge Area
Swilly/ Newmills	20	49	20	49	**0.41**	Mainly schist, small strip of quartzite and metadolerite
Deele/ Sandy Mills	80	113	80	113	**0.71**	Various – limestone, quartzite and schist
Finn/ Dreenan	330	353	30	34	**0.88**	Psammites
Finn/ Ballybofey	300	319	300	319	**0.94**	Psammites
Glenaddragh/ Valley Bridge	13	13.5	13	13.5	**0.96**	Schist, small pods of metadolerite
Cranna/ Tullyarvan	110	99	110	99	**1.11**	Quartzites

**DWF represents 'Dry Weather Flow', which are EPA data.*

Adjusted areas and flows are derived by subtracting contributing areas and flows from upstream gauges.

Although the well productivity data for these rocks span all of the classes, they primarily fall into classes IV and V (Figure 4.2). The wells within productivity classes I and II (1 of which is 'excellent' yielding wells) abstract groundwater from coarse-grained Precambrian rocks (quartzites and psammitic paragneiss).

Generally, these data support the lithological inferences of a slightly higher permeability in the coarse grained (quartzites, gneisses) Precambrian rocks. It is noted that there are three additional 'excellent' yielding wells (productivity classes I and II) that abstract water from the Termon rock unit, which is also part of this group. However, the borehole logs for these wells encountered a relatively thick, highly permeable sand and gravel deposit over the Termon unit, which is considered to be an aquifer in its own right (Section 4.11.8). In this instance, the gravel is thought to provide additional storage that contributes directly to the well yields (Minerex Environmental Ltd, 2001). This situation is considered to be atypical of the Termon rock in other parts of the county and these data are therefore omitted from the assessment of the *bedrock* aquifer potential. However, the data do indicate that productivity of this unit should be further investigated.

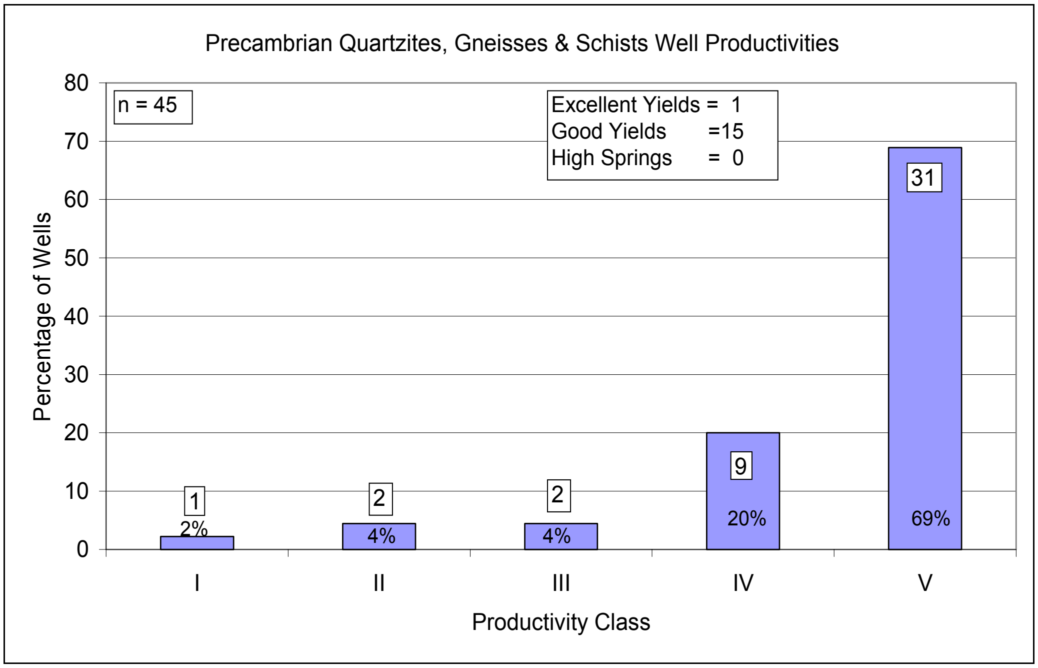

Figure 4.2 Well Productivities in the Precambrian Quartzites, Gneisses & Schists

The Precambrian quartzites, gneisses and schists group contains a large number of different units. Primarily on the basis of lithological characteristics, which is supported by the trend in the productivity data towards Class V and IV, the majority of these rocks are classified as **Poor Aquifers, which are Generally Unproductive Except for Local Zones (Pl)**.

Where rock units consist solely of fine grained metamorphic rocks such as pelite or schist, they are likely to be more consistently unproductive than the coarse grained and more varied units. These rocks (AP, CH, CW, FS, GP LF, LO, MS, pe, PA, RHC, SWB, UF) have therefore been classified as **Poor Aquifers which are Generally Unproductive (Pu).**

4.7 Classification of the Igneous Aquifer

Igneous rocks predominantly occur in the northwest of the county, extending in a southwest-northeast trending band from Ardara to Glen Lough (c.10% of the county, dominated by the Main Donegal Granite), and along the northwest coastline from Gweebarra Bay to Bloody Foreland (mainly comprising Thorr Granite over c.5% of the county). Other igneous rocks are to the northeast of Lough Eske, and the northern portions of the Rosguill and Fanad Peninsulas. The latter areas are a continuation of the southwest-northeast igneous band.

Granites are generally considered to be relatively coarse grained, massive (un-bedded) rocks, which renders them relatively resistant to erosion. Accordingly, they form spectacular upland landscape as exemplified by the Derryveagh Mountains and Leahanmore, which are both in the Glenveagh National Park, as well as the Glendowan and Bluestack Mountains. Natural drainage density on these rocks is characteristically high and soil development is frequently limited to thin peat or peaty podzols. These surface indicators suggest that this rock has a relatively low permeability and rejects a high proportion of effective rainfall.

The massive nature of these rocks generally restricted groundwater flow to their upper weathered portion and around faults and fractures. Finer grained volcanics are typically hard rocks that also fracture cleanly. Although younger than the Precambrian rocks that dominate Donegal, the igneous rocks have undergone some deformation, which has resulted in increasing localised zones of higher permeability along additional fractures and faults. Although the storage capacity of granite is generally considered to be low, the fact that it can weather to a sand means that its water storage capacity may potentially be enhanced on a local scale.

Data for these rocks in County Donegal are limited. The available hydrochemical data (3 wells) exhibit soft (<50 mg/l $CaCo_3$) to slightly hard (101-150 mg/l $CaCo_3$) water. Generally, the minerals associated with these rocks are acidic, which may result in corrosion and the leaching of metals such as iron and manganese. However, these issues have not been highlighted in this limited dataset.

Although no productivity data are available for Donegal, work has been carried out on granites in the east of the country. The granites in both areas are of similar age and composition and therefore these data are also thought to be representative of the Donegal rocks. Figure 4.3 highlights a trending in the data towards productivity classes IV and V with only one 'good' yielding well.

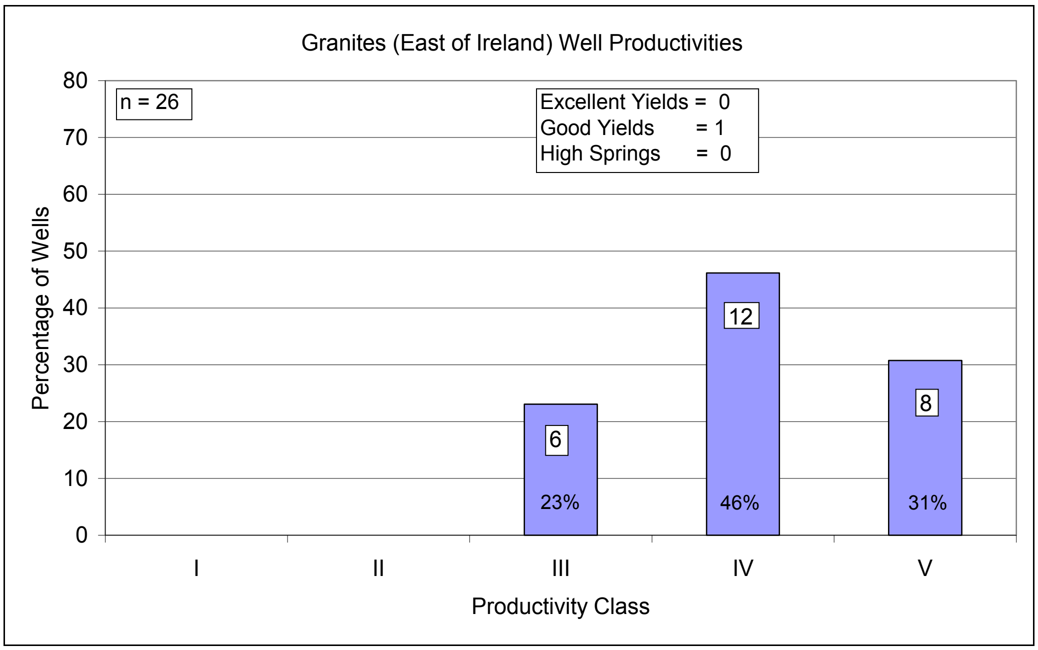

Figure 4.3 Well Productivities in the Granites in the East of Ireland.

The surface indicators and national hydrogeological data support the overall lithological assessment that these rocks have a low permeability. However, due to the clean fracturing and faulting, localised zones of higher permeability are likely. Accordingly, the Igneous group of rocks are categorised as a **Poor Aquifers that are Generally Unproductive Except for Local Zones (Pl)**.

4.8 Classification of Sandstone Aquifers

County Donegal has a number of predominantly sandstone rocks of Devonian or Dinantian Age (Table 4.4). These rocks share similar hydrogeological characteristics and are therefore considered together. In total, the sandstones cover 3% (c.150 km^2) of the county, mainly outcropping in the lowland area to the southwest of the Bluestack Mountains; between Lough Eske and McSwyne's Bay. Other smaller areas include the Dinantian Sandstones to the east of Lough Derg and the Dinantian Mixed Sandstones, Shales and Limestones to the northeast of Muff. The Dinantian (early) Sandstones, Shales and Limestones outcrop as a small number of discrete, thin bands to the south of Lough Eske.

Table 4.4 Rock Units in the Sandstone Aquifer

Rock Unit Group	Rock Units	Approximate Area (km^2)
Devonian Old Red Sandstone	Ballymastocker Sandstone Conglomerate (BA) Edergole Sandstone and Conglomerate (ED)	10
Dinantian Sandstone	Claragh Sandstone (GH) Banagher Sandstone (BG) Killin Sandstone (KG) Muckros Sandstone (MK) Mullaghmore Sandstone (MU) Rinn Point Limestone basal unit (RPbc)	127
Dinantian (Early/Mixed) Sandstones, Shales and Limestones	Ballyshannon Limestone basal unit (BSbc) Culmore Unit (CU)	12

Groundwater will circulate primarily though fissures as these rocks do not show significant intergranular permeability. The absence of clay minerals within the predominantly sandstone and conglomerate matrix makes them more susceptible to rupturing or brittle fracturing. The end result is an increase in permeability due to the greater development of clean fracturing.

Fissure permeability is generally more developed in the top 20 to 30 metres of fractured weathered rock and close to fault zones. Fault zones are shown on the Bedrock Map (Map 1) and indicate the degree of folding and faulting that these relatively young rocks have undergone. Fractures are wider at shallow depths; the weight of burial decreases fracture apertures. Fracturing caused by release of surface pressure after glaciation is concentrated close to the surface of the rock (Fitzsimons, 2003).

Some of the sandstones, in particular the basal sandstones, were deposited on an irregularly weathered erosion surface, or unconformity (continuous deposition has not occurred). Where a weathered surface exists, it increases the likelihood of preferential flow paths occurring, which act as a focus for groundwater flow. The likelihood of preferential flow is compounded when the first sediments laid down after deposition resumed are coarse conglomerates. Although not established in Donegal, drilling in other parts of the country have shown that conglomerates infilling an unconformity can be consistently productive. Furthermore, where sandstones have a calcareous cement such as the Muckros and Mullaghmore units, there is a possibility of dissolution occurring that would act to increase the permeability of these rock units.

The hydrochemistry data for these rocks indicates that the groundwater is moderately hard (151-250 mg/l $CaCO_3$) to hard (251-350 $CaCO_3$), which is possibly associated with calcareous nature of some of these units. Elevated iron and manganese levels are common and high potassium concentrations have also been identified. All of these parameters are naturally occurring in sandstone although their precipitation is exacerbated by reducing conditions, which are often caused by contamination. The occasionally increased ammonia concentrations may also be reflecting possible contamination.

Productivity and yield data are limited for these rocks; one 'poor' yielding well in productivity class II and another 'good' yielding well. Despite these limited data, the lithology and experiences in other parts of the country suggests that at a *minimum*, these rocks can be considered **Locally Important Aquifers that are Moderately Productive in Local Zones (Ll)**.

However there is evidence to suggest that some of the sandstone units do have a greater aquifer potential:

- The Claragh Sandstone (GH) comprises basal clastics that are deposited unconformably on the weathered surface of less permeable rock units. This rock is therefore likely to act as a focus for groundwater flow.

- National data for the Mullaghmore unit (MU) highlight a higher degree of fissures and fractures that could potentially support a regional flow system. Due to the similarity between this unit and the Banagher (BG), Kilin (KG) and Muckros Sandstones (MK), they are all considered together.

These five rocks units are all further categorised as **Locally Important Aquifers that are Generally Moderately Productive (Lm).**

4.9 Classification of the Pure Bedded Limestone Aquifer

The Ballyshannon Limestone (BS) is the only Pure Bedded Limestone in Donegal and underlies some 135 km^2 (c.3%) of the county. It is restricted to the south, occurring in three main bands: from Bundoran to Lough Eske; from St John's Point to northwest of Inver; north-eastwards from Pettigo, along the southeast county boundary.

The rock unit is described as a generally pure, massively bedded limestone. The absence of clay minerals within the limestone beds makes them more brittle than their impure limestone counterparts, resulting in the greater development of clean fracturing, and hence increased permeability. This unit has been subjected to two major deformation events, resulting in regular faulting through the limestone (Map 1) and therefore, the likelihood of an increased permeability along these zones.

The pure nature of the limestone has made it susceptible to solution and karstification, which often further enhances the bulk permeability of the rock. Enlargement by solution occurs in joints, fissures, fractures and faults, and karstification can be accentuated along structural features, such as fold axes and faults. This can result in very high permeability and throughput in relatively narrow zones.

Chert bands are recorded throughout this unit, increasingly so towards the base. These bands can act as barriers to flow and in certain situations, the subsequent diversion of groundwater circulation may encourage solution to be focused along these layers. 'Sandy' layers (up to 2 m thick) and dolomite at surface have been recorded in this limestone. The presence of both of these features can further increase the permeability, depending on their frequency throughout the unit.

Little work has been undertaken on the Ballyshannon Limestone in Donegal. At present, 17 karst features have been recorded (Figure 4.4), which are highlighted on Map 4. The recorded features compromise caves, enclosed depressions (or 'dolines'), springs and swallow holes. From local knowledge, it is understood that there are further unrecorded features.

Further evidence of the degree of karstification is provided by work undertaken to the north of Ballyshannon Town. This investigation identified a spring that is described as large and that has never been know to run dry. Given the karst environment, the spring probably represent a single discharge area for a specific conduit/fissure zone. The variable discharge recorded at the spring (250-c.2000 m^3/d) is likely to reflect a relatively rapid response to rainfall and a limited storage capacity due to groundwater flow being localised in solutionally enlarged conduit/fissure zones. This spring has also exhibited high levels of bacteria on a number occasions, suggesting that it is particularly vulnerable to pollution. This is not unusual for karst springs as there is negligible filtering of groundwater as it flows through large conduits/fissures. Poor water quality may be further compounded if contaminated surface water enters through karst features, thus bypassing the attenuation capacity of the topsoil and subsoil.

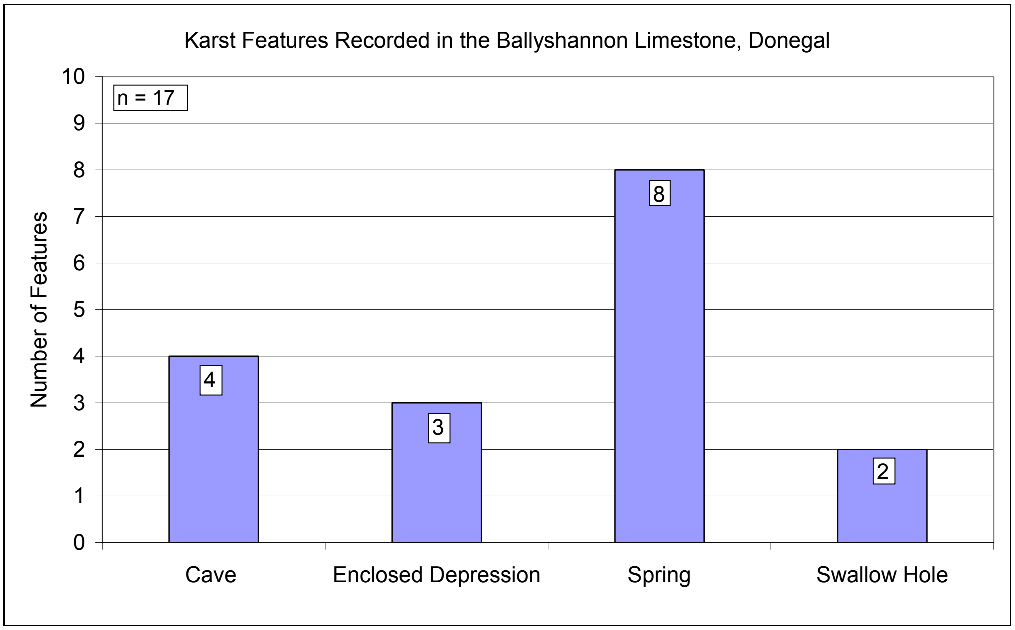

Figure 4.4 Recorded Karst Features in the Ballyshannon Limestone, Donegal.

Karstified areas frequently have a high degree of interconnection between surface water and groundwater. The natural drainage density over the Ballyshannon Limestone appears to be lower than over the surrounding rocks although it is noted that the overlying, low permeability till (drumlins) is likely to increase the drainage density. However, where the till is absent or limited, the lack of surface drainage is marked, indicating that surface water is being drained into the groundwater system e.g. to the south of Ballyshannon Town and on the peninsula to St. John's Point. Furthermore, there are a number of isolated and discontinuous lengths of streams that may represent the presence of swallow holes, enclosed depressions or caves through which the streams are recharging the aquifer. Both the lower drainage density and the irregular drainage pattern (potentially sinking streams) indicate a relatively high degree of interconnection between the surface water and the groundwater.

The productivity (two wells in class I) and yield (two 'excellent' and five 'good' yields; one 'fail') data are too limited be to be conclusive. However, they do reflect the nature of karst aquifer i.e. most of the groundwater flow is limited to conduit/fissure zones, which can be widely and unpredictably spaced. Therefore consistently high yields can often be sustained where wells intersect these zones and wells intersecting the rock outside of the zones are prone to failure. One 'high' yielding spring is recorded in this rock unit although the spring discharges through an overlying sand and gravel body. This combination can form very reliable supplies, with the added advantage that the primary porosity in the sand and gravel can allow for bacterial die-off.

There are five hydrochemical sample locations within the same area; four boreholes and one spring in the Parkhill townland, north of Ballyshannon. The data highlight a hard (251-350 mg/l $CaCo_3$) calcium bicarbonate hydrochemistry signature, which would be expected from a pure limestone.

Given the pure nature of this limestone and the evidence of karstification, the permeability is likely to be high, which is indicated from the limited data. Furthermore, the rock thickness (commonly over 300 m) and coverage suggests that an extensive network of groundwater flowpaths can develop, possibly to some depth. On this basis, the Ballyshannon Limestone is mainly categorised as a **Regionally Important Karst Aquifer that is characterised by diffuse flow** (**Rk^d**). Where the groundwater recharge over the outcropping Ballyshannon Limestone is considered to be limited due to the area of outcropping rock or by thick, overlying low permeability subsoil, it is unlikely that these units will be able to sustain large yields. Consequently, these rocks have been categorised as **Locally Important Karst Aquifer** (**Lk**).

4.10 Classification of the Dinantian Shales and Limestones and Dinantian Impure Limestones Aquifers

The Dinantian Shales and Limestones (Bundoran Shales (BN)) and Dinantian Impure Limestones (Rinn Point Limestone (RP); Argillaceous Limestone & Calcareous Shale (BSag)) all have similar hydrogeological characteristics and are therefore considered together. These rocks cover just under 150 km^2 (3%) in the southwest of the county.

The rock units in this group are predominantly interbedded shale and limestone with little or no sandstone content. The limestone beds are generally thin and clay rich and therefore, these rocks are dominated by fine grained material. Groundwater circulates primarily though fissures as these rocks do not show significant intergranular permeability. However, fine grained rock, such as mudstone and shale, deform chiefly by plastic flow rather than jointing and are likely to have a lower fissure permeability than coarse grained rocks. Fractures in fine grained rocks are often infilled by weathered material, reducing their ability to transmit groundwater. Consequently, impure limestone and finer grained rocks will have a lower fissure permeability than pure limestone or sandstone.

Development of fissure permeability tends to be confined to weathered zones close to the surface of the rock and in the vicinity of fault zones. Thus the northeast-southwest trending faults across the south of Donegal, including the fracturing that may be associated with these faults, are likely to have a higher permeability than areas outside of these zones.

Dissolution and dolomitisation of the limestone interbeds in these rock units is possible if the limestone is relatively pure with a low shale content. For example, dolomitisation has been reported near the base of the Bundoran Shale where it overlies the Ballyshannon Limestone in County Monaghan. However, the large proportion of impurities in the limestone beds makes the development of karst features and accompanying improvements in permeability unlikely.

Only two groundwater samples (from the same location) are available for hydrochemical assessment and therefore these results are not considered to be representative. However, both samples reflect a 'moderately soft' to 'slightly hard' groundwater (51-150 mg/l $CaCO_3$), which suggests that any limestone influence is minimal.

No productivity or yield data are available for these rocks in Donegal. Based on the lithology, groundwater flow is expected to be limited to the fractured and weathered zones in the upper portion of the rock and in the vicinity of faults. Where shale dominates the lithology there will generally be a lower frequency of fractures and a higher proportion of fractures infilled with weathered, fine grained material, resulting in a lower fissure permeability. These units are therefore categorised as **Locally Important Aquifers that are Moderately Productive only in Local Zones** (**Ll**).

4.11 Classification of the Sand and Gravel Aquifers

4.11.1 Introduction

Donegal has a number of small to medium sized sand and gravel deposits. Many of these are located along the coast, representing beach or raised beach deposits, although one of the largest is associated with alluvial deposits. Although none of the mapped deposits are extensive (greater that 10km^2) or significant enough to be considered as regionally important aquifers, some of them are able to sustain 'good' to 'excellent' yields.

Most deposits have not been significantly developed in Donegal and their water supply capability has not been determined. Until exploratory drilling data become available, they should be regarded as *potential* aquifers. Site investigation may also prove other sand and gravel deposits to be aquifers but in the absence of more detailed information, some of the smaller deposits and those of unknown thickness or suspected thin saturated zones are identified but are not included in this assessment.

4.11.2 Ballyshannon Deposit

The Ballyshannon 'wind blown sand' (Meehan, 2004) is located approximately 1 km west of Ballyshannon Town, on the southwest coast of Donegal. The deposit underlies c.2.75 km^2, most of which is occupied by the Finner Camp Military Base.

Drilling data indicate that this deposit is thicker that 5 m and likely to be greater than 10 m deep. The available logs record at least 5 m of loose, fine to medium sand. Some of the logs have also recorded approximately 0.5 m of peat at around 3 m below ground. The Particle Size Analysis (PSA) data indicate that the samples comprise in the region of 95% sand sized particles.

No yield or productivity data are available for this deposit although water levels are recorded at around 0.5 m below the surface. The available data suggest that this deposit has a high permeability, which combined with the saturated thickness and extent, suggests that the aquifer should be able to sustain relatively high yields. From these data, this deposits is categorised as a **Locally Important Sand and Gravel Aquifer (Lg)**.

4.11.3 Buncrana Gravels – Luddan Raised Beach

The Luddan raised beach (c.1 km^2) occupies a relatively flat area some 1.5 km south of Buncrana Town, on the west coast of the Inishowen Peninsula. This deposit is bounded to the east by a steep, cliff-like, rock outcrop which rises to approximately 250 m. The entire landscape is the result of isostatic rebound during and after deglaciation, which has been equated to a relative sea level drop of some 0.3 m per century (K.T. Cullen & Co. Ltd, 1991).

The available drilling data (six trial wells) indicate that the rock outcrop recorded to the east continues to slope down beneath the deposit. The deposit is some 16 m deep at its centre and possibly deepens towards the coastline. One available PSA exhibits over 90% gravel, or larger, sized clasts. Due to the glacial history and sea level changes, it is thought that in some places, cleaner sand and gravel overlie an undulating till surface, which was encountered in two of the trial wells. The remaining four wells generally record fine sand that become more pebbly with depth, over fine to coarse gravel with cobbles. There are differing amounts of fine grained material in these deposits, which suggests that the material may be of morainic origin that has since been flooded (K.T. Cullen & Co. Ltd, 1991).

All four trial wells in the sand and gravel abstracted 'excellent' yields. Three fell into productivity class I and the remaining well was within class II. These data concur with the PSA information in indicating a permeable deposit that is capable of supplying excellent yields. However, the limited extent of this deposits restricts its long term recharge and it is therefore classed as a **Locally Important Sand and Gravel Aquifer (Lg)**.

4.11.4 Carndonagh Gravel Deposit

The Carndonagh Gravel Aquifer is situated to the north of the Inishowen Peninsula, between Carndonagh Town and Trawbreaga Bay. At less than 30 m O.D., the aquifer is located in a low-lying, relatively flat landscape. The *deposit* is bounded to the west, south and southeast by the lower permeability Precambrian Quartzites, Gneisses and Schists rock group, which rapidly rises to form a more pronounced, mountainous landscape. The gravel is considered to continue underneath the locally mapped peat, which is interpreted as being thin where it has not been drained or cut. However, the *aquifer* is defined by the existence of at least 5 m of saturated sand and gravel, which has been extrapolated from the available static water level data (see Section 2, Volume II). The resulting aquifer is c.9 km^2 in area.

Drilling data show the gravel to have an average thickness of just over 5.0 m, although ranging from 4.5 m to >8.0 m thick. The borehole logs generally record an underlying 1-2 m of 'SILT with bands of gravel' over 'sandy SILT' (up to 6.5 m thick), and a 0.7-0.8 m covering of 'silty CLAY' (K.T. Cullen & Co. Ltd, 1992). Due to the depositional environment (possibly fluvio-glacial outwash, or deltaic), the material is likely to grade from coarser sand and gravel near Carndonagh town to finer material at the coast (McCarron, 2002). PSA data for this deposit exhibit greater than 95% sand and gravel, or larger, sized clasts (Solmec, 1974; Farrell, 1989). These data indicate a clean, permeable deposit.

Three 'excellent' yields have been recorded in this deposit, one of which falls into productivity category I. This well, which is the Carndonagh Public Water Supply Scheme, has a specific capacity (Sc) of c.460 m^3/d/m and the estimated transmissivity (T) for this deposit is in the region of 350-600 m^2/d. Based on the average recorded saturated thickness of the aquifer (c.5.0 m) the bulk permeability (K) is in the region of 80 m/d.

The available hydrogeological data is further supported by the PSA data in highlighting a highly permeable sand and gravel aquifer that is capable sustaining large yields. This aquifer is, however, limited by its minimal saturated thickness and extent and is therefore categorised as a **Locally Important Sand and Gravel Aquifer (Lg)**.

4.11.5 Carrigans Alluvial Deposit

This alluvial deposit is located along the floodplain of the River Foyle, extending as far south as Lifford, beyond which it becomes much narrower. The broader section of this deposit, including the adjoining alluvium associated with the lower reaches of the River Deele and Swilly Burn, is in the region of 20 km^2. Many of the steeper sided valleys in this part of Donegal are thought to be infilled with sand and gravel at depth and more superficial fines-dominated material (Dr. R. Meehan, *pers.comm.*, 2004). Furthermore, this sequence of sediments has been identified by a geophysical investigation at Islandmore, some 1.5 km northeast of Lifford; 10-20 m thick sand/gravel layer with some clay generally found at between 10-20 m below ground level (Minerex Environmental Ltd, 1998).

Drilling data at Carrigans, which is 3 km northeast of St. Johnstown, found 11m of clay over 4-7 m of silty or sandy gravel (K.T. Cullen & Co. Ltd, 1996). These data generally support the interpretation at Islandmore. Productivity and yield data from two wells located 80 m apart from each other at this location were variable; a 'good' yield in productivity category I, and a 'moderate' yield in productivity class III. The accompanying investigation report concluded that the more productive well could probably sustain an 'excellent' yield. Overall, the data demonstrate that this deposit includes areas or lenses of more/less productive material, which is likely to depend on the amount of fines at that particular location. Despite this variability, the data do highlight that there are productive zones within this deposits and therefore, it is classified as a **Locally Important Sand and Gravel Aquifer (Lg)**.

4.11.6 Fanad Sand and Gravel Deposit

Located to the west of Fanad Head, the Fanad sand and gravel deposit, which is adjacent to Ballyhiernan Bay, covers approximately 2.5 km^2. The local rock outcrop and limited borehole data suggest that this deposit occupies a bedrock trough that deepens to at least ten metres below ground level. It is assumed that the trough trends parallel to the coastline. The deposit initially comprises a very flat area (at c.11 m O.D.) adjacent to a northeast-southwest trending band of lakes (Loughs Shannagh, Magheradrumman, Kinny, Eelburn and Kindrum). The flat area then rises up to form a line of undulating, grassed sand dunes (up to 27 m O.D.) before forming a sand beach along the bay.

The deposit has previously been described as 'beach sand and gravel' (K.T. Cullen & Co. Ltd, 1998), and its surface sediment has been more recently mapped as 'wind blown sand' (Meehan, 2004). Two wells are located within this deposit, one of which records c.2 m of dune sand over some 5 m of clean gravel with a 2 m layer of peat between the two. No log is available for the other well, which is the part of the Fanad Public Water Supply Scheme (Tri-a-Lough Borehole). However personal communication with the drilling contractor revealed that this production borehole encountered 4-5 m of sand overlying roughly 8-9 m of coarse gravel, which is underlain by some 3 m of till.

The main flow of groundwater is associated with the underlying gravel although the high degree of hydraulic connection with the overlying, permeable sand results in a static water level of less than 1.5 m below the ground surface. Both of the wells in this deposit have 'excellent' yields and fall into productivity category I. The specific capacity (Sc) for the Public Supply borehole is at least 310 $m^3/d/m$ and a transmissivity value (T) in the region of at least 400 m^2/d has been estimated. At this location, the permeability (K) of the deposit is estimated to be 35 m/d.

Recharge to this aquifer is expected to occur primarily via rainfall over the sand and gravel aquifer. However, there is an assumed connection between the aquifer and the adjacent lakes, which are thought to provide a small proportion of recharge to the aquifer. It is also noted that some recharge *may* come from beneath the lakes and from the underlying bedrock.

Although the permeability of the material in this aquifer is capability of sustain 'excellent' yielding wells, its limited extent restricts the potential recharge to the groundwater reserve and therefore it is classed as a **Locally Important Sand and Gravel Aquifer (Lg)**.

4.11.7 Gleneely River Deposits

The extent of this gravel deposit is assumed to coincide with the 1.3 km^2 of mapped alluvium along the Gleneely River. The adjoining downstream alluvial material of the Culdaff River is more likely to be fines-dominated due to the likely change in depositional environment; high energy along the steeper sided Gleneely River valley and a lower energy, possibly ponded environment, along the lower-lying Culdaff River (Dr. R. Meehan, *pers.comm.*, 2004). Further drilling would be required to confirm the exact area and composition of the alluvium although the Gleneely Public Water Supply Scheme is located in this aquifer. The supply borehole encountered gravel between 1.1-4.5 m and 6.3-12.0 m below the surface. The two gravel layers are separated by a 1.8 m thick clay layer.

The available hydrogeological data comprise an 'excellent' and a 'good' yield with a productivity classification of I from the newer, deeper (12 m) well (K.T. Cullen & Co. Ltd, 1998). From the hydrogeological data, aquifer thickness and estimated area along the Gleneely river, this deposit is categorised as a **Locally Important Sand and Gravel Aquifer (Lg)**.

4.11.8 Letterkenny Alluvial Deposit

This deposits is located along the floodplain of the River Swilly, immediately south of Letterkenny. Mapped surficially as alluvium (Meehan, 2004), these sediments extend from the source to the mouth of the Swilly, over a distance of some 17 km. Although narrow for the first few kilometres from the source, the deposits become significantly broader downstream of Newmills, covering approximately 5.5 km^2 between this point and the mouth of the river.

The exact composition along the full length of these sediments is not completely known however sand and gravel under more superficial fines-dominated material are expected in the valleys in this part of the county (Dr. R. Meehan, *pers.comm.,* 2004). Furthermore, in order to assess the aquifer potential of these sediments, ground investigation work focussing on an area extending 2.5 km upstream of Letterkenny has been on-going since the mid 1980s (Minerex Environmental Ltd, 2001). The outcome of this work shows that the existing gravel layers are generally greater than 5 m thick and are overlain by 10-15 m of silt, or sometimes clay. Some of the site investigation logs record interbeds of silt and/or clay in the gravel and one log records only 3 thinner gravel layers (0.5-2 m thick) within the profile. Even though the gravel layers are not uniform, they generally become increasingly thicker towards the centre of the deposit where they are greater than 10 m in thickness. These results are likely to represent other similar zones within this alluvial deposit.

There are a number of productivity and yield data from the investigation. Five 'excellent' yields, one productivity class I and two productivity class II, and three 'good' yields have been recorded from eight different boreholes with slightly varying thicknesses of gravel. In terms of quantity, the data highlight that this deposit is a productive aquifer, which is only limited by its size. It is therefore categorised as a **Locally Important Sand and Gravel Aquifer (Lg)**.

It is noted that consistently high ammonia, iron and manganese levels (in excess of the MAC) were identified in the gravel abstractions. It is thought that the presence of organic matter in the inter-bedded silt/sand layers results in reducing conditions, which are frequently associated with elevated levels in these parameters (Minerex Environmental Ltd, 2001). Therefore the cost of treatment is the main disadvantage of abstracting from the gravel aquifer as opposed to using the underlying bedrock aquifer, even though this is significantly less productive.

4.11.9 Rossnowlagh Raised Beach

The Rossnowlagh beach deposits are located on the southern part of Donegal Bay, some 5 km west of Ballintra. The 'wind blown sand' is mapped along the coastline, covering just over 1 km^2 around Rossnowlagh and extending over an additional 2.75 km^2 into Murvagh Lower. The deposit is adjacent to a large area of alluvium that may constitute a continuation of the aquifer as it includes areas dominated by sand and gravel as well as areas of finer material or peat (Dr. R. Meehan, *pers.comm.,* 2004). The Rossnowlagh Caravan Park Water Supply Scheme is located within the mapped alluvial material, although is very close to the boundary between the alluvium and the sand and gravel deposit. The borehole log for this scheme records 3 m of sand over 4 m of gravel over at least 2 m of sand (K.T. Cullen & Co. Ltd, 1999), which supports the existence of areas of high permeability material within the alluvium. However, further investigation would be required to determine the exact extent of the aquifer into the alluvial material.

The above supply borehole has a 'good' yield and falls into productivity category I. The associated drawdown is very small ~ 0.14 m, which gives a high specific capacity of 935 $m^3/d/m$. The static water level reading indicates that all but the top metre of this deposit is saturated and surrounding site investigation boreholes and trial pits also highlight a shallow water-table (Glover Site Investigations Ltd, 2001). These data suggest that this aquifer may be able to sustain higher ('excellent') yields. Based on the limited hydrogeological data, saturated thickness and extent, this deposits is categorised as a **Locally Important Sand and Gravel Aquifer (Lg)**.

4.11.10 Remaining Sand and Gravel Deposits

As mentioned previously, a number of mapped sand and gravel deposits in Donegal have no evidence of development and therefore minimal data relating to their aquifer potential i.e. their extent, saturated thickness, composition and productivity. The larger of these deposits are given in Table 4.5 below, however, until exploratory drilling data become available, they have not been classified as aquifers.

Table 4.5. Additional Sand and Gravel Deposits.

Deposit	Approximate Location (NGR)	Approximate Area (km^2)
Portsalon	224106 438829	1.0
Rutland Island	170648 414243	1.0
Derrybeg	179852 425963	1.1
Portnoo	172733 399906	1.3
Melmore Head (Rosses – Gortnalughoge)	212519 442394	1.4
Doagh Island (opposite side of estuary)	242725 452595	1.5
Gweebarra Bay	175713 401363	1.9
Meenlaragh	190977 434473	2.0
Inishmeene	180448 428016	2.5
Loughros More Bay	168793 395171	2.65
Murvagh Golf Course	189851 373484	2.7
Dunfanaghy	199545 437046	2.75
Doagh Island	240249 451010	5.0
Carrickart	211627 436155	6.75

4.12 Summary of Aquifer Classification for County Donegal

The rock units and sand and gravel deposits in County Donegal are classified into the different aquifer categories, as summarised in Table 4.6 below. The percentages refer to the proportion of area of each aquifer that are shown on Map 5. The bedrock units are shown on Map 1.

Table 4.6. Summary of Aquifer Classifications for County Donegal.

Aquifer Category	Subdivision	Rock Unit Group	Bedrock Unit
Regionally important (R)	Karst – diffuse flow dominant ($\mathbf{Rk^d}$) (3%)	Dinantian Pure Bedded Limestones	• Ballyshannon Limestone (BS)
	Fissure flow dominant (**Rf**)		None identified
	Sand & Gravel (**Rg**)		None identified
Locally important (L) (12%)	Karst bedrock that is generally moderately productive (**Lk**) (<1%)	Dinantian Pure Bedded Limestones	• Ballyshannon Limestone (BS)
	Bedrock that is generally moderately productive (**Lm**) (3%)	Dinantian Sandstones	• Banagher Sandstone (BG) • Claragh Sandstone (GH) • Killin Unit (KG) • Muckros Sandstone (MK) • Mullaghmore Sandstone (MU)
	Bedrock which is moderately productive only in local zones (**Ll**) (8%)	Dinantian Sandstones	• *Rinn Point Limestone Basal Unit (RPbc)*
		Dinantian (Early/Mixed) Sandstones, Shales & Limestones	• *Ballyshannon Limestone Basal Unit (BSbc)* • Culmore Unit (CM)
		Devonian Sandstones	• Ballymastocker Unit (BA) • Edergole Unit (ED)
		Dinantian Shales & Limestones	• Bundoran Shale (BN)
		Dinantian (Upper/Lower) Impure Limestones	• Rinn Point Limestone (RP) • *Ballyshannon Limestone Argillaceous Limestones & Calcarous Shales (BSag)*
		Precambrian Marbles	• Main northern area of Aghyaran & Killygordon Limestone (DG) • Culdaff Limestone (CU) • Falcarragh Limestone (FL) • *Aghyaran & Killygordon Limestone Marble Unit (DGmb)*
	Sand & Gravel (**Lg**) (1%)		• Ballyshannon • Buncrana • Carrigans • Carndonagh • Fanad • Gleneely • Letterkenny • Rossnowlagh

Table 4.6. Summary of Aquifer Classifications for County Donegal (cont'd).

Aquifer Category	Subdivision	Rock Unit Group	Bedrock Unit
Poor **(P)** **(85%)**	Bedrock which is generally unproductive except for local zones **(Pl)** (77%)	Precambrian Marbles	• Altan Limestone (AL) • Southern area Aghyaran & Killygordon Limestone (DG) • *Sessiagh-Clonmass Clonmass Limestone (SCcl)* • Cranford Limestone (CR) • Glencolumbkille Limestone (GL) • Marble (mb) • *Sessiagh-Clonmass Port Limestone (SCpl)*
		Granites & other Igneous Intrusive rocks	• Appinite suite (Ap) • Dolerite and Gabbro (D) ***Granites:*** • Ardara Granite (ArG1; ArG2; ArG3) • Barnesmore Granite (BaG1; BaG2; BaG3) • Fanad Granite (FA) • Main Donegal Granite (MdGr) • Rathilin Obirne Granite (RaGr) • Rosses Granite (RsG1; RsG2; RsG4;RsE3; mGr) • Thorr Granite (Th; spTh; ThMi) • Toories Granite (To) • Trawenagh Bay Granite (TrG1; TrG2; TrG3; TrAg; TrTr) • Tullagh Point Granite (Tu)
		Precambrian Quartzites, Gneisses & Schists	• Appinite suite intrusive breccia (Ab) • Ards Quartzite (AQ) • Boultypatrick (Grit) Unit (BO) • Claudy Unit (CY) • Cloghan Green Beds (FGcg) • Creeslough Unit (CS) • Croveenananta Unit (CV) • Fahan Grit (FG) • Gaugin Quartzite (GA) • Greencastle Green Beds (GR) • Hornblende diorite (H) • Inishowen Head Grits and Phyllites (IH) • Killeter Quartzite (KT) • Knockletteragh Unit (Tekg) • Lifford Volcanic Unit (DGlv) • Lithologically diverse (mx) • Lough Eske Psammite (LE) • Upper Crana Quartzite (UC) • Lough Foyle Succession (LFS) • Lough Foyle Succession (undifferentiated) (LGS) • Lough Mourne Unit (LM) • Lower Crana Quartzite (LC) • Metadolerite (Md) • Metadolerite & Lithologically diverse (mxMd) • Metavolcanic green bed (vg) • Mullyfa and Deele Units (MF) • Psammitic paragneiss (SWQ) • Quartzite (qz) • Reelan Unit (RE) • Semi-pelite (sp) • Sessiagh-Clonmass Unit (SC) • Sessiagh-Clonmass & Marble (mbSC) • Slieve League Unit (SL) • Slieve Tooey Quartzite (ST) • Tectonic schist (ts) • Termon Unit (TE)
	Bedrock which is generally Unproductive **(Pu)** (8%)	Precambrian Quartzites, Gneisses & Schists	• Ards Pelite (AP) • Croaghgarrow Unit (CW) • Croaghubbrid Pelite (CH) • Fahan Slate (FS) • Glencolumbkille Pelite (GP) • Loughros Unit (LO) • Lower Falcarragh Pelite (LF) • Malin Schist (MS) • Pelite (pe) • Port Askaig Unit (PA) • Rhinns Complex (RHC) • Semi-pelitic biotite schist (SWB) • Upper Falcarragh Pelite (UF)

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 et al., 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, and
- the contaminant attenuation capacity of the geological materials through which the water and contaminants infiltrate.

All groundwater is hydrologically connected to the land surface; 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 travel time, attenuation capacity and quantity of contaminants are a function of the following natural geological and hydrogeological attributes of any area:

- the type and permeability of the subsoil that overlie the groundwater,
- the thickness of the unsaturated zone through which the contaminant moves, and
- 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 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. For bedrock aquifers, the target needing protection is the water-table where the water-table is below the top of the bedrock. However, where the aquifer is fully saturated, the top of the bedrock is the target. 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.

With the exception of areas where point recharge occurs (e.g. swallow holes), the vulnerability depends on the type, permeability and thickness of the subsoil. For the purpose of identifying permeability regions, the subsoil described in Chapter 3 are not necessarily treated as individual units. Instead, permeability boundaries may cross mapped subsoil units in order to show areas of similar permeability. The subsoil units are therefore incorporated into permeability regions, which are described in this chapter.

The vulnerability map is derived from combining the permeability and depth to rock maps using GIS functions in ArcGIS. There are three subsoil permeability categories: high, moderate and low; and five depth to rock categories: shallow rock (<1m), <3m, 3–5m, 5–10m and >10m. The resulting vulnerability classifications are shown in Table 5.1.

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

	HYDROGEOLOGICAL CONDITIONS				
	DIFFUSE RECHARGE: SUBSOIL PERMEABILITY AND TYPE			POINT RECHARGE	UNSATURATED ZONE
SUBSOIL THICKNESS	**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 focused on assessing the permeability of the different subsoil deposit types (Map 2), so that they could be subdivided into the three permeability categories. This involved:

- Describing selected exposures/sections according to the British Standard Institute *Code of Practice for Site Investigations* (BS5930:1999).
- Collecting samples for particle size analysis (PSA) in the areas of till. Additional samples were collected in permeability boundary areas.
- Assessing the recharge characteristics of selected sites using natural and artificial drainage, vegetation and other recharge indicators.

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 (see Chapter 2, Map 1)
- the GSI well database
- the GSI karst database
- the General Soils Map of Ireland (Gardiner *et al*., 1980)

5.3 Permeability of the Subsoil

5.3.1 Methodology

The permeability categories, and resulting vulnerability categories depicted on the Vulnerability Map (Map 6), are qualitative regional assessments of the subsoil based on how much potential recharge is infiltrating and how quickly potential contaminants can reach groundwater. The permeability of subsoil is largely a function of (a) the grain size distribution; (b) the amount (and sometimes type) of clay size particles present; and (c) how the grains are sorted and packed together. It can also be influenced by other factors such as discontinuities (fissures/cracks, plant roots, pores formed by soil fauna, isolated higher permeability beds or lenses, voids created by weathering of limestone clasts) and density/compactness of the deposit. In poorly sorted sediments such as glacial tills, which are common and widespread in County Donegal, these characteristics describe the engineering behaviour of the materials as detailed in the subsoil description and classification method derived from

BS5930:1999 (Swartz, 1999). This method is used to assess the permeability of the subsoil at each exposure, and is combined with recharge and drainage observations in the surrounding area for a regional, three-dimensional classification. Each of the approaches used in assessing the permeability are discussed briefly here. Some of these are described in more detail in the research theses of Lee (1999) and Swartz (1999):

Subsoil Description and Classification Method *(derived from BS5930:1999).* Using this method, subsoil described as sandy CLAY or CLAY have been shown to behave as low permeability materials. Subsoil classed as silty SAND and sandy SILT, on the other hand, are found to have a moderate permeability (Swartz, 1999). In general, sand and gravel that are sorted are considered to have a high permeability. Permeability mapping focuses on areas where soil and subsoil are thicker than 3m, since those thinner than this are automatically considered 'Extremely Vulnerable'.

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 have 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).

Once the general characteristics and variations have been identified, these can be extrapolated to other similar areas where permeability observations may be lacking.

Subsoil Parent Material. The subsoil parent material, which is often the bedrock, can be a factor in providing the particles that have created different subsoil permeability. Sandstone, for example, give rise to a high proportion of sand size grains in the deposit matrix, pure limestone provides a relatively high proportion of silt, whilst shale, shaly limestone and mudstone break down to the finer, clay size particles. Therefore, a good knowledge of the nature of the bedrock, the direction of glacier movement, and the modes of subsoil deposition are all very useful. Understanding the processes at work enable predications 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 certain vegetation species can indicate low permeability subsoil once iron pans, underlying low permeability bedrock, high water-tables, and excessively high rainfall are ruled out. Well-drained land suggests a moderate or high permeability once artificial drainage is taken into consideration (Lee, 1999). Rigorous analysis of drainage density was not undertaken in this project, but general abundance or absence of drainage ditches was recorded.

Soil Type. Although no specific topsoil map exists for Donegal, the General Soil Map of Ireland (Gardiner *et al*., 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 gley 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 10 m/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 obtain 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. 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 the size of County Donegal, 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. Brief descriptions of the permeability assessments are presented in Section 5.4. The vulnerability, which is partly based on the permeability mapping, is presented on Map 6. Details of the supporting data for each permeability decision can be found in Appendix II.

5.4 Permeability Regions

There are six broad permeability regions within County Donegal. Although these divisions have been based on all of the available data, it is noted that given the scale of mapping, these regions are likely to include smaller, discrete units of differing permeability. The presence of samples with contradicting data reflect this variability and where possible, these units have been delineated. However, in many instances there have been insufficient data to delineated differing units, which further highlights the need for individual site assessment. The six permeability regions are discussed in the following sections.

5.4.1 Low Permeability Areas

In Donegal, the low permeability deposits are clay-rich glacial tills, peat, and estuarine and lake deposits. Clay-rich tills dominate the southern part of the county, which is characterised by drumlin landscape. There are extensive areas of blanket peat in Donegal that are frequently associated with the upland, more mountainous areas, although are also mapped in the lower lying, shallow rock areas. The peat deposits are more common in the western, northern and central areas of the county. The mapped estuarine and lake deposits throughout the county are generally limited in extent and usually quite thin (1-2 m maximum). Where thin, they do not significantly influence the vulnerability classifications, which are based on the thicker underlying subsoil. The broad distribution of low permeability till and peat is shown in below. The low permeability estuarine and lake deposits are too small for the scale of Figure 5.1.

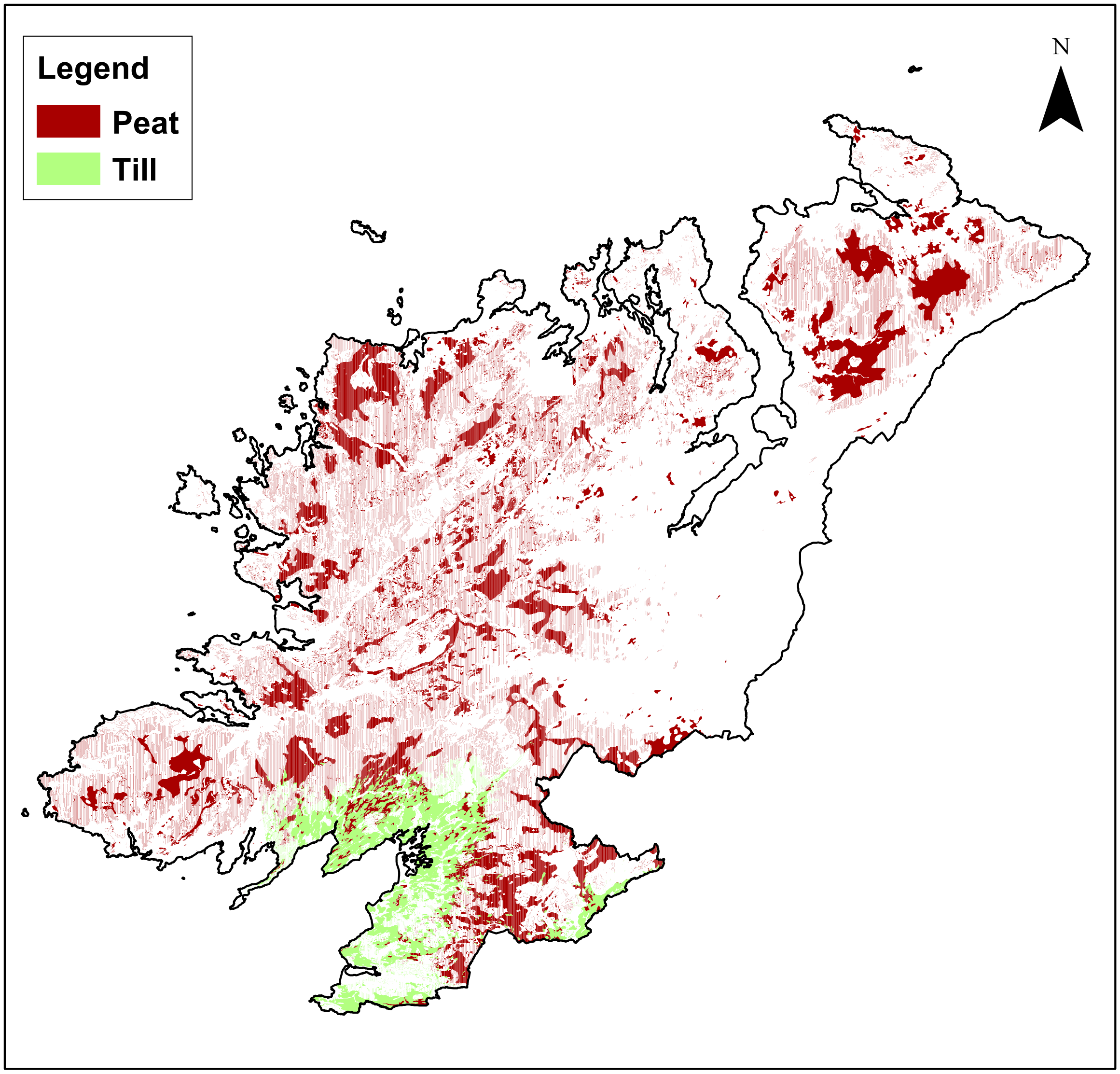

Figure 5.1 Distribution of Low Permeable Subsoil in Donegal (>3 m thick).

Permeability Region 1: Southern Area

This permeability region is essentially south of the Bluestack Mountains. The lower lying areas around Donegal Bay and to the north of the Lough Erne (Lower) are characterised by east-west and southwest-northeast trending drumlins. The bedrock is very mixed with large areas of Precambrian quartzites, gneisses and schists, Dinantian limestones (including the pure, karstified and highly permeable Ballyshannon Limestone), shales and sandstones. The overlying till is described as limestone, sandstone and metamorphic till. It is likely to have originated to the east and southeast of this area, as indicated by the orientation of the drumlins, and mainly comprises mica shists and impure sandstone (Dr. R. Meehan, *pers.comm.* 2004). The underlying shales and impure limestones and sandstones may have also contributed to the fines-rich matrix of the till. The extensive blanket peat and inter-drumlin pockets of cutover (raised) peat occur throughout the southern area, but are discussed separately as part of Permeability Region 5. Alluvium pockets are also mapped in this part of the county and are included in Permeability Region 6.

Overall, the till is this area is poorly drained, as indicated by the abundant rushes and field drainage channels. The natural drainage density is high over the majority of the area, although is noticeably lower over the karstified limestone bedrock. Over 80% of the available subsoil samples are described as 'CLAY', and 60% of the PSAs have 14%, or more, of clay. These data all indicate a unit of low permeability material. In addition, the topsoil associated with the drumlin topography is predominantly poorly drained gley, which supports the low permeability classification.

Permeability Region 5: Peat

Deposits of blanket peat are extremely common throughout County Donegal, mainly occurring as large, continuous expanses over generally shallower rock. They are characteristic of the higher mountainous areas, although are also common in the lower lying areas. Interestingly, pockets of cutover (raised) peat in Donegal are mainly limited to the inter-drumlin areas in the south of the county.

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 (quartzites, gneisses, schists, granites and igneous intrusives) and appropriate topographic setting that inhibits surface water drainage. The available BS 5930 and PSA data for the delineated peat are variable, showing little correlation with the peat itself. However, these data mainly describe the underlying material, which is thought to have less relevance to the distribution of peat.

On Map 2 and, peat is mapped where it is greater than 1 m thick (Dr. R. Meehan, *pers.comm.*2004). However, where the peat is thinner than 2.5-3.0 m, the underlying subsoil is likely to control the permeability. As blanket peat frequently develops on rock, many of these thinner areas of peat are categorised as 'Extremely Vulnerable' (<3 m to bedrock). 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 3 m thickness of peat and, apart from the less compacted upper layers, have a relatively low permeability.

5.4.2 Moderate Permeability Areas

Moderately permeable deposits in County Donegal are typically silty or sandy till, or alluvium. Till described as 'SILT' or 'SAND' is the most prevalent type of till in the county. One distinct area of silt dominated till is identified around Letterkenny – principally to the east and southeast of Letterkenny, as highlighted on Figure 5.2. The tills in the central, western and northern regions of the county appear to be comprise a high proportion of sand and/or gravel. These areas may also have pods of coarser or finer grained material, which have been delineated where possible, although are not specifically described here. Thicker deposits of alluvium are also discussed in this section.

Permeability Region 2: Central-Eastern Area

This is a reasonably discrete permeability region extending from the Rathmelton/Kilmacrenan area down to the south of the county (south of Castlefinn), and as far east as Muff. The central part of this region is underlain by Precambrian Marbles. Despite having a relatively low permeability in a national context, these rocks have a noticeably higher permeability than the surrounding quartzites, gneisses and schists. The subsoil mainly comprises (metamorphic) till, although there are alluvial deposits along the base of the east-west trending valleys (Permeability Region 6).

The vegetation on the till generally reflects its higher drainage capacity, which is also suggested by the land use; a high proportion of tillage and larger field sizes than other parts of the county. Similarly, these areas of till have a characteristically lower artificial drainage density. The natural drainage pattern over this area is noticeable sparser than much of Donegal, although this may be a combination of the free-draining tills over the slightly more permeable marble bedrock. The overall impression of good drainage in the till is supported by the subsoil samples; 54 of the 59 samples are described as 'SILT', 'SAND' or 'GRAVEL'. The grain size data show that 75% of the samples tested have <12% clay and although 11 of the 15 PSAs have 'inconclusive' fines, all of these samples dilated during the BS 5930 field tests, which indicates that they allow water to move through them and are therefore moderately (or highly) permeable. The topsoil across this area are mainly mapped as brown podzolics, which are considered to be a relatively well drained soil. All of the available data for this region independently indicate a moderately permeability material.

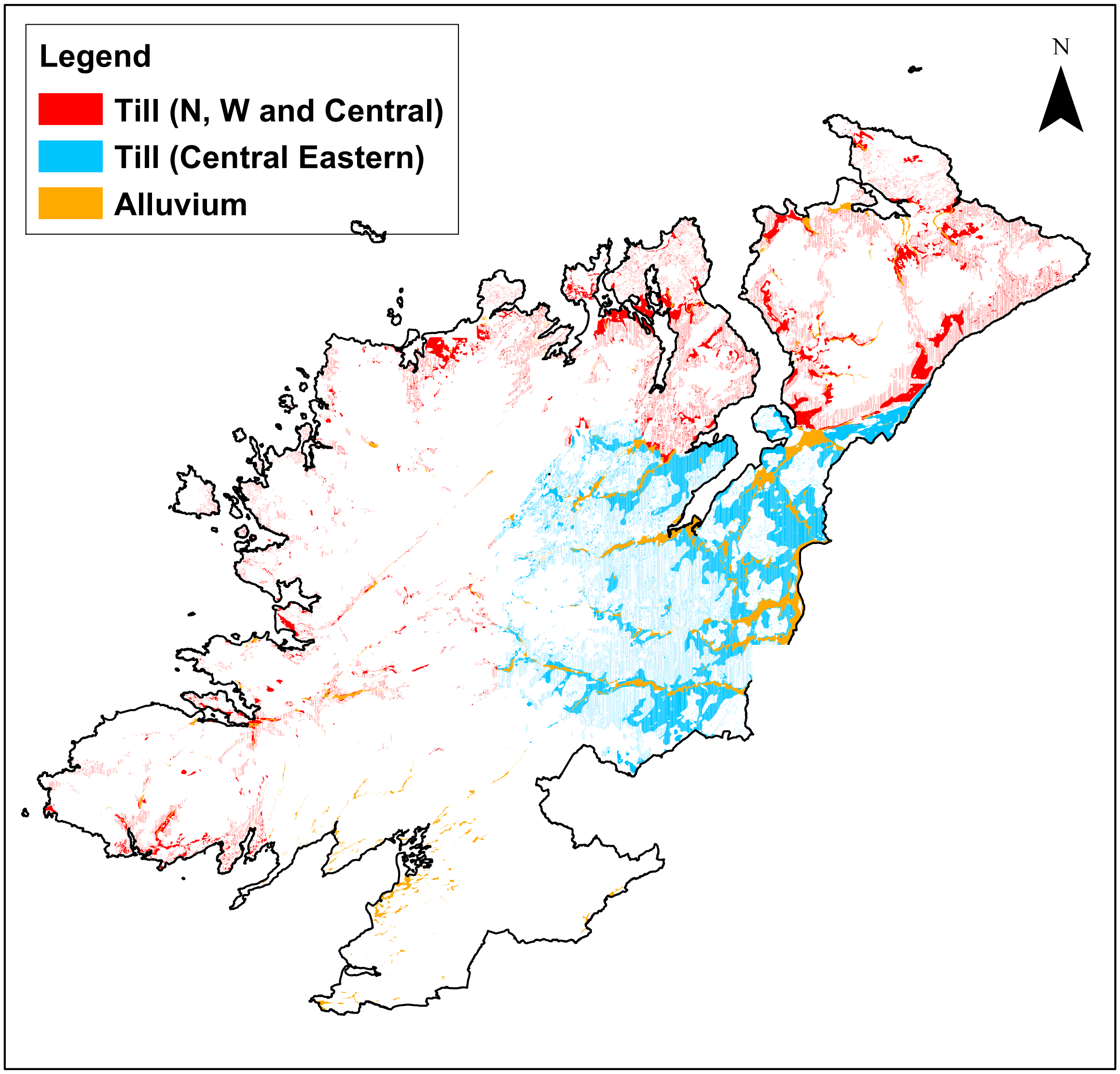

Figure 5.2 Distribution of Moderately Permeable Subsoil in Donegal (>3 m thick).

Permeability Region 3: Central, Western and Northern Area

Covering the majority of the county from Killybegs to Bloody Foreland and over to Inishowen, this region is underlain by a southwest to northeast trending outcrop of granite and igneous intrusive rocks, which is surrounded by Precambrian quartzites, gneisses and schists. The harder of these rocks form spectacular landscape (Derryveagh Mountains; Bluestack Mountains; the upland areas between Killybegs, Glencolumbkille and Ardara), and all of them have a low permeability. The most extensive subsoil is blanket peat, which is generally deposited on higher, more mountainous areas (Permeability Region 5). Till is limited to the lower lying areas, both surrounding the central mountains, and within the inter-mountain valleys, the latter of which also include small pockets of alluvial material (Region 6). The till descriptions range from granite till in the western area, to metamorphic over the main, eastern area, and quartzite till within the Fanad Peninsula. The distribution of till types reflects the underlying bedrock, from which they are probably derived. It is noted that the majority of these rocks are essentially coarse-grained and in many cases, the overlying till constitute a 'immature', or poorly developed subsoil, due to minimal glacial movement that grinds, crushes and mixes the material (Dr. R. Meehan, *pers comm.* 2004).

In many of the till areas, the vegetation and land use reflect a relatively well drained subsoil, however there is some variability across this region. Areas exhibiting indicators of higher water content (higher natural and artificial drainage density, rushes, rough grazing) do exist, although are likely to result from a combination of lower topographic/high water-table locations, large areas of relatively shallow (albeit greater than 3 m), low permeability bedrock, and high rainfall.

The till-specific data, however, clearly indicate a moderate permeability material: BS 5930 descriptions of 'SAND/GRAVEL' or 'SILT'; low clay contents (all nine PSAs have 12%, or less) and only one PSA having greater than 50% fines. These descriptions and grain size data further reflect the coarse-grained nature of the bedrock from which the till were derived and the poorly developed nature of the material. Furthermore, free draining brown podzolic topsoil is mapped in some of the lower lying areas and larger valleys, especially on the Inishowen Peninsula.

Permeability Region 6: 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.

In County Donegal, a high proportion of these deposits are quite narrow and thin (1-2 m maximum, Dr. R. Meehan, *pers.comm.* 2004), and do not generally influenced permeability classifications, which are 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. Nationally, the dominant proportion of the PSA is frequently silt and therefore the alluvium tends to be of moderate permeability. In Donegal, 12 of the 16 available BS 5930 field tests for these deposits yielded a description of 'SILT', 'SAND' or 'GRAVEL'. This was generally supported by the PSA data. Interestingly, a number of PSAs had over 50% fines, which would generally indicate a low permeability. However, these samples are considered to be dominated by silt, which dictates the behaviour of the material i.e. dilatancy is evident, thus indicating a moderate permeability. This situation was illustrated by the one available hydrometer analysis, which recorded 76% silt.

5.4.3 High Permeability Areas

In County Donegal, the high permeability deposits are the well-sorted sand and gravel sediments. The various depositional processes of these materials are likely to have removed the smaller silt and clay particles. These deposits are limited within the county, frequently occurring as small discontinuous units, predominantly in low lying areas along the coastline (Figure 5.3). The sediments are discussed together as they are considered to have similar permeability characteristics.

Permeability Region 4: Sand and Gravel Deposit

Sand and gravel in County Donegal is thought to have a number or origins: deposited by glacial melt-water after being eroded from local bedrock (mainly metamorphic rocks); beach or raised beach material; wind blown sand and sand dunes. Most of these deposits form a flatter, low lying landscape around the coastline. The largest areas of sand and gravel shown on Map 2 are:

- metamorphic sand and gravel at Carndonagh;
- marine gravel at Doagh Isle, around Melmore Head and Falcarragh;
- wind blown sand and dunes around Carrickart, Fanad Head, Dunfanaghy, Bunbeg, Rossnowlagh and Finner Camp;
- beach and raised beach around Loughros More/Beg Bay, Gweebarra Bay and Inishfree Bay.

All of the small and large deposits are underlain by a number of different bedrock units, of a generally lower permeability.

Of the 21 available samples located in these deposits, 18 have been described as 'SAND & GRAVEL'. There are 12 available PSAs, eight of which have less than 8% fines, which suggests a high permeability (O'Suilleabhain, 2000). The vegetation, lack of field drainage ditches and streams also infer very good drainage capacity. The main soil type over these deposits is the free-draining acid brown earth. Thus all of the available information indicate that these deposits have a predominantly high permeability.

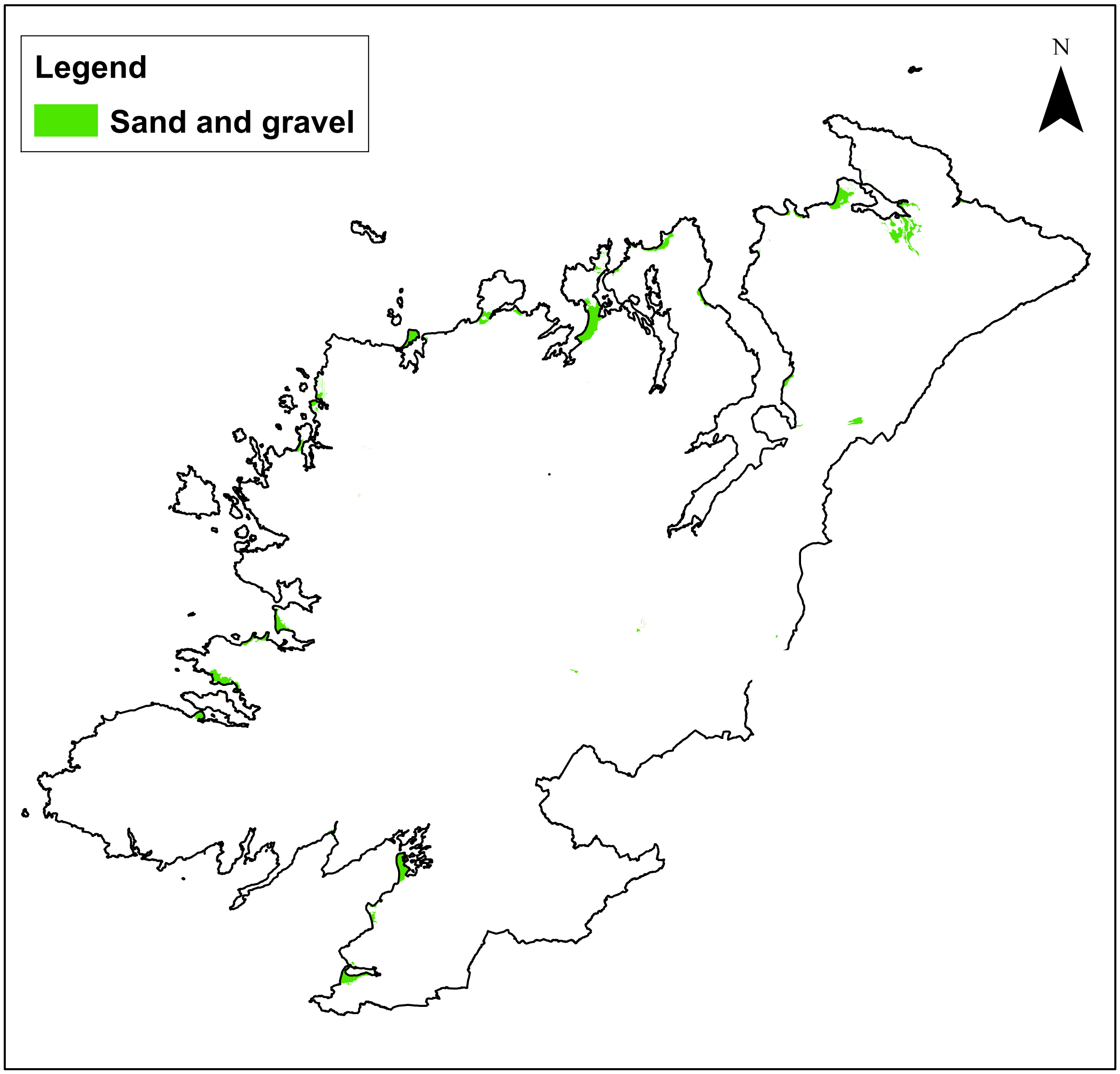

Figure 5.3 Distribution of High Permeable Subsoil in Donegal (>3 m thick).

5.4.4 'Rock Close' Areas and Areas Less than 3 m

'Rock close' describes areas where the depth to bedrock is generally less than 1 m from the surface, and consequently where the subsoil deposits are too thin to be effective for groundwater protection. The types of bedrock and glacial history of Donegal has resulted in a general removal of glacial material from large parts of the county (Section 3.3). Therefore 'rock close' units are ubiquitous throughout Donegal, covering just over 16% of the entire area. They are more commonly associated with upland landscape of the northwest of the county, although are not unusual in lowland areas. Over the lower lying area in the south and southeast of the county, there has been some deposition of glacial material in the form of drumlins. Over this region, the inter-drumlin area has a higher proportion of 'rock close'. A permeability classification is not attached to these regions, as the depth to bedrock results in an automatic 'Extreme Vulnerability' rating.

Similarly, areas where the depth to bedrock is less than 3 m from the surface are automatically rated 'Extreme Vulnerability', which means that permeability classifications are not applied. The permeability of these areas may be higher than those where sediments are deeper, due to a greater amount of weathering and glacial abrasion of the material over its bedrock 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 thickness throughout the county is given in Section 3.3. The source data are shown on 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 karstic features, including along the area of loss of losing or sinking streams, and within 10 m on either side up-gradient of the area of loss.

In Donegal, karst features are generally uncommon. However, there is an extensive area of pure, karstified Ballyshannon Limestone in the south of the county where these features may exist and therefore, where these classifications are applicable.

5.7 Groundwater Vulnerability Distribution

The vulnerability (Map 6) is derived by combining the contoured depth to bedrock data with the subsoil permeability. Areas are assigned vulnerability classes of low, moderate, high or extreme.

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 demand site investigations in order to assess the site-specific risk to groundwater. Detailed subsurface investigations and permeability measurements may reduce the area of extreme vulnerability. However, the Vulnerability Map is considered to provide a good basis for decision-making in the short and medium term.

A large proportion of the county is classed as having either extreme or high vulnerability while areas of moderate and low vulnerability are uncommon. The 3 m contour, which influences the extreme and high vulnerability categories, is based on outcrop information, subsoil mapping and borehole data. The presence or absence of 5 m and 10 m contours, which influence the moderate and low categories, is reliant solely on borehole data and uses the shallower contours as a guide for their interpretation. These contours cannot be drawn without data from boreholes. Consequently, there are possibly more areas of moderate and low vulnerability than are currently depicted on Map 6. As more information becomes available, the maps should be up-dated.

Large areas of extreme vulnerability where rock is generally at, or close to, the surface are common throughout the county, due to the competency of the rock and the glacial history of this region. These areas generally have a more limited development potential. Many small pockets of deeper subsoil are likely to exist even within areas where rock outcrop is common. This is particularly likely to be the case in southern Donegal, over karst limestone areas.

Areas of low vulnerability occur where the subsoil has a low permeability and the depth to bedrock information indicates a subsoil thickness of greater than 10 metres. Based on the available data, this combination of permeability and thickness is limited to the larger drumlins of low permeability till in the south of the county.

6 Groundwater Protection Zones

6.1 Introduction

The general groundwater protection scheme guidelines were outlined in Chapter 1, and in particular, the sub-division of the scheme into two components – land surface zoning and codes of practice for potentially polluting activities – was described (see also Appendix I). Subsequent chapters described the different geological and hydrogeological land surface zoning elements as applied to County Donegal. This chapter draws these together to give the ultimate elements of land surface zoning – the groundwater protection scheme map and the source protection maps. While these maps can be used as 'stand alone' elements, when considering sites for on-site wastewater treatment systems, landfills or the landspreading of organic wastes, they must be considered and used in conjunction with the relevant groundwater protection responses, listed below. Two further responses are in preparation.

- **Groundwater Protection Responses for On-site Wastewater Treatment Systems for Single Houses** (DELG et al., 2001)
- **Groundwater Protection Responses for Landfills** (DELG et al., 1999)
- **Groundwater Protection Responses for Landspreading of Organic Wastes** (DELG et al., 1999).

6.2 Groundwater Protection Maps

The Groundwater Protection Map (Map 7) is 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). Not all of the possible hydrogeological settings are present in County Donegal. Those present, and the percentage of the area they cover, are shown in Table 6.1.

Table 6.1 Percentage of Area Covered by each Zone in County Donegal

VULNERABILITY RATING	RESOURCE PROTECTION ZONES (%)[3]							
	Regionally Important Aquifers (R)		Locally Important Aquifers (L)				Poor Aquifers (P)	
	Rk	Rf	Lk	Lm	Ll	Lg	Pl	Pu
Extreme (E)	1.4	_	0.1	1.5	3.9	0.3	60.3	6.0
High (H)	0.7	_	<0.1	0.7	2.8	0.6	13.5	1.6
Moderate (M)	0.4	_	–	0.3	1.3	–	2.4	0.2
Low (L)	0.1	_	–	<0.1	0.2	–	0.3	<0.1

[3] 1.0% of the area does not have available subsoil information. <1% of the area is covered by the Source Protection Zones.

6.3 Groundwater Source Protection Reports and Maps

To date, source protection zones have been delineated around four public supply sources in Donegal:

1. Ballyshannon PWS
2. Carndonagh PWS
3. Culdaff PWS
4. Fanad North (Tri-a-Lough) PWS
5. Magherabeg/Veagh PWS
6. Pettigo PWS

These are included in Volume II.

6.4 Integration of Groundwater Protection Zones and Response

The integration of the groundwater protection zones and the 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 and the contaminant loading. With respect to the value of the groundwater, sources are considered more valuable than resources and regionally important aquifers more valuable than locally important and so on. By consulting a **Response Matrix**, it can be seen:

- whether such a development is likely to be acceptable on that site,
- what kind of further investigations may be necessary to reach a final decision, and
- what planning or licensing conditions may be necessary for that development.

Thus, the groundwater protection responses are a means of ensuring that good environmental practices are followed. More information on the use of these responses is presented in Appendix I.

As the appropriate level of response takes aquifer category, proximity to Public Supply Schemes 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 an indication of the acceptability of certain activities in Donegal with respect to groundwater contamination.

Table 6.2 Acceptability of Certain Potentially Polluting Activities in Donegal

Activity* (more will be identified in the future)	Percentage of Donegal Occurring within Each Response Level			
	Not acceptable (R4)	Not generally acceptable subject to certain exceptions (R3)	Acceptable subject to certain conditions (R2)	Acceptable (R1)
Landfill	2.8	3.3	90.5	2.4
Landspreading (IPC licensable) **	<0.1	73.7	<0.1	25.2
On-site Treatment Systems	–	<0.1	74.4	24.5

** Details on the precise response requirement for each activity can be found in (DELG/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 Donegal 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 is an important means of preventing groundwater contamination.

The Donegal Groundwater Protection Scheme provides guidelines that will assist the County Council with decision-making regarding the location and nature of developments and activities, with a view to ensuring the protection of groundwater. Groundwater protection schemes and the delineation of the groundwater protection zones are dependent on the available data. Thus, Donegal County Council can 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 requirements for site specific investigations depend mainly on the degree of hazard provided by the contaminant loading and, to a lesser extent, on the availability of hydrogeological data. If the available data for an area are insufficient to provide the correct groundwater protection zone, the onus rests with the developer to provide new information enabling the protection zones to be altered and improved and, in certain circumstances, the planning or regulatory response to be changed.

The scheme has the following uses for Donegal 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 special 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, and
- it helps ensure that the pollution acts are not contravened.

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8 Appendices

Appendix A. Excerpt from 'Groundwater Protection Schemes' (DELG et al., 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.

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.

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.

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 downgradient side of the source and may under-protect on the upgradient side, particularly in karst areas. It is particularly inappropriate in the case of springs where there is no part of the downgradient 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 reappraised 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.

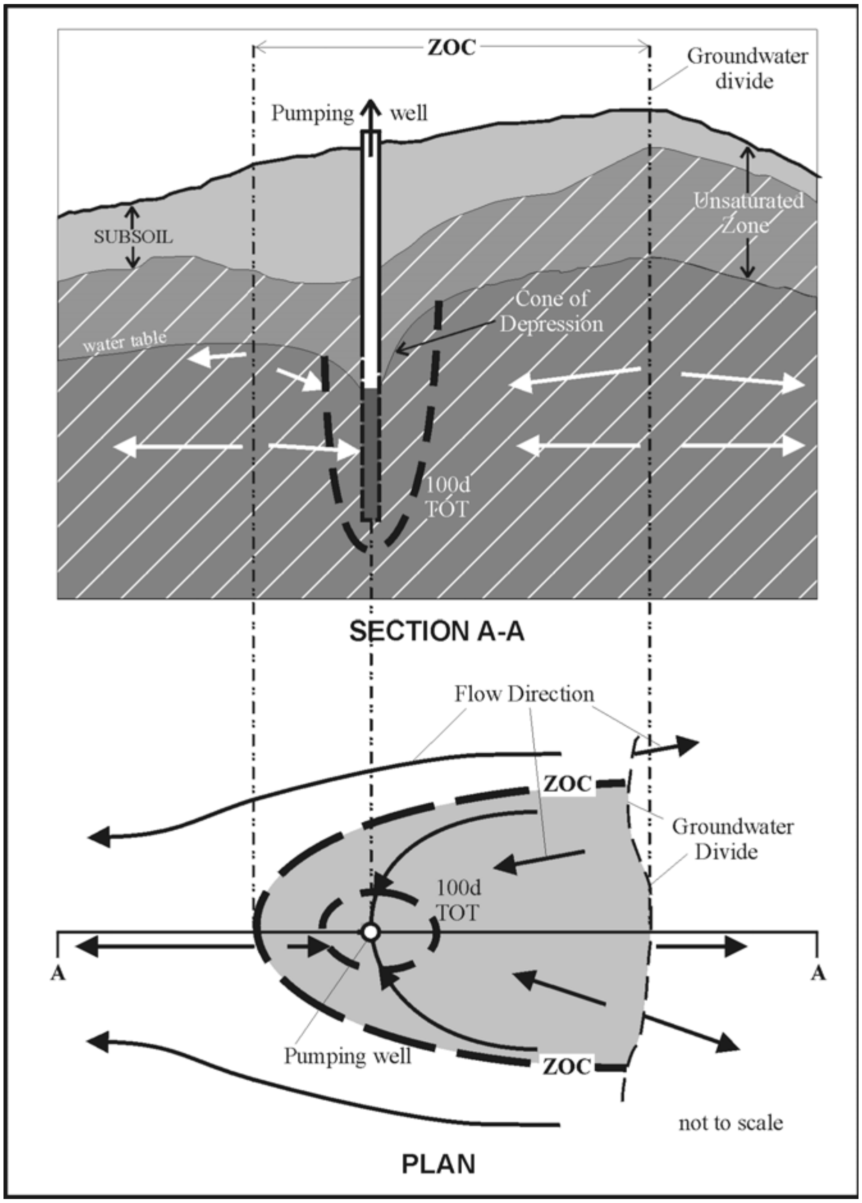


Fig. A.1 Conceptual model of the zone of contribution (ZOC) at a pumping well (adapted from US EPA, 1987)

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.

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

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.

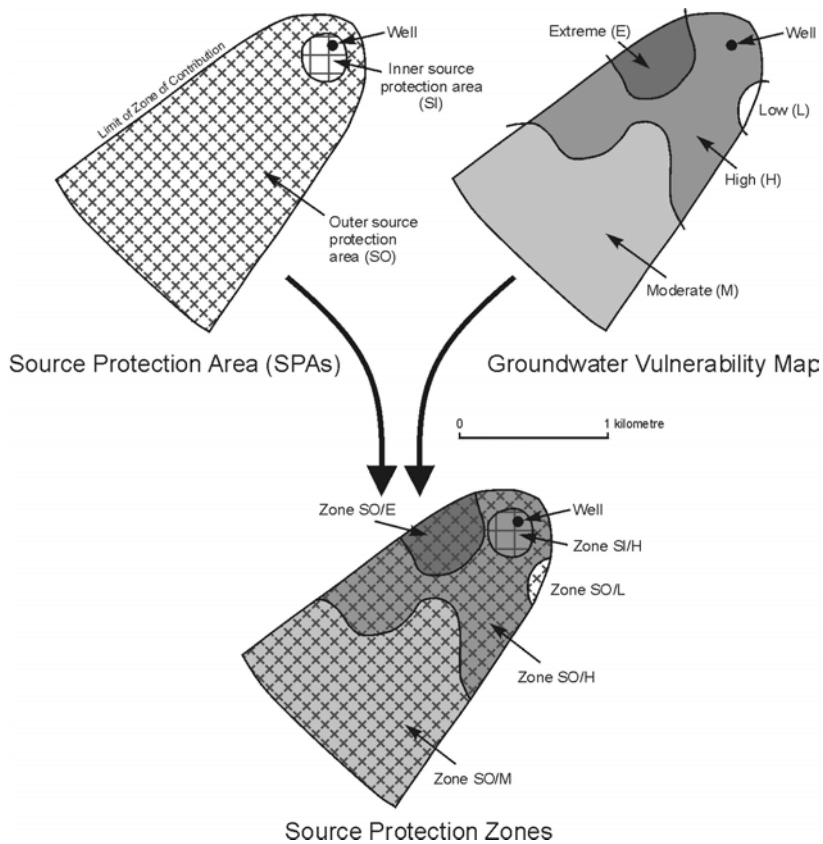


Fig. A.2 Delineation of Source Protection Zones Around a Public Supply Well from the Integration of the Source Protection Area Map and the Vulnerability Map

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.

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)

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.

Use of a Scheme

The use of a scheme is dependent on the availability of the groundwater protection responses for different activities. Currently draft responses have been developed for three potentially polluting activities: landspreading of organic wastes, single house systems and landfills. Additional responses for other potentially polluting activities will be developed in the future.

Appendix B. Permeability Regions in County Donegal.

Summary of Permeability Data and Analyses for Permeability Region 1: Southern Area.

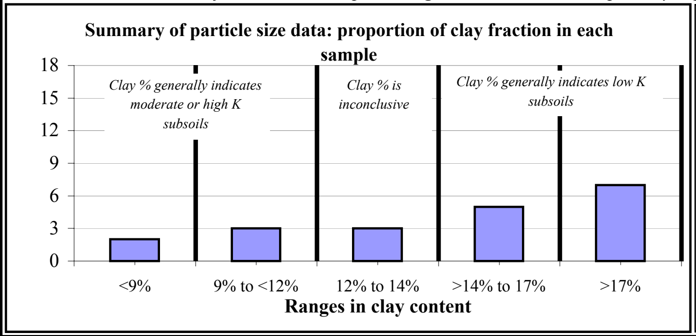
Description of unit location:	South of the Bluestack Mountains.
Why is this a single K unit?	Large areas of uniform till, topsoil and landuse.

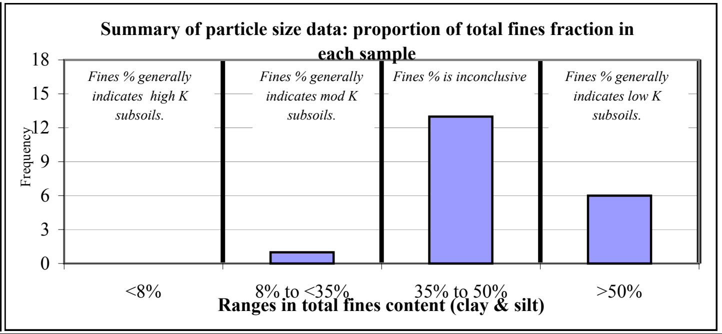
1. General Permeability Indicators and Region Characteristics

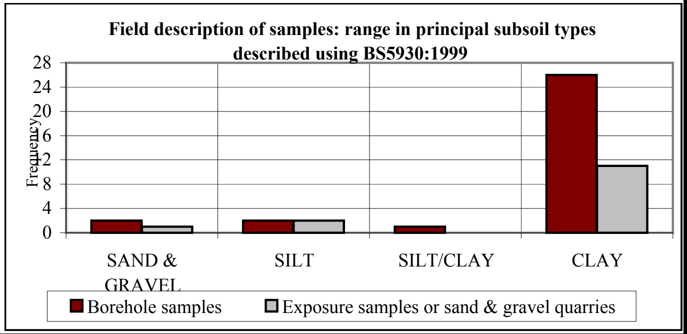
Rock type	Mixed: mainly Precambrian Quartzites, Gneisses and Schists (SWQ, then CW,TE,LM,MF); Dinantian Limestones (BS,Bsag), Shales (BN) and Sandstones (KG,BG).
Depth to bedrock	Variable. Frequently shallow (0-3m) in lower areas to east and in the higher areas to west. Drumlins dominant in east, which often create deeper pods.
Subsoil type	East mainly covered by blanket peat. West and southeast dominated by glacial till: sandstone and metamorphic; smaller areas of limestone and granite till.
Soil type	Gley dominant over till areas, with small area of brown podzolics to the south.
Vegetation and land use	Mainly grazing with frequent to abundant rushes throughout.
Artificial drainage density	Generally quite high
Natural drainage density	Moderate to high
Topography and altitude	Higher, mountainous area to east and northeast (up to 450m) bounds lower area around Donegal Bay. Drumlins dominate landscape in lower lying area to the west.
Ave. effective rainfall (mm)	500 (east) to 1000 in higher western areas

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	Tills generally have a clay matrix, possibly derived locally from shaly limestones.	>>>	low
Particle size data	>14% clay in 60% of samples. >50 fines in a third of the samples.	>>>	low
Field description data	Borehole samples	>>>	low
	Exposure samples	>>>	low
Soil type	Mainly gley and peat	>>>	low
Artificial drainage density	Drainage ditches common	>>>	low
Natural drainage density	Moderate to high natural density	>>>	low
Permeability test data	No data	>>>	-
Rock type	Quartzites, gneisses and schists, sandstones, limestones. Lower K rocks although yield variable matrices	>>>	low-moderate
Land use	Mainly grazing. Frequent to abundant rushes throughout.	>>>	low
	Overall conclusion	>>>	**LOW**

5. COMMENTS: Majority of data suggest low permeability subsoil. The sources of the clayey matrix are mica shists and impure sandstone to the east and southeast of the county. The shaly rock, as well as impure limestones and sandstones, beneath this area are also likely to be contributing to the fines-rich till matrix. There are likely to be pockets of moderate permeability till although many of these are though to be superficial and underlain by clay-rich till.

Summary of Permeability Data and Analyses for Permeability Region 2: Central-Eastern Area.

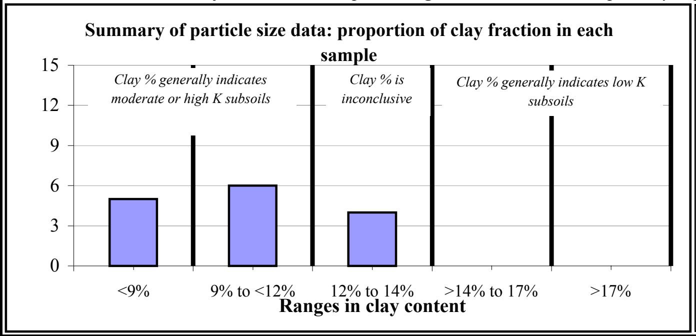
Description of unit location:	Central-Eastern Area: mainly SE and E of Letterkenny. Stretching from Rathmelton/Kilmacrenan to south of Castlefinn, and over as far as Muff.
Why is this a single K unit?	Uniform till, topsoil and land use. Similar bedrock types. Relatively uniform topography.

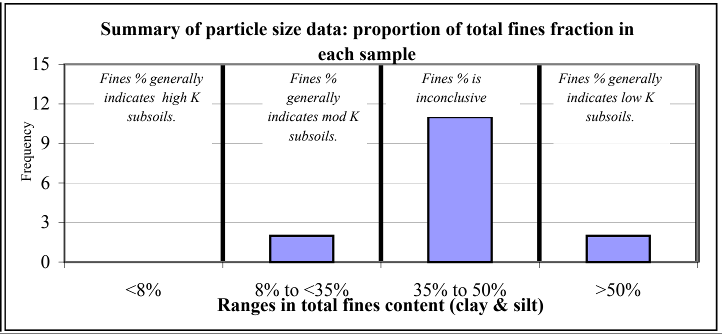
1. General Permeability Indicators and Region Characteristics

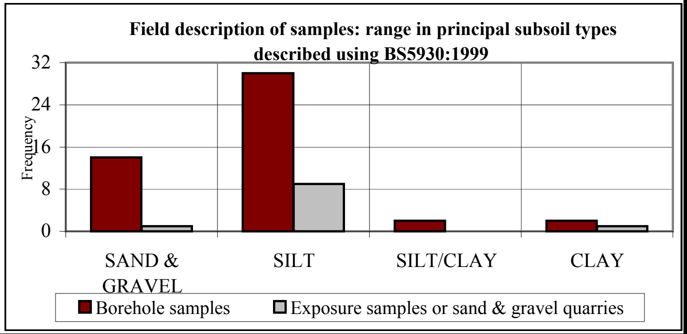
Rock type	Precambrian Marbles (DG, DGmb, DGlv) and Precambrian Quartzites, Gneisses & Schists (BO, LC, LE, LFS, LM. MF, TE). Aquifers are lower permeability ranging from Pl to lower Ll.
Depth to bedrock	Higher areas are generally shallow (0-3m), with some outcrop. Increases to >10m along the low-lying valley areas.
Subsoil type	Mainly glacial till (described as Metamorphic till) although there is alluvial material along the base of the valleys.
Soil type	Brown Podzolics are the predominant topsoil type. Gley underlie some of the western portion of this unit.
Vegetation and land use	Grazing and the highest proportion of tillage in County Donegal. This unit is generally quite free draining.
Artificial drainage density	Low
Natural drainage density	Moderate to Low
Topography and altitude	Upland areas with series of parallel, east-west trending valleys. Highest area to the west (c250m), falling to <10m around Loughs Swilly (north) and Foyle (east).
Ave. effective rainfall (mm)	500

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	Generally till (predominantly described as limestone) with a silty matrix.	>>>	moderate
Particle size data	<12% clay in 12 of 16 available PSDs. <50% fines in 14 of 16 PSDs.	>>>	moderate-high
Field description data	Borehole samples	>>>	moderate-high
	Exposure samples	>>>	moderate
Soil type	Brown Podzolics	>>>	moderate
Artificial drainage density	Few drainage ditches	>>>	moderate
Natural drainage density	Relatively low density compared to other parts of Donegal	>>>	moderate
Permeability test data	No data	>>>	-
Rock type	Marbles, quartzites, gneisses and schists. Marbles maybe influencing till	>>>	moderate-low
Land use	Tillage and grazing. Quite free-draining	>>>	moderate
	Overall conclusion	>>>	**MODERATE**

5. COMMENTS: Majority of available data suggest a moderate permeability subsoil. There are also a number of samples with a high proportion of sand and gravel. These samples are likely to be influenced by the underlying quartzites and other coarse grained metamorphic rocks. This is the most commonly tilled area in County Donegal.

Summary of Permeability Data and Analyses for Permeability Region 3: Northern, Western and Central Areas.

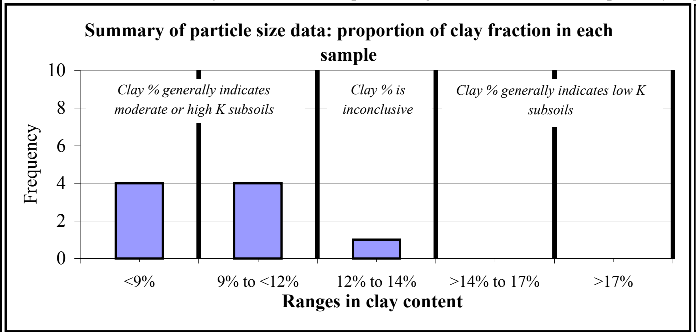
Description of unit location:	Northern, Western and Central Area of the County.
Why is this a single K unit?	Similar underlying rock types. Large areas of uniform subsoils and topsoils. Topographically similar.

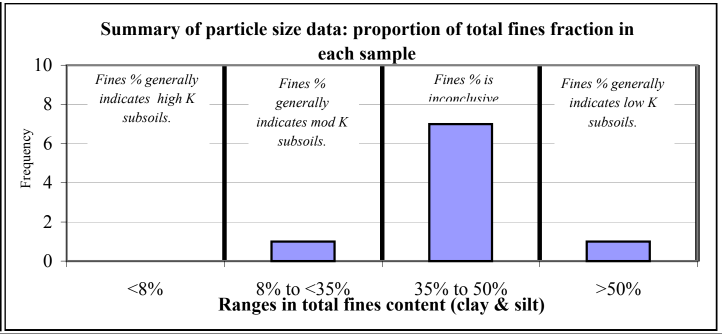
1. General Permeability Indicators and Region Characteristics

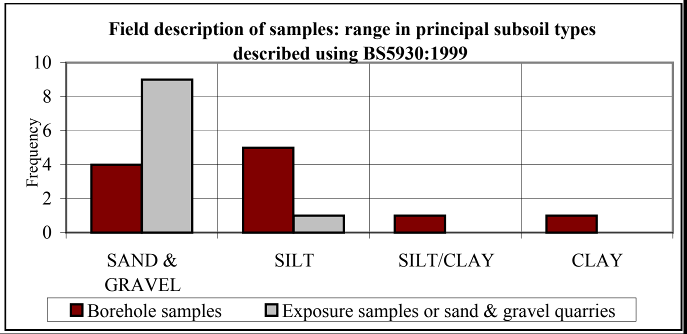
Rock type	Granites/Igneous Intrusives (MdGr,ArG3,TrG1,TrG2,RsG3,Th) surrounded by Precambrian Quartzites, Gneisses and Schists (TE,ST,LC,AQ,SC,CS,UF,LF).
Depth to bedrock	Higher areas generally shallow (0-3m), with outcrop. Increases to >10m along valley and down to the coastal areas.
Subsoil type	Till (granite to the northwest; metamorphic to the east and southwest; quartzite till to the northeast) in valley and coastal areas.
Soil type	Peaty podzols (not distinguished from upland areas) and lithosols common. Smaller pods of brown podzolics and some gleys in lower (valley) areas.
Vegetation and land use	Dominated by grazing. Occasional tillage.
Artificial drainage density	Moderate to Low
Natural drainage density	Moderate to High
Topography and altitude	Narrow SW-NE valleys trending (secondary valleys; SE-NW trend) within mountainous area, and lower area surrounding mountains.
Ave. effective rainfall (mm)	800 in the northeast to 1300 in the southwest

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/silt matrix - probably derived locally from coarse-grained metamorphic and (some) granite rocks.	>>>	moderate
Particle size data	<12% clay and <50% fines in 10 of 11 PSDs.	>>>	moderate
Field description data	Borehole samples	>>>	moderate-high
	Exposure samples	>>>	moderate-high
Soil type	Lithosols; pods of Brown Podzolics	>>>	moderate
Artificial drainage density	Few drainage ditches	>>>	moderate
Natural drainage density	Quite high however anticipate that the underlying low permeability rocks have a strong influence	>>>	low
Permeability test data	No data	>>>	-
Rock type	Granites, igneous rocks, quartzites, gneisses and schists - hard and low permeability.	>>>	moderate-low
Land use	Grazing (often rough) and occasional tillage. Quite free-draining.	>>>	moderate
	Overall conclusion	>>>	**MODERATE**

5. COMMENTS: Majority of available data suggest a moderate permeability subsoil. There are also a number of samples with a high proportion of sand and gravel. These samples are likely to be influenced by the underlying quartzites and other coarse grained rocks. The natural drainage density is anticipated to reflect the influence of the low permeability rocks and topographic location (valleys, coastal discharge areas) rather than permeability of the till.

Summary of Permeability Data and Analyses for Permeability Region 4: Sand and Gravel.

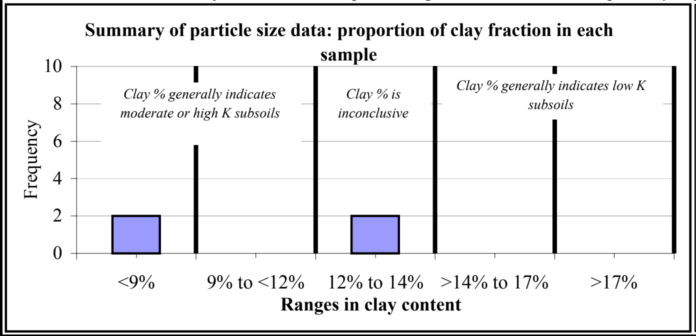
Description of unit location:	Sand and Gravel Areas
Why is this a single K unit?	Delineated as sand and gravel. Similar topsoil land use and topography.

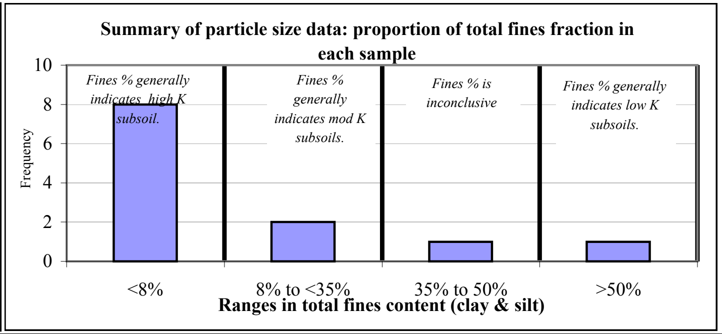
1. General Permeability Indicators and Region Characteristics

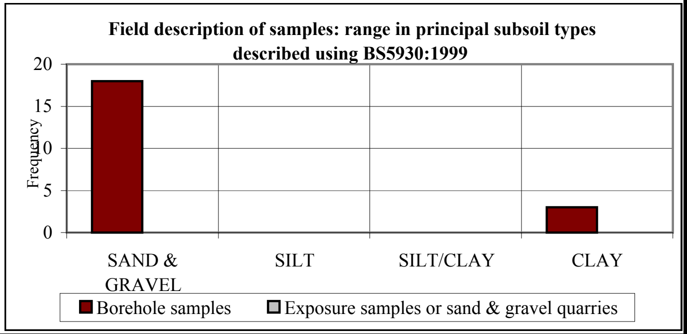
Rock type	Various. Generally low permeability rocks.
Depth to bedrock	Generally >5m and sometimes >10m.
Subsoil type	Sand and gravel from various sources; metamorphics, granites, marine, raised beaches, wind-blown sand and sand dunes.
Soil type	Mainly acid brown earths. Some brown podzolics and occasional gleys.
Vegetation and land use	Grazing. Very free draining land. Some small quarries located in these areas.
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	Frequently low lying and flat areas adjacent to the coast, <50m altitude. Dunes up to 15m high.
Ave. effective rainfall (mm)	Variable (500-1000)

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/gravel from glacial melt-water/deltaic or wind-blown deposition.	>>>	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 characteristically 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 5: Peat.

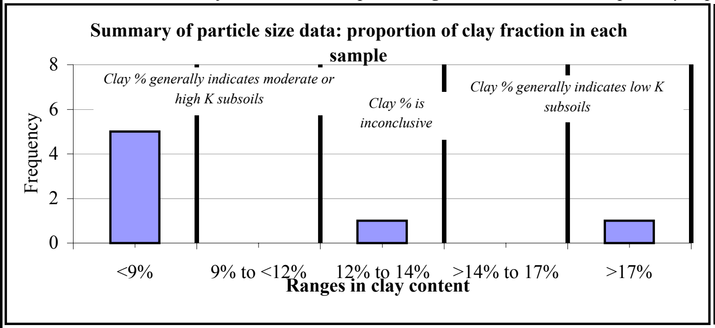
Description of unit location:	Peat
Why is this a single K unit?	Delineated as peat. Uniform subsoil and topsoil. Similar topography and land use.

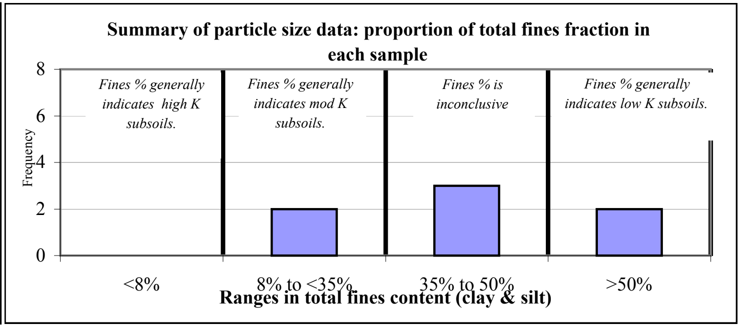
1. General Permeability Indicators and Region Characteristics

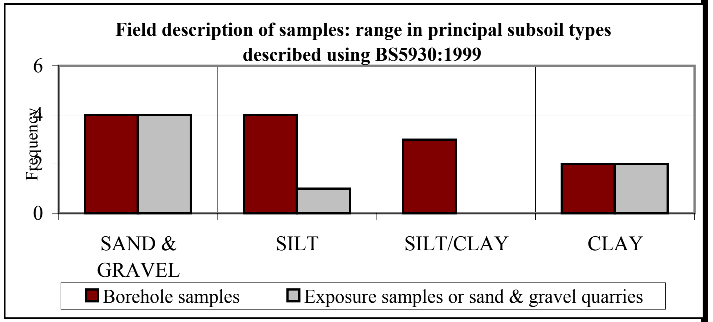
Rock type	Mainly Precambrian Quartzites, Gneisses and Schists. Also Granites/Igneous Intrusives. All poor aquifers.
Depth to bedrock	Generally grading from outcrop/shallow areas to 10m.
Subsoil type	Predominantly Blanket Peat over the higher areas. Some areas of 'Cutover Peat' that are likely to be sitting on top of lake clays and silts.
Soil type	Frequently recorded as Blanket Peat. Also associated with peaty podzols and gleys.
Vegetation and land use	Heather, moss and rushes. Difficult to utilise except for sheep grazing in the higher areas. Some small areas cut for turf.
Artificial drainage density	Many areas are not developed/utilised. High on worked 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. Altitudes variable although up to 700m.
Ave. effective rainfall (mm)	Variable (500 - 1500)

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	Variable - mainly for material underlying peat.	>>>	low - high
Field description data	Borehole and exposure samples for material underneath the peat are variable	>>>	low - high
		>>>	low - high
Soil type	Blanket Peat, peaty podzols, gleys.	>>>	low
Artificial drainage density	High where developed	>>>	low
Natural drainage density	Intermediate - low	>>>	moderate to low
Permeability test data	-	>>>	-
Rock type	Variable	>>>	moderate
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. They developed in the warmer and wetter post glacial period. The water logged conditions are related to the low permeability of the underlying rocks which inhibits drainage of the surface water and thus creating ideal conditions for peat development. 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 6: Alluvium.

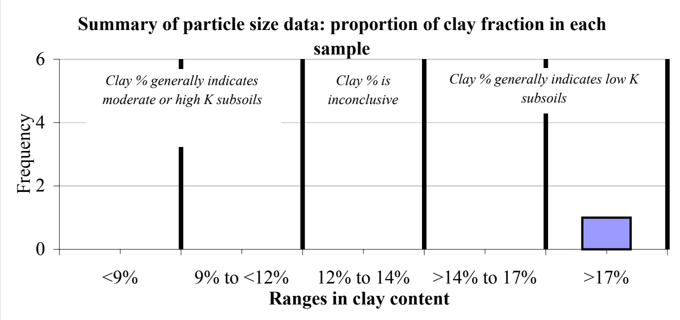
Description of unit location:	Alluvial Areas.
Why is this a single K unit?	They are primarily fine-grained water-lain deposits found on the banks and flood-plains of rivers.

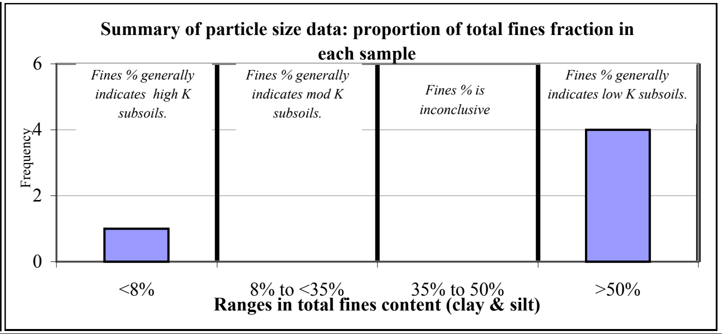
1. General Permeability Indicators and Region Characteristics

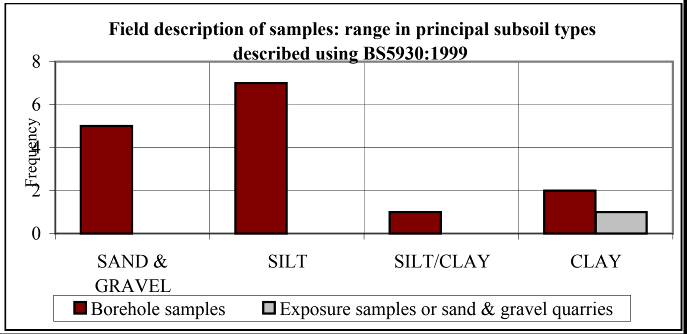
Rock type	Variable
Depth to bedrock	Typically greater than 3m. The alluvium generally overlies till or gravel deposits.
Subsoil type	Interbedded, predominantly fine-grained: sandy, silty and clayey water-lain alluvial deposits.
Soil type	Various. Not differentiated from surrounding till. Locally, groundwater 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 - 1000)

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, 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 likely to be thicker along the larger rivers although are likely to have an influence on the overall permeability in most instances.