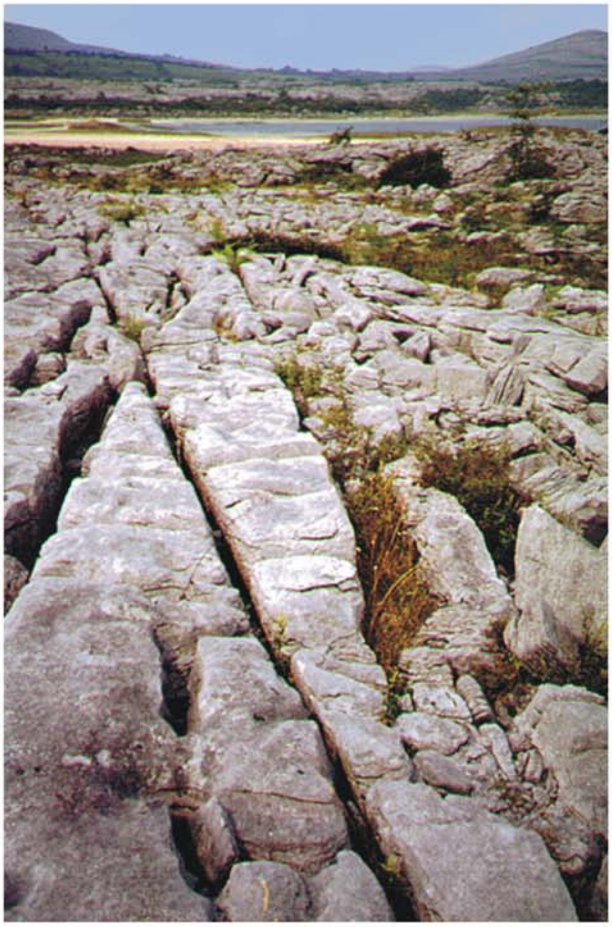
County Clare
Groundwater Protection Scheme



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County Clare
Groundwater Protection Scheme

Main Report

Clare County Council
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Ennis

Geological Survey of Ireland
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Haddington Road
Dublin 4

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Table of Contents

List of Figures

List of Tables

Schedule of Maps

Map 5 Aquifers

Map 6 Groundwater Vulnerability

Map 7 Groundwater Resource Protection Zones

The county is sub-divided into 3 areas – east (E), central (C) and west (W).

1 Introduction

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

- since groundwater flow and contaminant transport are neither readily observed nor easily measured, and both processes are generally slow, there can be a lack of awareness about the risks of groundwater contamination;
- 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;
- there has been a significant increase in the application of inorganic fertilisers to agricultural land and in the usage of pesticides in recent years;
- there are greater volumes of road traffic and more storage of fuels/chemicals; and
- chemicals of increasing diversity and often high toxicity are being manufactured, distributed and used for a wide range of purposes.

The main threats to groundwater are posed by (a) point contamination sources – farmyard wastes (mainly silage effluent and soiled water), septic tank effluent, sinking streams where contamination of surface water has occurred, leakages, spillages, pesticides used for non-agricultural purposes and leachate from waste disposal sites, and (b) diffuse sources – 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 integrating hydrogeological factors into land-use policy and planning by means of groundwater protection schemes.

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

1.4 'Groundwater Protection Schemes' – A National Methodology for 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/EPA/GSI, 1999). The publication **Groundwater Protection Schemes** was launched in May 1999, by Mr. Joe Jacob TD, Minister of State at the Department of Public Enterprise. Two supplementary publications were also launched, namely, **Groundwater Protection Responses for Landfills** and **Groundwater Protection Responses for Landspreading of Organic Wastes**. Similar 'responses' publications will be prepared in the future for other potentially polluting activities and developments, such as on-site wastewater treatment systems.

There are two main components of a groundwater protection scheme:

- **Land surface zoning**;
- **Groundwater protection responses for potentially polluting activities.**

These are shown schematically in Fig. 1.1.

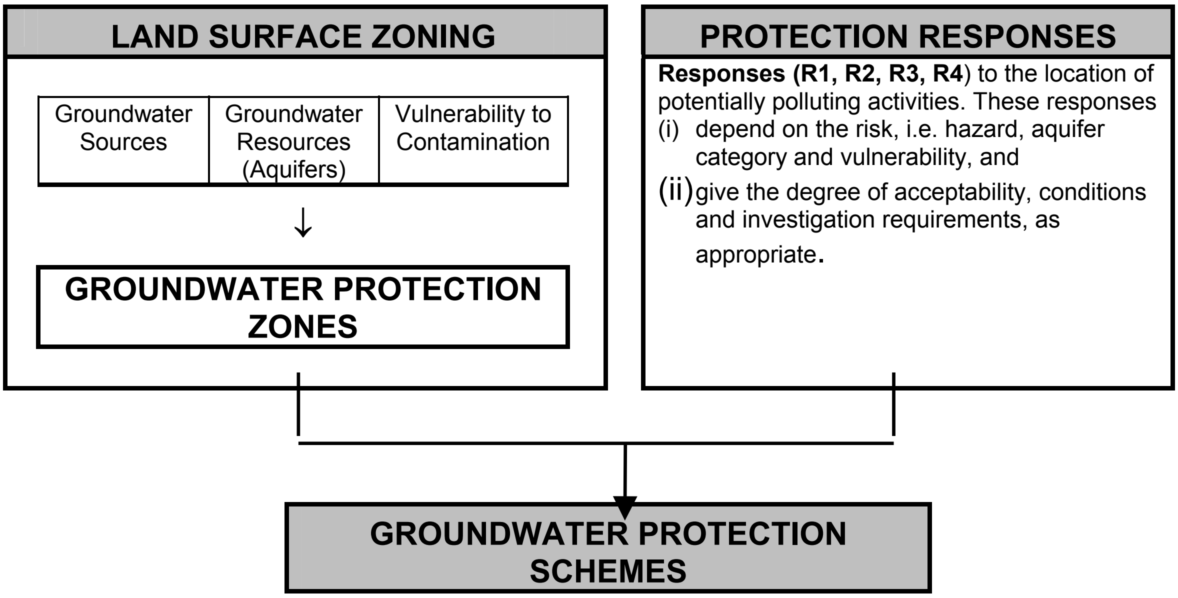

Fig. 1.1 Summary of Components of Groundwater Protection Scheme

Land surface zoning provides the general framework for a groundwater protection scheme. The outcome is a map, which divides any chosen area into a number of groundwater protection zones according to the degree of protection required.

There are three main hydrogeological elements to land surface zoning:

- Division of the entire land surface according to the **vulnerability** of the underlying groundwater to contamination. This requires production of a vulnerability map showing four vulnerability categories – extreme, high, moderate and low.
- Delineation of **areas contributing to groundwater sources** (usually public 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 A. While these describe the two main components of the national groundwater protection scheme, it is recommended that, for a full overview of the groundwater protection methodology, the **Groundwater Protection Schemes** publication (DELG/EPA/GSI, 1999) should be consulted.

1.5 Objectives of the County Clare Groundwater Protection Scheme

The overall aim of the groundwater protection scheme is to preserve the quality of groundwater in County Clare 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 Clare Groundwater Protection Scheme

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

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

(i) delineation of aquifers;
(ii) assessment of the groundwater vulnerability to contamination;
(iii) delineation of protection areas around five public supply wells and springs (Ballyvaughan, Drumcliff, Pouladower, Whitegate and Mountshannon); and
(iv) 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 and sets in place a database within the Geological Survey of Ireland (GSI), which can be accessed by the local authority and others, and which can be up-dated as new information becomes available.

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

(i) Primary Data or Basic Maps
- bedrock geology map
- subsoils (Quaternary) geology map
- outcrop and depth to bedrock map
- hydrogeological data map

(ii) Derived or Interpretative Maps
- aquifer map

- groundwater vulnerability map

(iii)Land-use Planning Map
- groundwater protection scheme map

These 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. They are not however, a substitute for site investigation.

It is important to recognise however, that detailed regional hydrogeological investigations in County Clare are limited to a number of public supply sources, Environmental Impact Statements and research publications. Consequently, the available data are somewhat limited and it is not possible to provide a fully comprehensive scientific assessment of the hydrogeology of County Clare. However, this report provides a good basis for strategic decision-making and for site specific investigations.

1.7 Clare County Development Plan

This is the groundwater protection scheme referred to in Sections 2.6.2, 3.2 and 5.3.3.1 of the Draft Clare County Council Development Plan.

1.8 Structure of Report

The structure of this report is based on the information and mapping requirements for land surface zoning. The groundwater resources 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 subsoils map (Map 2), the depth to rock map (Map 3) and an assessment of specifically relevant permeability and karstification information. This is illustrated in Fig. 1.2.

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

Chapters 2 and 3 provide brief summaries of the bedrock and subsoils geology, respectively. Chapter 4 summarises and assesses the hydrogeological data for the different rock units, gives the basis behind each of the aquifer categories, and describes the potential for future groundwater development. Chapter 5 gives a summary of a separate report on the hydrochemistry and groundwater quality in Co. Clare. Chapter 6 describes the permeabilities within each of the subsoil types and gives the basis behind the vulnerability categories. Chapter 7 draws the whole lot together and summarises the final groundwater protection zones present in Co. Clare.

1.9 Acknowledgements

The preparation of this groundwater protection scheme involved contributions and assistance from many people:

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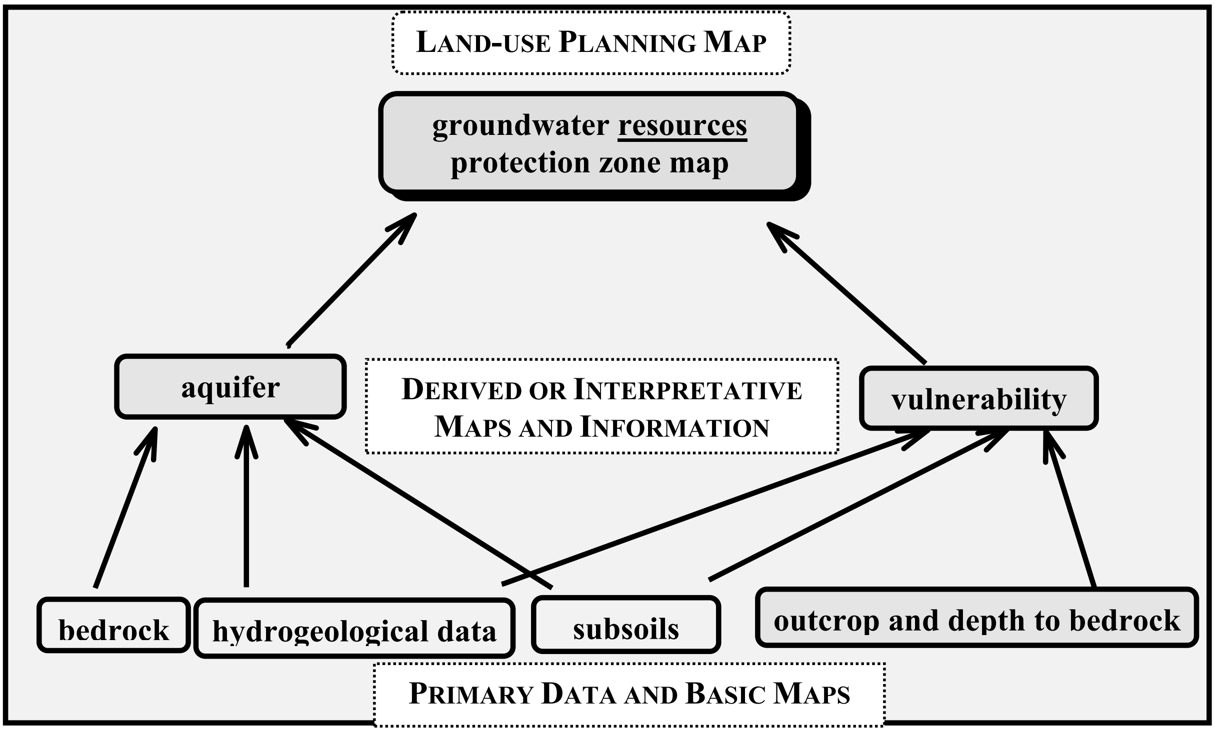

Figure 1.2 Conceptual framework for production of groundwater <u>resource</u> protection zones, indicating information needs and links.

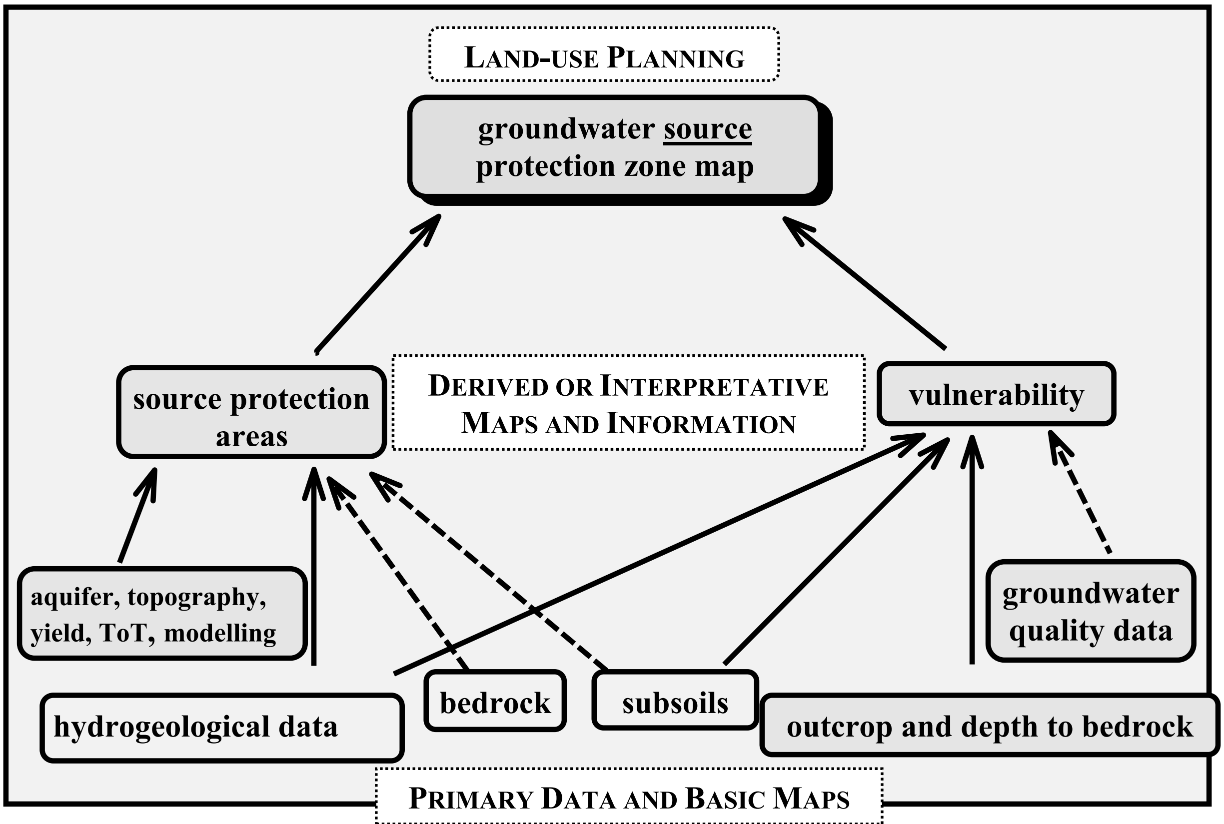

Figure 1.3 Conceptual framework for production of groundwater <u>source</u> protection zones, indicating information needs and links.

2 Bedrock Geology

Introduction

This chapter presents a brief description of the elements of the bedrock geology of Co. Clare 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 range in age from Ordovician (c. 500 million years old) to the Namurian of the Upper Carboniferous (c. 300 million years old) and are mainly sedimentary in origin, consisting of limestones, sandstones and shales. There is one small outcrop of volcanic rocks to the east of the county near Kilkishen.

The landscape of Co. Clare reflects the varied underlying geology. The mountains to the northeast and southeast of the county are composed largely of the resistant Old Red Sandstone with older, less competent Silurian and Ordovician aged sandstones and siltstones in their cores. The younger, softer and more soluble Carboniferous limestones and shales underlie an extensive low lying plain stretching from the Ennis area northwards to Gort and the Burren plateau, and eastwards to Scarriff in an area known as the East Clare Syncline. The upland area of the west of the county is underlain by the sandstones, siltstones and shales of Namurian (Upper Carboniferous) age.

These rocks were folded and faulted in response to a deformation event which originated to the south of the country. The intensity of rock deformation generally decreases northwards throughout the county.

The geology of the county is complex with both temporal and lateral changes in rock composition. A brief description of the different rock units and their inter-relationships is given in this report; a more detailed description is given in Sleeman and Pracht (1999). In describing the rock units the emphasis is placed on the rock lithology or 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) Ordovician Rocks*;
(ii) Silurian Rocks*;
(iii) Devonian Old Red Sandstones;
(iv) Lower Carboniferous Rocks;
(v) Namurian (Upper Carboniferous) Rocks.

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, Sheet 17 (Sleeman et al., 1999) and from unpublished field mapping and compilation carried out by Conor MacDermot, Bedrock Section, GSI.

*The Ordovician and Silurian rocks are also collectively referred to as the Lower Palaeozoic rocks.

Table 2.1 Bedrock Succession in Co. Clare

Age	(million years)	Main Succession		East Clare Syncline		South Clare	
Upper Carboniferous	Namurian	**Central Clare Group (CCG)**	Sandstones, siltstones and mudstones				
		Tullig Sandstone (TS)	Thickly bedded pale sandstones				
		Gull Island Siltstone (GI)	Grey siltstones and sandstones				
		Ross Sandstone (RS)	Thickly bedded pale sandstones				
	(290)	**Clare Shales (CS)**	Dark grey shales and mudstones				
Lower Carboniferous	Visean	**Slievenaglasha Lst (SL)**	Pale grey clean coarse grained limestone with chert bands and fossiliferous horizons	**Slievenaglasha Lst (SL)**	(See main succession)	**Parsonage Lst (PA)**	Striped cherty and muddy limestones and shales
				Turret Volcanics (SLtu)	Basaltic tuffs and lavas		
				Aylecotty Lst (Slay)	Thinly bedded dark grey cherty limestones	**'mudbank lst' (mk)**	Massive grey shelly limestones
		Burren Lst (BU)	Pale to medium grey fossiliferous clean medium to coarse grained limestone. Clay wayboards towards the top	**Burren Lst (BU)**	(See main succession)	**Visean Lst (VIS)**	Undifferentiated clean and muddy limestones
		Tubber Lst (TU	Fossiliferous medium grey clean fine and medium grained limestones, with shaly partings, cherts and dolomites	**Tubber Lst (TU)**	Argillaceous bioclastic limestones	***Volcaniclastic rocks (v)***	*Blue, green, red and purple fine to coarse grained volcanic rocks (tuffs)*
				Finlough Lst (FL)	Dark grey or black earthy fetid fine grained limestone with cherts and shale partings		
		Cregmahon Lst (TUcm)	Thickly bedded silicified and dolomitised cherty medium to coarse grained limestone with some shale partings	**Ballycar Lst (BC)**	Dark grey highly silicified fine grained limestone with chert	**Lough Gur Lst (LR)**	Dark grey to black cherty argillaceous limestones
	Courceyan	**Waulsortian Lst (WA)**	Massive pale grey fine-grained clean fossiliferous limestone, dolomitised in places				
		Ballysteen Lst (BA)	Dark muddy fossiliferous limestones				
		Ballymartin Lst (BT)	Thin pale grey muddy limestones and dark grey calcareous shales				
	(355)	**Lower Lst Shales (LLS)**	Dark grey fine-grained mudstones, siltstones and sandstones				
Devonian	(410)	**Old Red Sandstone (ORS)**	White, yellow and brown coarse grained sandstones, conglomerates, siltstones and mudstones				
Silurian	(438)	**Silurian (SIL)**	Grey to green siltstones, mudstones and muddy sandstones				
Ordovician	(510)	**Ordovician (ORD)**	Red to black shales and grey cherts				

Ordovican Rocks

The Ordovician rocks are the oldest rocks in Clare, cropping out mainly in the high ground southwest of Broadford. They are described as red to black coloured mudstones (shales) and grey cherts. The shales locally contain fossils (graptolites).

Silurian Rocks

During Silurian times, sands, silts and clays were washed in from the north and deposited on the floor of a deep ocean. The present day rocks are visible in both the north-east and south-east upland regions, forming the Slieve Aughty and Slieve Bernagh hills, respectively, and usually comprise the core of these upland areas. The rocks may be generally described as a series of siltstones, mudstones and muddy sandstones (greywackes) which are of varying colours from pale grey to green. A brief description of each rock unit is given below, beginning with the oldest:

Cornagnoe Formation (CE)	Grey and green mudstones and siltstones
Broadford Formation (BF)	Grey mudstones with sandstone and siltstone beds
Slieve Bernagh Formation (SB)	Laminated siltstones and mudstones with sandstones and conglomerates at the base. The Killaloe Slates are found in this rock unit.
Cratloes Formation (CR)	Thin to medium bedded, laminated, grey to green siltstones with some fine sandstones. Approximately 300 m thick.

Old Red Sandstones

Deposition of the Old Red Sandstone (ORS) rocks took place in a sub-equatorial arid environment, where there was intense erosion and then deposition of gravel, sand, silt and some clay in the flood plains of meandering rivers. These rocks surround the older Lower Palaeozoic rocks and are the most extensive rock type in the upland areas of east Clare. They consist primarily of yellow, white and brown/red coarse and fine-grained, high energy, sandstones and conglomerates with some siltstones and mudstones. The red colour reflects the arid sub aerial oxidising conditions under which these rocks were formed. The coarser grained sediments are usually present towards the base of this rock unit, with greenish-grey siltstones becoming more common towards the top. These rocks have not been studied in detail in Co. Clare and there may be local variations present.

Lower Carboniferous Rocks

The Lower Carboniferous was a period of marine deposition as warm tropical seas transgressed northwards over the Devonian Old Red Sandstone continent. At the same time, earth movements caused the sea bed to subside into a large basin, the Shannon Trough, along the present day Shannon Estuary. A great variety of sediments were laid down depending on the depth and the turbulence of the waters, and their position in relation to the developing basin. Clean limestones (such as the limestones in north Clare) were laid down in shallower water with periodic emergence, due to world-wide sea-level changes. In the deeper basinal waters, where subsidence was greater than deposition, more shaly limestones (such as the limestones to the west of the Fergus Estuary) were formed in the quieter environment due to the presence of silts and muds.

Lwr Lst Shales (LLS)	Dark grey fine-grained sandstones, siltstones and mudstones at the base incorporating the transition from terrestrial to marine sediments and equivalent to the Mellon House Beds in other areas (40 m thick). Overlain by poorly exposed dark grey to black

	calcareous shales with thin bands of fossiliferous limestones equivalent to the Ringmoylan Formation in other areas (50 m). Present as a narrow band around the Slieve Aughty and Slieve Bernagh hills. Includes the thin Ballyvergin Mudstone Formation which is not differentiated on the maps.
Ballysteen Lst (BA)	Dark muddy fossiliferous limestones present in east and south Clare in the lowlands adjoining Slieve Bernagh and Slieve Aughty and in the Shannon area. Two subunits incorporating lower dark muddy well bedded fossiliferous limestones (~140 m thick) and upper limestones with a greater mud content (~50 m thick). Also includes the underlying Ballymartin Limestones (thin pale grey muddy limestones and dark grey calcareous shales) which are not always differentiated on the maps.
Waulsortian Lst (WA)	Massive pale grey fine-grained clean fossiliferous limestone which formed in mound structures. Original cavities are now filled with calcite which may form a significant proportion of the total volume of the rock. Located in the lower lying areas south of Newmarket-on-Fergus, Kilmurry and Tulla. Thickness ranges from ~500 m in the north to ~1000 m in the south.
Ballycar Lst (BC)	Dark grey highly silicified fine grained limestone interbedded with nodular black chert bands (0.1–0.25 m thick). Coarser grained towards the bottom of the unit and more cherty towards the top. Equivalent to the Cregmahon Limestone (TUcm) in mid Clare and the Lough Gur Limestone (LR) in southeast and in Limerick (see below). Thickness is 38 m at Newmarket-on-Fergus.
Lough Gur Lst (LR)	Dark grey to black cherty argillaceous limestones. Equivalent to the Ballycar and Cregmahon limestones.
Finlough Lst (FL)	Dark grey or black earthy fetid fine grained limestone with cherts and shale partings. Present in the vicinity of Finlough in east Clare. Laterally equivalent to the Tubber Lst in north Clare and to the Calp in other parts of the country. Approximately 75 m thick.
Tubber Lst (TU)	Fossiliferous medium grey clean fine and medium grained limestones, with shaly partings and cherts. Similar to the overlying Burren Limestone except for the presence of dolomite. Found east of Ennis and in the Tubber area. These rocks host the east Clare calcite mineralisation and are mapped there as argillaceous bioclastic limestones.
Cregmahon Lst (TUcm)	Thickly bedded silicified and dolomitised cherty medium to coarse grained limestone with some shale partings. Laid down in hollows and draped on the sides of the Waulsortian knolls, e.g. the Curraderra Lough area, north of Barefield where the Waulsortian bedrock mounds are clearly mapped within the Cregmahon Limestones. Lowest part of the Tubber Limestone present in mid

	Clare. Laterally equivalent to the Ballycar and Lough Gur Limestones.
Burren Lst (BU)	Extensive rock unit present over much of central and north Clare. Pale to medium grey fossiliferous clean medium to coarse grained limestone, with clay wayboards towards the top. Main rock type in the Burren, extending in a band southwards to the Shannon Estuary. Subdivided into a number of members: Ballard Lst, Blackhead Lst, Fanore Lst, Maumcaha Lst and Ailwee Lst.
Ballard Lst (BUbd)	Dark grey medium bedded cherty coarse grained limestone with thin shaly partings. Present as the basal unit north of Ennis.
Black Head Lst (BUbh)	Thickly bedded limestones with dolomitic horizons. Present in north Clare around Black Head and in the Ballyvaughan area.
Fanore Lst (BUfn)	Clean medium bedded limestone with some thin shale and chert bands. Present in the Burren area.
Maumcaha (BUam)	Thick massive pale grey limestone which has been poorly jointed. Present in the Burren and north of Ennis.
Ailwee (BUaw)	Thick clean limestone containing clay wayboards (clay bands). Forms the 'terraces' in the Burren which are due to cycles in sedimentation. The top of individual cycles are palaeokarstic surfaces overlain by clay wayboards. Seen clearly in the higher regions of the Ballyvaughan valley.
Slievenaglasha Lst (SL)	Pale grey clean coarse grained limestone with chert bands and fossiliferous horizons including the Upper Faunal Zone and the Lower Faunal Zone. Considerably more cherty than the underlying Burren Limestone. Local variations in east Clare are mapped as the Turret Volcanics and the Aylecotty Limestone.
Aylecotty Lst (SLay)	Thinly bedded dark grey cherty limestones.
Turret Volcanics (SLtu)	Interbedded basaltic tuffs and lavas which are 85 m thick. Present in a small area west of Kilkishen.
Parsonage Lst (PA)	Pale to dark grey fine grained limestone (~23 m thick) with coarse grained horizons and a striped appearance. Overlain by unfossiliferous, occasionally cherty, dark muddy limestones and interbedded dark shales (~30 m thick). The latter are mapped as the Corgrig Lodge Beds but as they are thin they are grouped with the Parsonage Limestones on the map. Located in a small area west of the Fergus estuary and on the estuary islands. Equivalent in age to the Slievenaglasha and 'mudbank' Limestones.
'mudbank lst' (mk)	Massive grey shelly limestones which have formed in 'reef like' structures in deep water with an influx of muds. Equivalent in age to the Parsonage and Slievenaglasha Limestones.

Visean Lst (VIS) There are three areas where the limestones are undifferentiated due to lack of exposures and drilling information, although it is known that they are likely to be Visean in age:
(a) north of Newmarket on Fergus. Likely to be clean limestones equivalent to the Burren and Tubber limestones;
(b) west of the Fergus estuary. Deeper water dark grey shaly limestones likely to be similar to the Finlough Limestones;
(c) south east Clare around Parteen. Likely to be equivalent to the clean shelf limestones present around Limerick city.

Volcaniclastic rocks (v) Blue, green, red and purple fine to coarse grained brecciated and conglomeratic volcanic rocks (tuffs). Two very small areas occur in southeast Clare.

Namurian (Upper Carboniferous) Rocks

Subsidence and deposition in the Shannon Trough continued into Namurian times. Deep water shales were laid down first, followed by alternating sandstones, siltstones and mudstones. These were relatively unstable times when thick sandstone beds were deposited in the water by large density (turbidity) currents, triggered by earthquakes. By the end of the Namurian, the basin had filled to become a coastal plain with extensive mudflats and river deltas. The Namurian rocks now underlie west Clare.

Clare Shales (CS) Dark grey shales with siliceous mudstones towards the base and nodules and bands of ironstone near the top. Crops out along the western margin of the limestones.

Ross Sandstone (RS) Sandstones with interbedded dark shale. Only present in southwest Clare in the Loop Head area

Gull Island Siltstone (GI) Grey siltstones with sandstones at the base, decreasing towards the top. 135–400 m thick.

Tullig Sandstone (TS) Thickly bedded pale sandstone. Present near Killadysert.

Central Clare Grp (CCG) Interbedded grey sandstones, siltstones, shales with some thin coal horizons. Deposited in cycles, each 10s of metres thick; with a total thickness >300 m.

Structural History

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

The earlier Caledonian orogeny marked the collision of two continents, Gondwana and Laurentia which were once separated by an ancient ocean (The Iapetus Ocean). The boundary between the continents is a suture line running between the present day Shannon Estuary to Silvermines, Navan and Clogher Head. The collision affected the older rocks only (the Ordovician and the Silurian rocks) and the intensity of deformation increases southwards towards the line of suture.

The Variscan Orogeny was a north-south compression event and as the deformation front was located further to the south of the country, there are only weak effects of the strain seen in Co. Clare. Gentle east-west trending anticlines and synclines dominate and there are numerous north-south cross faults. The degree of deformation can be correlated with the lithology of the rocks; the least competent shales and thin muddy units are characterised by brittle folding and faulting while the more competent clean limestones deform with more open, gentle, simple folding, e.g. the hill at Mullaghmore. Deformation decreases moving northwards through the county.

On a more local scale there are two other deep seated areas of deformation which are essentially extensive fault zones: the Fergus Shear Zone and the Quin Shear Zone. The Fergus Shear Zone trends in a narrow band from the Fergus Estuary north-northeastwards through Ennis towards Gort. The faulting is not easily recognised on the surface although there are subtle indications of it. The Quin Shear Zone is an east-northeast trending fault zone located in the East Clare Syncline, from the Fergus Estuary through O'Callaghan's Mills towards Scarriff.

3 Subsoils Geology

Introduction

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

During the Pleistocene, the glaciers and ice sheets laid down a wide range of deposits which differ in thickness, extent and lithology. Material for the deposits originated from fresh and weathered bedrock and previously deposited materials. They were subjected to different processes within (englacial), beneath (subglacial) and around (ice-marginal) the ice. Some were deposited randomly and so are unsorted and have variable grain sizes, while others were deposited by water in and around the ice sheets and are relatively well sorted and often coarse grained. During the Holocene, rivers have deposited alluvial and estuarine deposits which vary from fine grained to coarse grained materials depending on the energy of the system. Peats have also formed in low-lying poorly drained hollows, former lakes and on high ground where precipitation is high.

Data Availability

Data for the subsoils and depth to rock maps have been generated through an extensive 3 year subsoils mapping programme carried out as part of the protection scheme project.

The mapping programme involved:

- an initial compilation stage where all existing archival GSI map data, academic papers and borehole and outcrop data were compiled;
- a comprehensive field reconnaissance programme where subsoil exposures throughout the county were examined, described and put in context with an interpreted glacial history of the area;
- a drilling programme where approximately 160 holes were drilled to get an estimate of depth-to-rock and to collect samples at depth;
- collection of almost 400 bulk samples for laboratory particle size analysis;
- a period in the office when the subsoil boundaries and depth to rock contours were drawn up using field observations and aerial photographs;
- digitising, editing and checking the maps.

The subsoil maps were compiled, drawn and digitised at 1:25,000 scale, while the depth-to-rock map was contoured at 1:50,000 scale. (The depth-to-rock contour map is not a stand alone map but is an integral part of the vulnerability map.)

Subsoil Types

There are 8 main subsoil types identified in Co. Clare which are shown on Map 2:

- till
- sand/gravel
- till with gravel
- alluvium
- peat
- lake sediments
- marine deposits
- estuarine deposits

The units on the maps refer to the top 1 m of subsoil deposits. Areas where bedrock comes within 1 m of the surface are also shown as areas of ‘rock close’.

3.1.1 Till

Till (often referred to as boulder clay) is the most widespread subsoil in Clare. It is a diverse material which is deposited subglacially and it has a wide range of characteristics due to the variety of parent materials and different processes of deposition. In Clare the most common morphological expression of till is in drumlins (small elongated hills, typically 500–800 m long, 200–300 m wide and 20–35 m high). Drumlins are a glacial feature which are elongated in the direction of ice movement.

Till is classified in Clare on the basis of the dominant clast lithology (i.e. stone type) and the matrix composition (texture), e.g. silty limestone till is a boulder clay derived principally from limestone bedrock which has a high percentage of silt in the matrix. Four main till categories are identified in Co. Clare: Limestone till, Devonian sandstone till, Lower Palaeozoic shale till and Namurian sandstone and shale till.

The subdivision of tills based on matrix composition depends on the proportions of fine gravel, sand, silt and clay particles present in the matrix. There are four broad categories; clayey till, silty till, sandy till and stony till which are also usually subdivided to identify the secondary particle sizes, e.g. a sandy silty limestone till is a limestone derived deposit with a predominantly silt matrix and a relatively high proportion of sand. A stony till has a high percentage of small angular stones and an admixture of the sand, silt and clay fractions. The methods of determining the categories is by visual and manual assessment on-site and using laboratory particle size analysis where appropriate. Boundaries based on till texture are not drawn but symbols indicate the texture at specific locations.

Limestone Tills

Limestone tills are generally found throughout the central area of Clare around Ennis, in the Burren and in the low-lying area of east Clare. The tills are predominantly derived from the underlying Carboniferous limestone bedrock although in bedrock boundary areas, where they have been transported onto an adjacent different bedrock type, material from these rocks is also incorporated. This is particularly relevant at the limestone/Namurian sandstone and shale boundary in the midwest of the county. Here, limestone stones are found in a clay-rich matrix which is locally derived from the Namurian shales.

Limestone tills vary from light-brown/grey to dark brown/black in colour, depending on the parent material and the weathering processes which have occurred. Textures vary from predominantly silty in the Burren area where the limestones are clean, to more clayey silty and clayey around Bodyke and in the Bunratty-Shannon area where the limestones are more shaly. Limestone tills found in the areas

overlying the Namurian sandstone and shale bedrock unit, e.g. around Kilnamona and Kilfenora, have the highest clay proportion of all the limestone tills. Tills found close to bedrock and where the deposits are relatively thin, comprise a coarse matrix with angular clasts and can be described as broken up bedrock or immature till. Sandy tills are found in limestone areas where the bedrock has been dolomitised (refer to Section 4.5.5).

Devonian Sandstone Tills

Devonian Sandstone tills are found in the northeast and southeast of the county, associated with Old Red Sandstone bedrock in the Slieve Aughty and the Slieve Bernagh hills. They are typically a reddish colour and have a variable matrix which usually has a relatively high percentage of sand with significant clay. This is attributed to the nature of the Old Red Sandstone bedrock which comprises both coarse red sandstones and interbedded shales. The sandstones break down to sand sized particles while the shales give rise to silt and clay-sized particles.

The tills can be either clay rich, well consolidated, firm to stiff deposits which have been laid down under the ice as lodgement tills; or much looser, more sandy deposits which may have been laid down as the ice melted. In some places, the more sandy deposits are found overlying the clayey tills.

Lower Palaeozoic Tills

Lower Palaeozoic tills are present to the southeast and northeast of the county where the Lower Palaeozoic Silurian bedrock (sandstones and shales) crops out between the Devonian Sandstones. The till matrix varies from being clay rich in the more mature thicker tills, due to the high percentage of shale in the parent material, to a coarse grained stony type sediment. These latter deposits are found on the southern shores of Lough Derg between Ogonello and Tuamgraney where they reach more than 10 m thick.

Namurian Tills

The Namurian tills are present in the west of the county overlying the Namurian rocks (shales and sandstones). The shales which overlie the limestones at the base of the upland area have given rise to a significant band of clayey tills trending north south, parallel to the limestone/shale boundary. Further west the tills are more variable: those in the drumlins are typically clayey while the inter-drumlin areas are often comprised of a coarser, stony deposit described as broken up bedrock or immature till. The exception to this is the area around Ennistymon and Lahinch where there is an area of thicker deposits (>10 m) of the coarse stony deposit which is described from the mapping programme to be large blocks of broken up bedrock which have been lifted and shunted a short distance and are evident today in small hills or hummocks.

This rock type has also given rise to a number of rock cored drumlins which are easily confused with the drumlins comprised of till. The relatively soft shale rock has been moulded by the glaciers into the characteristic drumlin shape.

3.1.2 Sand/gravel

Deposition of sand/gravel takes place mainly when the glaciers are melting. This gives rise to large volumes of meltwaters with great erosive and transporting power. The sands and gravels deposited in this high energy environment are primarily well rounded, sorted gravels with sand, with the finer fractions of clay and silt washed out. Deposits of this nature are present in Clare in the valley east of Broadford, e.g. the Ballyquin Sand Quarry.

A second type of sand/gravel, which is more prevalent in Clare, is referred to as morainic sand/
gravel. These sediments are laid down either at the ice-margin or as heaps of sediment as the glacier retreats. They are not as well sorted and washed, contain significant clay and silt fractions, and may have tills deposited amongst them in places. Deposits of this type are found southwest of Killaloe at the foot of the mountains, in the Mountshannon area and to the west of the county around Kilrush and Cooraclare.

3.1.3 Till with Gravel

The till with gravel deposits are complex subsoils which comprise relatively coarse grained intermixed tills and sand/gravel. In Clare these occur only in a small area to the northeast of the county in the Whitegate area. They are principally derived from Devonian sandstones and are typically unconsolidated loose, sandy materials which contain particles of all sizes (boulders, pebbles, sand etc.).

3.1.4 Alluvial Deposits

Alluvial sediments are deposited by rivers and include unconsolidated materials of all grain sizes, from coarse gravels down to finer silts and clays. They may also contain organic detritus.

Alluvial deposits may be subdivided according to dominant grain size fraction, however, there was insufficient information in most instances in Clare to enable this subdivision to be shown on the subsoils map. Alluvial sediments in flood plains, where flow velocities are relatively low, are expected to be primarily silty deposits with some clay. Close to the hills and mountains they are likely to be more sandy or gravelly as flow velocities are faster. These deposits are relatively isolated in Clare and are associated with the smaller rivers. The deposits around the Fergus and Shannon estuaries are mapped as Estuarine deposits (see below).

3.1.5 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 undecomposed plant matter which has accumulated in a water logged environment. It has an extremely high water content averaging over 90% by volume although many have now been drained.

The largest areas of peat in Co. Clare are the blanket peats on the higher ground in the west on the poorly drained Namurian shales and sandstones, and in the mountainous areas of the Slieve Aughty and Slieve Bernagh hills. Basin peats are found in isolated patches in the low-lying limestone areas to the north and east of Ennis and are often associated with alluvium, estuarine deposits and marls. The two peat types are not differentiated on the subsoils map.

3.1.6 Lake Sediments

Small areas of post-glacial lake clays and silts are scattered over the low lying limestone plain in small, often isolated, hollows.

3.1.7 Marine Deposits

Marine and wind blown sands are mapped in small areas around the well known beaches on the west coast. The deposits are usually coarse sand which form large dunes in places.

3.1.8 Estuarine Deposits

Estuarine deposits in Clare are also post glacial in age and are deposited in a tidal environment by the actions of the present day Shannon estuary. They occur on the southern coast of the county in the Shannon estuary and in the tidal flats area of the Fergus Estuary, in particular around Clarecastle and west of Newmarket-on-Fergus. They are predominantly silty muds (clayey silt).

Subsoil Thicknesses

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

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 thicknesses of the deposits. Those on the southern lee-side flanks of rock features are usually thicker than those plastered on the up-ice side.

A depth-to-rock map (Map 3) has been created from the Geological Survey databases. It highlights areas where rock crops out at surface, and depth-to-rock data from borehole records. There are three groups of borehole records which are colour coded according to the degree of confidence in locating the data point. Red coloured data are plotted to within an accuracy of 50 m, the green data are less accurately located and are correct to within 100–500 m, while the blue borehole data are often only referenced by the townland in which they were drilled and accuracies to within 1 km are to be expected.

In general, the thickest deposits are in the drumlin areas of the Devonian sandstone tills on the southern side of the Slieve Aughty hills, the Devonian sandstone and Silurian sandstone and shale tills on the southern side of the Slieve Bernagh hills, and the north-south band of Namurian shale rich tills west of the limestone-Namurian shale boundary. There is also an area of thick Namurian sandstone and shale till towards Loop Head where the till has been deposited in a thick sheet rather than in drumlins. In contrast, deposits in the limestone areas north of Ennis and in the Burren area are usually thin and there is much rock cropping out at surface. Elsewhere, the thicknesses of the tills are often less than 3 m, reaching more than 10 m in the drumlins.

Sand/gravel deposits are usually more than 10 m thick, in particular where they have been laid down with tills as morainic type deposits. Thicknesses of lake, alluvial and estuarine deposits are usually unknown but it is unlikely that they are more than 10 m thick. Peat on higher ground is typically 3 m thick or less. The greatest thickness of peat occurs in former lake basins (e.g. Doonbeg, and the area around Kilkishen-Bodyke) where they are usually between 3 m and 10 m thick.

4 Hydrogeology and Aquifer Classification

Introduction

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

Data Availability

Groundwater data from the GSI, County Council and EPA (Johnstown Castle) files were compiled and all existing well records were entered into the GSI database. Relevant data were obtained from the main hydrogeological consultants and from published hydrogeological reports on Co. Clare. The local well drillers were also visited in an attempt to record some of their experience and knowledge.

The assessment of the hydrogeology of County Clare is based on the following data and reports:

- Information from more than 1200 well records now held in the GSI database.
- Well information for local authority and group schemes sources, and for a limited number of other high yielding private wells, e.g. creameries and industry.
- Information from the well improvement grant scheme.
- Specific capacity data for some wells, mainly local authority owned and grant scheme wells. (Specific capacity is the rate of abstraction per unit drawdown; the unit used is $m^3/d/m$.).
- Pumping tests carried out on wells at 4 of the public supplies as part of this project.
- Findings of two MSc theses carried out in junction with GSI during the course of the project; one on the hydrogeology of Ballyvaughan (Kelly, 1998) and the other on the occurrence of lead in groundwater in the Mountshannon and Whitegate area (Jones, 1998).
- Information on large springs.
- The GSI karst database.
- Reports by engineering and hydrogeological consultants.
- Relevant academic research papers.
- Local drillers' experience.
- General hydrogeological experience of the GSI, including work carried out in adjacent counties and for other groundwater protection schemes.

Rainfall and Evapotranspiration

Mean annual rainfall in Clare for the period 1961–1990 varied from <1000 mm in the lower topographic areas of east and mid Clare to over 1600 mm in the mountainous areas of northwest Clare where the highest rainfall is recorded at the rainfall station on top of the corkscrew hill (Meteorological Service data).

The closest Meteorological Service evapotranspiration station at Shannon Airport calculates the long term mean annual potential evapotranspiration to be 534 mm (Meteorological Service data). Actual evapotranspiration is taken to be about 95% of the potential evapotranspiration and the mean annual potential recharge (rainfall minus actual evapotranspiration) is therefore estimated to be of the order of 500 to 1100 mm, with the lowest levels in the low-lying areas and the highest in the upland areas of northwest Clare.

Groundwater Usage

There are approximately 30 public water schemes in Co. Clare, of which almost half are supplied by groundwater, including the town of Ennis. In total these groundwater schemes abstract in the region of 15,000 m^3/d (3.3 Mgal/d), although the springs supplying Ennis and its surrounds are by far the biggest supply with a current abstraction of approximately 12,000 m^3/d. Based on County Council records for total water consumption in 1998, groundwater contributes 35–40% of the total public water supply in the county (sources summarised in Table 4.1). Areas not served by the County Council and Ennis Urban District Council Water Schemes generally rely on individual private wells as the main source of water supply and therefore the actual proportion of the population in Clare served by groundwater may be significantly higher.

Aquifer Classification

4.1.1 Aquifer Categories

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 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)**

Aquifers are defined on the basis of the following:

- Lithological and/or structural characteristics of geological formations which indicate an ability to store and transmit water. Clean washed and sorted sands and gravels for example, are more permeable than poorly sorted glacial tills. Clean limestones and sandstones are also more permeable than muddy limestones, and sandstones interbedded with shales, respectively. Areas where folding and faulting has produced extensive joint systems tend to have higher permeabilities than areas where this has not occurred.
- Hydrological indications of groundwater storage and movement. For example, the presence of large springs can indicate a good aquifer; the absence of surface drainage can suggest high permeability; and high groundwater base flows in rivers indicates good aquifer potential.
- Information from boreholes, such as high permeabilities from pumping tests, specific capacities (pumping rate per unit drawdown), and well yields.

Table 4.1 Public Supply Groundwater Abstractions in Co. Clare

Supply	Source	Approx. current abstraction		Max. yield in dry summer
Ballyvaughan	Newtown borehole	500 m^3/d	110,000 gal/d	61,000 gal/d
	Acres springs (×3)	136 m^3/d	30,000 gal/d	2 springs dry up. usually >10,000 gal/d
	Turlough borehole	500 m^3/d	110,000 gal/d	62,000 gal/d
Barefield/Crusheen	borehole	30 m^3/d	7,000 gal/d	7,000 gal/d
Bridgetown	Ardataggle borehole	90 m^3/d	20,000 gal/d	20,000 gal/d
	Clonboy dug well (backup)	55 m^3/d	12,000 gal/d	12,000 gal/d
Broadford	spring/mountain stream	65 m^3/d	14,000 gal/d	Goes dry
Carron	Termon springs (×2)	45 m^3/d	10,000 gal/d	1 spring dries up
	borehole (backup)			400 gal/d
Ennis	Drumcliff spring	12,000 m^3/d	2.6 Mgal/d	3.3 Mgal/d
	Pouladower spring (not harnessed)			2.9–13.6 Mgal/d
Feakle	Booley House borehole	91 m^3/d	20,000 gal/d	40,000 gal/d
	Backup Baurroe House boreholes (×2)	22 m^3/d	4,700 gal/d	4,700 gal/d
Kilkeedy/Tubber	borehole	30 m^3/d	6,000 gal/d	6,000 gal/d
Lisdoonvarna	Killeany spring	490 m^3/d	108,000 gal/d	Goes dry. 78,000 gal/d after 3–4 days rain.
	Kilmoon spring/mt stream	410 m^3/d	90,000 gal/d	Goes dry
Killaloe	Garraunboy spring and infiltration gallery	525 m^3/d	115,000 gal/d	115,000 gal/d
Kilrush	borehole (backup only)			120,000 gal/d
Montpellier	borehole	275 m^3/d	60,000 gal/d	70,000 gal/d
Mountshannon	new artesian bore	230 m^3/d	50,000 gal/d	200,000 gal/d
	old spring	230 m^3/d	50,000 gal/d	50,000 gal/d
Scarriff	new borehole	180 m^3/d	40,000 gal/d	60,000 gal/d
	backup reservoir boreholes (×2)	135 m^3/d	30,000 gal/d	28,000 gal/d
Whitegate	springs (×3)	275 m^3/d	60,000 gal/d	60,000 gal/d

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.

4.1.2 Bedrock Aquifers

The bedrock aquifer categories take account of the following factors:

- the overall potential groundwater resources in each rock unit;
- the area of each rock unit;
- the localised nature of the 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'.

4.1.3 Sand/Gravel Aquifers

A sand/gravel deposit is classed as an aquifer if the deposit is more than 10 m thick and is greater than one square kilometre in areal extent. The thickness of the deposit is taken rather than the more relevant saturated zone thickness as the information on the latter is rarely available. In many instances it may be assumed that a deposit with a thickness of 10 m will have a saturated zone of at least 5 m. This is not the case where deposits have a high relief, for example eskers or deposits in high topographic areas, as these gravels are often dry.

Sand/gravel aquifers are therefore classified based on the areal extent of the deposit, the thickness of the saturated zone and the estimated annual throughput (see Table 4.2). The permeability of the deposits can vary considerably depending on how they were laid down so in practice the geological history of the deposit is also considered. Morainic sand/gravel (refer to Section 3.3.2) for example, rarely has a high enough permeability to enable sufficient throughput to be achieved, due to the presence of clays and silts.

4.1.4 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 collapses, caves, swallow holes, sinking streams, turloughs and dry valleys, and a distinctive groundwater flow regime where drainage is largely underground in solutionally enlarged fissures and conduits. The solution is influenced by factors such as: the type and solubility of the limestone; the degree of jointing, faulting and bedding; the chemical and physical character of the groundwater; the rate of water circulation; the geomorphic history (upland/lowland, sea level changes, etc.); and the subsoil cover. One of the consequences of karstification is the development of an uneven distribution of permeability which results from the enlargement of certain fissures at the expense of others and the concentration of water flow into these high permeability zones.

Table 4.2 Sand/Gravel Aquifer Classification

	Regionally important	***Locally important***
Areal extent	> 10 km^2	1-10 km^2
Saturated thickness	> 5 m	> 5 m
Throughput	> 10 Mm^3/a	1-10 Mm^3/a

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 such as FLOWPATH.

4.1.5 Dolomitisation

Dolomitisation is a weathering process where calcium ions are replaced by magnesium ions in the crystal lattice of dolomite ($Ca\ Mg\ (CO_3)_2$). There are two different grades of dolomitisation evident in Clare which have significantly different effects on permeability. The first is the typical well known, highly weathered, yellow/orange/brown dolomitisation which is usually evident in boreholes as loose yellow-brown sand with significant void space and poor core recovery occurring. This type often occurs along fault zones, can cross bedrock lithology boundaries and results in unpredictable very high permeability zones. The other is a less highly weathered, stratigraphically controlled type of dolomitisation which is often a black colour on the surface. This type is considered to be a barrier to groundwater flow. A good example occurs amongst the usually pale coloured Burren Limestones at Black Head in north Clare.

4.1.6 Use of Well Yields in Defining Aquifers

Although the main type of information available for aquifer classification in County Clare is well yields, many other sources of information have been used (for example bedrock lithology, structural deformation, pumping tests, surface drainage and the degree of karstification). It should be remembered that the aquifer delineation is a generalisation which reflects the overall resource potential, and that because of the complex and variable nature of Irish hydrogeology, there will often be exceptionally low or high yields obtained which do not detract from the overall category given to any particular rock unit. It is also important to remember that the top few metres of all the bedrock types are likely to be relatively permeable.

The rock units in County Clare are listed in Table 4.3, together with a summary of the useful well data, the karst features present in each unit, any useful transmissivity data (a measure of the productivity of the rocks) and the aquifer category. The wells (a total of approximately 150) were categorised as 'excellent', 'good', 'moderate', 'poor' and 'failed' for each rock unit. Any available specific capacity data are also given.

Well data are considered to be useful if they indicate high yields, i.e. 'excellent' or 'good', if they are failed wells or if they have a specific capacity, as these enable an assessment of the productivity of the aquifer. It should be noted that in compiling the useful well data there will be a bias towards higher yielding wells for the following reasons:

Table 4.3 Well Yield Categories and Karst Features

Rock Unit	**Well Yield Categories** *number in each category* (available specific capacity data in brackets)					**Karst features** *Number of features*	**Aquifer Category**
	Excellent **>400m^3/d**	**Good** **100-400m^3/d**	**Moderate** **40-100m^3/d**	**Poor** **<40m^3/d**	**Failed** **<2.5m^3/d**		
Glenomra Sands/gravels							**Lg**
Central Clare Group	*3* (35)	*17* (17)	*2* (4,10)				**Ll**
Volcaniclastic rocks							**Lm**
Undifferentiated Visean limestones		1					**Rk^d** S Ennis **Lm** SE Clare **Ll** SW Clare
Gull Island Fm. (incl Ross and Tullig Ssts)	*3* (36,63)	*12*		*3* (<1,1,1)		Windows into underlying lst	**Ll**
Clare Shales						Windows into underlying lst	**Pu**
Slievenaglasha Lst (incl Turret volcanics)		*2*			*7*	*~200*	**Rk^c** N Clare **Rk^d** E Clare syncline
Burren Lst	*2* (>500)	*16* (24,129)	*1* (33)	*6* (<1,<1, 2,2,3,4)	*14*	*~220*	**Rk^c** N Clare **Rk^d** E Clare syncline
Tubber Lst (except Cregmahon Lst)	6 (1724)	*3*	*1* (25)	*2* (1,4)		*18*	**Rk^c** N Clare **Rk^d** E Clare syncline
Finlough Lst **Parsonage Lst** **mudbank lst**							**Ll**
Waulsortian Lst (incl Ballycar, Lough Gur and Cregmahon Lsts		*5* (12)		*5* (<1,<1, 2,7,7)	*3*	*6*	**Ll**
Ballysteen Lst (incl Ballymartin Lst)		*4* (70)	*4* (2,4,9,11)	*4* (<1,<1, 1, 2)	*1*		**Pl**
Lower Lst Shales				*2* (<1,1)			**Pl**
Old Red Sandstone	*1* (artesian)	*7* (17,53,242)	*3* (7,8,15)	*5* (1,1,1, 1,2)	*1*		**Ll** in south **Pl** in north
Silurian		*6* (2, 2, 5, 35, 47)		*11* (4×<1, 3×1, 3,4,6,7)			**Pl**
Ordovician							**Pu**

Notes:

(1) These statistics are biased towards higher yielding sources – mainly Co. Co. and group scheme supplies.

(2) Specific capacity is the rate per unit drawdown. The units are m^3/d/m. The values in brackets are the only specific capacity data available. Where no specific capacity information is available for a well included in the statistics, the yield category indicates the maximum yield.

(3) While there are >1200 well records for Co. Clare, most have neither drawdown data to enable the specific capacities to be calculated, nor maximum yield information.

(4) Karst features include swallow holes, caves, collapses, turloughs, dry valleys, karst springs.

- The most reliable data are those obtained from the County Council for public supplies and these tend to be higher yielding than most wells.
- The majority of wells in the database are privately owned wells which were drilled during the 1960s. The abstractions are usually small, the wells were not properly tested and it is almost always unclear whether the yield given is the maximum supply available or just the amount required by the owner. These data are not therefore used in assessing aquifer categories and are used mainly to give depth to rock and water levels.

Well yields should never be used on their own as the basis for categorising a rock unit as a particular aquifer category. However they are often the main type of data available and they allow the three main aquifer categories to be conceptualised. Regionally important (**R**) aquifers would have (or be capable of having) a large number of wells yielding in excess of approx. 400 m^3/d (4000 gph); locally important (**L**) aquifers are capable of moderate well yields 100–400 m^3/d (1000–4000 gph); and poor (**P**) aquifers would generally have low yielding wells, i.e. less than 100 m^3/d.

The sections that follow examine the hydrogeological information for each rock unit and conclude by giving the aquifer category.

Ordovician Rocks

There are no well data for the red to black mudstones and cherts of Ordovician age, as the rock unit is relatively thin and crops out over a small area in the Slieve Bernagh Mountains. Permeabilities will be low however, as the shale content is high. Fracture zones are also often low permeability as the broken shales tend to fill any voids.

These rocks are classed as **poor aquifers** which are **generally unproductive (Pu)**.

Silurian Rocks

Well records in the Silurian sandstones and shales include six 'good' wells and 11 'poor' wells. The Scarriff and Feakle public supplies draw their water from these rocks and pumping tests were carried on some of the multiple wells in these areas to gain an understanding of the aquifer characteristics.

The new supply at Scarriff has a 'good' yield of approximately 242 m^3/d, a high specific capacity of 43 m^3/d/m, and the 10 hr pumping test returned a relatively good transmissivity of 32–47 m^2/d. The static water level in the borehole is lower than that of the nearby Bow river (12 m distant) and from the temperature and conductivity readings taken during the pumping test, it would appear that the river is not linked to the supply. The other two backup boreholes at the reservoir can yield 127 m^3/d between them (although they are usually pumped one at a time) but by contrast, they have very large drawdowns which gives rise to an inefficient supply.

The new borehole at Feakle was yield-tested over 72 hours at a rate of 170 m^3/d. The drawdown after pumping was relatively small (3.6 m) and the resulting specific capacity of 47 m^3/d/m is indicative of a good supply. The two backup boreholes at the reservoir affect each other when pumped and give a low yield (22 m^3/d) with corresponding drawdowns of more than 50 m.

The other useful data in this unit include a 'good' well east of Woodcock hill with a specific capacity of 35 m^3/d/m, and 8 'poor' wells with yields <45 m^3/d and specific capacities <10 m^3/d/m. The Broadford Supply spring/mountain stream also discharges from these rocks with a small yield of 55 m^3/d which dries up in summer.

In general, the permeability of Silurian rocks is relatively low. Permeabilities in the upper few metres may be higher where the rocks are more weathered but this decreases rapidly with depth. Local zones of higher permeability will be present along fault zones. It is likely that the rocks in southeastern Clare will be somewhat more jointed than in the Slieve Aughty mountains as they have undergone a greater degree of structural deformation, being closer to the Caledonian suture line (refer to Bedrock Geology Chapter). Further evidence of the relatively low permeabilities is provided by the high drainage density and flashy runoff response to rainfall in areas underlain by Silurian rocks.

Groundwater in the Silurian sandstones and shales can be confined by either the clayey till and peat deposits which usually overlie the rocks, or by lower permeability bedrock layers within the sequence. Low lying areas have better groundwater development potential as artesian (flowing) conditions can be encountered and there is good natural protection afforded in the immediate vicinity of the sources by the low permeability materials. Sustainable supplies will be only be accessible from the fault zones.

The Silurian rocks in Clare are classed as **poor aquifers** which are **generally unproductive except for local zones (Pl)**. The rocks in the Slieve Bernagh Mountains may be a little more productive than those in the Slieve Aughtys.

Old Red Sandstone (ORS)

This hydrogeological unit includes all Old Red Sandstone formations. In other counties the upper units of the ORS, e.g. the Kiltorcan Sandstone Formation and the Clonaslee Flagstone/Cadamstown Formation, have been shown to be a more productive unit than the lower rocks. A short reconnaissance study on the ORS in Clare and Limerick carried out by J. Deakin and M. Pracht (Deakin and Pracht, 1998) showed that the more productive units do not appear to be present in Clare as the rocks are of a different lithology.

The Slieve Aughty sandstones appear to have generally ‘poor’ yielding wells, with yields of less than 45 m^3/d and specific capacities less than 2 $m^3/d/m$. There are 5 ‘poor’ wells and one higher yielding ‘good’ well at Derryulk although there is no drawdown with the latter to indicate the actual capacity of the well. It should be noted that the lack of high yielding good wells in these sandstones may be attributable to a bias in the data set due to the lack of demand in north Clare.

The new artesian borehole supply at Mountshannon is located in the Old Red Sandstones. It has a very high yield of 680 m^3/d although this is likely to be influenced by the nearby very large fault. There are also seven ‘good’ wells in these rocks, 6 of which are located in the Slieve Bernagh Mountains. Three of the wells have recorded fairly high specific capacities of 242, 53 and 17 $m^3/d/m$, while two more have relatively high yields of approximately 380 m^3/d. There are also 3 ‘moderate’ wells with specific capacities 8–15 $m^3/d/m$, 5 ‘poor’ wells (specific capacities <2 $m^3/d/m$) and one failed dry well which was drilled to a depth of 182 m to the east of Woodcock hill. GSI records show that one of the moderate wells, located in Cratloe, had a transmissivity of 5 m^2/d when pumped over 72 hours at 56 m^3/d.

The permeability of the ORS in Clare appears to be relatively low due to: (a) the competent nature of the relatively coarse grained sandstones and conglomerates; and (b) the presence of interbedded mudstones and siltstones. Drainage in the areas underlain by these rocks is also often poor with most of the rainfall running off to the nearest surface water course.

Groundwater may be confined in places under the lower permeability units but in general most of the flow is likely to be in the upper few metres of fractured, weathered rock. The optimum area for

groundwater development is likely to be in the vicinity of the boundary with the overlying Lower Limestone Shales where groundwater will be confined. Good supplies may also be obtained where storage is increased by overlying sandy gravelly sediments, e.g. in the Mountshannon area, or where there are relatively low permeability horizons amongst the more permeable sandstones which can create artesian conditions. These rocks are suitable for smaller public supplies and group water schemes provided that the high permeability zones can be located. They may produce iron and manganese problems but otherwise the quality will be good as groundwater residence times are usually longer than the limestones and there is good protection given by both the overlying low permeability rocks and subsoils.

The Old Red Sandstones in the Slieve Bernagh area are classed as a **locally important aquifer** which is **moderately productive only in local zones (Ll)**. The equivalent rocks in the Slieve Aughty area are **poor aquifers** which are **generally unproductive except for local zones (Pl)** as the fracturing intensity decreases to the north. The ORS in Offaly for example is also classed as Pl while the same rocks in Limerick, Tipperary SR and Waterford are all Ll.

Lower Limestone Shales (LLS)

The Lower Limestone Shales is a relatively thin unit with minimal outcrop area and there are few available data to enable the hydrogeological characteristics to be assessed. Two wells are recorded with poor yields (<35 m^3/d) and large drawdowns giving very low specific capacities of <1 m^3/d/m. Another well located at Sunnagh also has a ‘poor’ yield but is reputed to have no drawdown during pumping suggesting that the well is capable of producing much more. The water is likely to be coming from the lower sandstone beds of the unit, equivalent to the Mellon House Beds in other counties.

The high shale content, particularly at the top of the unit, suggests that the permeabilities will be low. The sandstone units at the base of the unit, however, are likely to have a greater degree of fracturing than the more plastic interbedded shales permitting small yields to be obtained in local areas. Bores should preferably be drilled through to the underlying more productive Old Red Sandstone.

The Lower Limestone Shales are classed as a **poor aquifer** which is **generally unproductive except for local zones (Pl)**.

Ballysteen Limestone (BA)

Despite the areal extent of the Ballysteen Limestones, there are just 13 well records with adequate data for the hydrogeological assessment. Four of the wells have ‘good’ yields ranging 109–327 m^3/d. Three of these are located to the south of the county at Shannon, Bunratty and to the south of Woodcock Hill. The Woodcock Hill borehole is recorded as artesian and has a high specific capacity of 70 m^3/d/m which suggests the borehole would be capable of producing a greater yield. The rest of the wells are all located in the East Clare syncline and are classed as ‘moderate’ to ‘poor’ with an average yield of 54 m^3/d and specific capacities ranging from <1 to 11 m^3/d/m. A failed well was also drilled to 52 m into the upper part of the unit north of Fair Green. While these data suggest that the Ballysteen limestones to the south of the Slieve Bernagh Hills are more productive than the equivalent rocks further north, there are insufficient data to substantiate it and therefore both areas are considered together. There are no public supplies located in these rocks.

The permeability of the Ballysteen limestones is variable due to the variations in lithology throughout the succession. The underlying Ballymartin Limestones (usually combined with the Ballysteen

Limestones on the map) have a relatively high shale and muddy limestone content and are considered to be slightly lower permeability than the cleaner limestones of the Ballysteen unit. Towards the top of the Ballysteen Limestones, the rocks become more muddy once more and may have similar permeabilities to the Ballymartin limestones. These rocks appear to be impeding drainage which, while not definitive, can often suggest a low permeability. The Owenagarney/Ratty River system in the area around Sixmilebridge for example is underlain by these rocks.

Groundwater flow in these limestones is often concentrated in the upper few metres of fractured bedrock. The large outcrop in the village at Tuamgraney for example, shows good evidence of solution in these fractures at the surface. The 'good' well in Shannon gets its supply from the interface between bedrock and the overlying glacial deposits. The main supply of water to another well at Feakle was found in cavities at a depth of 24 m below surface, just 3 m into the top of bedrock. An exploration borehole drilled by Irish Base Metals at Bunratty encountered 3 m of karst at the top of bedrock between 7.5 and 10.5 m below ground level. There is also limited evidence for highly permeable zones cavities at depth. Exploration records show dolomitisation zones with associated poor core recovery found near Kilmurry up to depths of more than 400 m below ground level in a 43 m thick zone. In another area just outside the county near Tubber, a 6 m cavity was found at 11 m below ground level and there were other significant cavities found at greater depths.

Groundwater development in the Ballysteen Limestones is often not particularly successful: yields are low and the shales and shaly limestones often give rise to iron and manganese problems. Obtaining good yields depends on locating fault zones and/or dolomitisation at depth. The upper more permeable layer is unlikely to provide sustainable enough supplies for larger wells and will often contain lesser quality water than the deeper permeable horizons.

The Ballysteen Limestone, and the Ballymartin Limestones where differentiated, are classed as **poor aquifers** which are **generally unproductive except for local zones (Pl)**. These rocks are also classed as Pl in Offaly, Tipperary SR and Meath. Further to the south, in Limerick and Waterford, the fracturing is more intense and the same rocks are classed as Ll. Cleaner limestone units were also found in the succession in Limerick which served to increase the permeability there.

Waulsortian Limestone (WA)

There are only 14 wells providing useful information to assess the Waulsortian Limestones for their aquifer potential, so the general characteristics of the rocks and the degree of karstification have been primarily used.

There are 3 failed wells drilled to depths of 55–98 m below ground, although all three were located on the same site east of Tulla. Within 500 m of these boreholes, two successful wells were drilled to similar depths achieving 'good' yields of 110 and 260 m^3/d. The old Tulla Public Supply borehole which had a 'good' yield with a low specific capacity of 12 $m^3/d/m$ and a low transmissivity of 13 m^2/d, is also located in the same region. Contamination in this well was proved by tracing tests to be coming from slurry from a nearby farmyard to the north of the source and the well is consequently now abandoned. Two other wells drilled at the Kilbreckan Calcite mine site also had ‘good’ yields although there are no specific capacity data. The remaining 5 useful wells all have ‘poor’ yields with low specific capacities of <7 m^3/d/m, including the public supply borehole at Crusheen.

Karstification in these rocks is reported by David Drew in the Kilbreckan Calcite EIS. While it is not as extensive as found in north Clare or in other rock formations, some solutionally enlarged joints were found in fields near Ballyhickey Mine. The GSI karst database also shows a cave at the boundary with the Ballysteen limestones in the Tulla area and a nearby collapse feature.

An exploration borehole drilled by Irish Base Metals just south of Tulla (Grid ref: 15004, 17791) encountered a 2 m karst tunnel at a depth of 15 m below ground surface, approximately 10 m into bedrock. Reports from County Council staff would suggest the presence of swallow holes close to the old public supply well and that the nearby lake is spring fed. Further evidence is given for the spring fed lake in a report by KT Cullen and Co. (1985), where they analysed the water from the lake and found it to be hydrochemically similar to the borehole. There was also a sand filled cavity recorded in the borehole log at 8.5 m below ground level.

In the Tulla area, permeabilities in the Waulsortian limestones appear to be quite localised, probably related to the faulting and/or the karstification. Good wells can be developed for small public supplies and group schemes if these zones can be located. A hydrogeological investigation would be critical to achieve good results. There is also slightly more subsoil cover in this area than in other limestone areas which will provide good protection for groundwater. Elsewhere the permeabilities appear to be relatively low for clean limestones which is likely to be a consequence of the massive bedding typically found in these rocks. In other counties, e.g. Tipperary and Offaly, the absence of severe faulting and/or karstification in the equivalent rocks has yielded similar results.

The Waulsortian rocks are classed as a **locally important aquifer** which is **moderately productive only in local zones (Ll).** The karstification appears to be quite localised in the Tulla area and while better yields may be achievable in conduits in that area, the rocks are not considered to be regionally important.

Cregmahon Limestone (TUcm), Ballycar Limestone (BC) and Lough Gur Limestone (LR)

There are no hydrogeological data for the Cregmahon, Ballycar and Lough Gur Limestones as they are of quite limited areal extent and comprise a series of relatively thin rocks draped over the Waulsortian reef mounds. The lithologies of the rocks, however, being highly silicified, fine grained cherty limestones with shale partings, would suggest that permeabilities should be relatively low. Chert bands have been shown further up the limestone succession to be barriers to groundwater flow. Groundwater will preferentially flow along the bedding planes of these rocks until a significantly large fracture or conduit is intercepted (Drew, 1990). Successful groundwater development in areas underlain by these rocks will be dependent on penetrating a permeable bedding plane within or above the rocks, or by drilling through them completely to the underlying Waulsortian Limestone.

These rocks are all classed as **locally important aquifers** which are **moderately productive only in local zones (Ll)**.

Finlough Limestone (FL), Parsonage Limestone (PA), 'mudbank limestone' ('mk')

Data are also lacking for the Finlough, Parsonage and mudbank limestones, due to their limited areal extent and location in a sparsely populated area to the west of the Shannon Estuary.

The Finlough and Parsonage rocks were laid down in slightly deeper water environments on the edge of a basin which gives rise to interbedded shaly limestones and shales. The 'mudbank limestones', while they are a shallow water deposit, were laid down in muddy waters and are a massive unit. Permeabilities of these rock types are usually relatively low and obtaining groundwater sources are dependent on locating a fault zone or some cleaner beds within the sequence.

The equivalent rocks in Co. Limerick on the other side of the same basin (the Muddy Shelf Limestones) were classed as **locally important aquifers** which are **moderately productive only in local zones (Ll)** (Deakin et al., 1998) and this classification is therefore also adopted here.

Tubber Limestone (TU), Burren Limestone (BU), Slievenaglasha Limestone (SL)

The Tubber, Burren and Slievenaglasha Limestones are widespread over the county, comprising most of the limestone areas around Quin, Ennis, Corrofin, Ruan, Tubber, Carron, Ballyvaughan, and a narrow band stretching around Slieve Elva as far south as Doolin. They are considered together as a single hydrogeological unit as the groundwater characteristics are similar in each and groundwater flows readily across the boundaries.

These rocks have been studied in great detail in the past as they are responsible for the distinctive characteristics of the Burren and are hydrogeologically very interesting. The following data sources have been reviewed to gain an understanding of the groundwater flow regime which is presented here in summary. The reader is referred to the original data sources for a more detailed description of the hydrogeological characteristics of the area, in particular to two specific summary papers on Clare written by David Drew (1988, 1990).

- GSI well database
- GSI karst database
- Pouladower, Drumcliff and Ballyvaughan Source reports (Deakin, 1999; Deakin, 1999; Cronin et al, 1999)
- Clare Calcite, Kilbreckan EIS
- A report by David Drew to OPW on Mullaghmore Interpretative Centre (Drew, 1991).
- David Drew's research in the Burren and Upper Fergus catchment (e.g. Drew 1988, 1990, 1992).
- Catherine Coxon's work in the Lower Fergus catchment (e.g. Drew et al, 1995; Coxon and Drew, 1998).
- A report by Donal Daly and David Drew on groundwater and karstification in mid Galway, south Mayo and north Clare (Drew and Daly, 1993).
- An MSc. thesis by Denise Kelly on the Hydrogeology of the Ballyvaughan Valley (Kelly, 1998).
- A GSI report by Donal Daly on the flooding in the Gort-Ardrahan area (Daly, 1992).
- The report by Southern Global Water to the OPW on the flooding in the Gort area (Southern Water Global Ltd./Jennings O'Donovan and Partners, 1997).
- County Council data for public supplies including Killeany Spring, Kilkeedy/Tubber, Turlough and Carron, and County Council staff's local knowledge.

- Experience gained on various hydrogeology field trips in Clare, in particular with European karst experts working on similar topics.

The general characteristics of these rocks are typical of a highly karstified regime*:
- the lithologies are all clean, pale to medium grey limestones;
- there are many karst features such as swallow holes, collapses, turloughs, dry valleys, closed depressions and limestone pavements evident at the surface;
- there are extensive cave systems; much of the upland area has no surface water drainage and the low lying areas are subject to flash flooding during periods of heavy rainfall;
- many boreholes have been drilled which are dry; groundwater flows in a highly unpredictable manner and there is often no water table as can be found in other aquifer types;
- groundwater quality is variable and often contains bacteria;
- the region is drained by a small number of very large springs, some of which discharge at sea; and
- the discharges of these springs are highly variable from low to high stage conditions.

The groundwater in the area flows in three main hydrogeological regimes: (1) the epikarst; (2) discrete conduit flow systems; and (3) more dispersed fissure/joint networks

4.1.7 Epikarst Flow

The epikarst is an upper, shallow, highly karstified weathered zone in which groundwater moves rapidly through a dense network of solutionally enlarged conduits, in direct response to recharge. This upper, highly permeable unit is usually directly connected to the underlying groundwater via relatively widely spaced, individual, solutionally enlarged shafts. In times of extremely heavy rainfall, the shafts often cannot drain the epikarst quickly enough and the area may be subjected to a brief flood. It is likely that this is what happened in Ballyvaughan during the heavy rainfall in August 1997 and 1998, for example.

The epikarst is thought to have developed from solution occurring since the last ice age. It forms under thin soils or organic material due to the action of carbonic and other acids, facilitate the solution process. It does not appear to be present under areas of thicker glacial tills as they inhibit the dissolution process. This can be seen in a coastal section at Pollsallagh, northwest of Lisdoonvarna, where the glacial material is exposed over a smooth bedrock surface.

Good examples of epikarst can be seen over most of the bare rock areas of the Burren where solution has created the characteristically large klints and grikes.

4.1.8 Discrete Conduit Flow Systems

Underneath the shallow epikarst, the flow system is somewhat different. Groundwater moves through solutionally enlarged conduits and cave systems and discharges from the aquifer via discrete points, usually large springs. The group of springs at Kilnaboy are such an example. Elmvale spring is the largest and most persistent of these. It has a low flow of 320 l/s (27,600 m^3/d) and drains approximately 60% of the water in the Burren (Drew, pers comm). Submarine springs are also common, for example the large springs off the coast at Ballyvaughan and Pollsallagh.

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*Note that although there are less karst features recorded for the Tubber Limestones than for either the Burren Limestones or the Slievenaglasha limestones, these rocks are less well studied than the latter and there may be bias in the data set. There is also less coverage of this unit on the ground.

Groundwater flow through these systems is controlled by bedrock lithologies, the dip direction of the bedding planes, and structural deformation. The less permeable units such as the cherty and black dolomitic layers, and the clay wayboards inhibit vertical movement. Groundwater flows along the surface of these beds in the direction of dip of the rocks, until it intersects a vertical fracture or conduit which allows it to flow downwards to the next level. This creates the step-like characteristics of many of the cave systems throughout the county and is also responsible for the lack of a true water table and the many failed wells. A well recently drilled in Carron, for example, some 10 km from the coast, was drilled close to sea level before a water supply was found. Another well drilled in the same region encountered a small supply, at moderate depth, above one of the impermeable layers. The borehole was deepened in an effort to find a larger supply but on penetrating the low permeability bed, the water flowed down the borehole to a deeper system and the well failed. Another good example is the cherty bedrock layer which trends in a north-south direction between the Drumcliff and Pouladower Springs and appears to be playing a major role in separating the two groundwater catchments.

The fracturing over most of the area is principally in the north-south and east-west directions (northeast-southwest in the East Clare Syncline) and this controls zones of high permeability. The Drumcarron More and Poulacorey swallow holes which have been traced to Drumcliff Springs, and which lie directly west and north of the source respectively, may well be located along such fracture related high permeability zones. Similarly, the main flow to the Ballyvaughan borehole is likely to have a predominantly due north-south component.

Groundwater travel times through the conduits are rapid (up to 240 m/h in the Lower Fergus Valley) although it appears that flow in the east-west direction may be slower than that which is north-south. There is evidence for high velocity relatively shallow flow in the waters which discharge at Lough Aleenaun, from the south eastern Poulacapple Hill and Meggagh areas. The response time to rainfall is short and the flow velocities are likely to be high as considerable quantities of coarse sediment are carried in the spring waters under flood conditions. This sediment is interpreted as a reworked version of the subsoil infill found in many of the caves of the area, e.g. the Poulcarry Caves of the Meggagh depression (Drew, 1988).

This karst regime is likely to be a remnant of not only recent solution, but also glacial and pre glacial solution.

4.1.9 Dispersed Fissure/Joint Slow Flow System

A more dispersed, slower groundwater flow component is present in smaller joints and fissures outside, but usually linked to the main conduit systems. At very low flow conditions, more of the groundwater will be moving through these fissures than in the larger conduits. This slow flow component provides the constant base flow in the rivers throughout the area in dry weather.

All three groundwater flow regimes will be hydraulically connected in places with the degree of interconnection being dependent on the presence or absence of less permeable bedrock units and the joints associated with the structural deformation, particularly the north-south and east-west fault systems.

4.1.10 Surface Water/Groundwater Interaction

Within the areas underlain by these rocks, there is a high degree of interconnection between surface waters and groundwaters. The Fergus River, for example, although it now has two artificial stretches of channel, at one time did not have a continuous path to the sea. There are a number of sinks and rises along its course and depending on climatic conditions, at any given site the river water may be recharging the groundwater system or vice versa. The effects of heavy rainfall can be seen in the water quality at Drumcliff Spring within two days and this also highlights the sensitivity of the system.

Particular effects of surface water on the groundwater system are seen in the limestone areas adjacent to the Upper Carboniferous Clare Shales. The shales, and overlying sandstone and shale units, are of much lower permeability than the limestones, and most of the effective rainfall runs off in surface water streams to the lower lying limestones. The shaly rocks give rise to a highly acidic water which dissolves the carbonate rocks. This has resulted in a ring of swallow holes, sinks and large cave systems at the boundary between the two units where karstification processes are still active today.

4.1.11 Degree of Karstification

The available evidence would suggest that these rocks can be divided into two different hydrogeological subunits for the purposes of groundwater development: (a) the Burren to Ennis Limestone Group; and (b) the East Clare Syncline Limestone Group. The dividing line between them is somewhat arbitrary and is based on the maximum known extent of the Clare Syncline faulting, with some slight modifications based on the Kilbreckan data. It is likely that in reality there is a transition zone between them.

The Burren to Ennis Limestone Group

The Burren to Ennis Limestone Group is characterised by a more extreme degree of karstification than the East Clare Syncline. Groundwater flow is rapid and localised. There are large cave systems throughout and groundwater flows in a highly unpredictable manner which can vary significantly with different flow conditions. Even though recharge is high due to the high rainfall, low evapotranspiration and shallow or bare rock, and despite the large volumes of groundwater flow through the limestones, storage capacity is low and there are few successful boreholes, e.g. in the Ballyvaughan area 11 boreholes were drilled before an adequate public supply was obtained. Three of these were contaminated and most of the others had inadequate yields. In the upland areas of the Burren, about 50% of wells drilled for domestic supplies fail (Drew, 1992). In the lowland areas, the concentration of groundwater flow is highlighted by the presence of large springs. While hydrogeological investigations, using techniques such as geophysics, would increase the likelihood of locating conduits and successful wells, groundwater development using boreholes is difficult. Springs are the best option for groundwater development, whether by using the overflow, deepening or drilling in the vicinity. However, they usually have a flashy flow regime, with high turbidity and occasionally high iron from surface water flowing off the Namurian rocks.

The East Clare Syncline Limestone Group

The East Clare Syncline Group is also highly karstified in places, for example the Rine River at Quin has large springs, swallow holes, estavelles and caves associated with it. Some of the bedrock units however, are slightly darker and more shaly in places and this appears to have restricted the overall development of the more intensive type of karstification that is prevalent in north Clare. From the relatively limited data, it would appear that there is a better success rate in locating a successful borehole in this area. At the Kilbreckan Calcite mine for example, 9 excellent or good wells were drilled within the local area of the mine. Weekly water level monitoring for over a year in 8 boreholes showed an average water level fluctuation of 2.4 m [1.76–4.2 m]. A groundwater gradient of 0.007 was estimated and the area was modelled using a conventional flow model; this would not have been possible in north Clare. Bedrock permeabilities were found to be an order of magnitude greater in the top 30 m and the transmissivity calculated from a short pumping test was 20 m^2/d. There is also a more extensive glacial deposit cover which may have hindered more recent karst development. In addition, borehole logs show evidence of loose dolomitised sand in sand filled cavities; this dolomitisation is likely to significantly increase the permeability. The fault pattern is also slightly different with a main northeast-southwest direction and several cross-fault joint sets. This is likely to create a better network of fracturing which may be influencing groundwater flow.

The rocks of the Tubber, Burren and Slievenaglasha Limestone Formations are classed as **regionally important karst aquifers**. The rocks in the East Clare Syncline are likely to have better groundwater development potential and are grouped in the **Rk^d** subcategory, while the rest of the rocks are classed as subcategory **Rk^c**. The Turret volcanic rocks (SLtu) are classed with the rest of the Slievenaglasha rocks as the outcrop area is small and there are no specific hydrogeological data available.

Visean Limestones (VIS)

There are almost no data for any of the undifferentiated limestones of Visean age due to lack of drilling and exposure, and the lack of demand for water in those areas. Experience in other counties and the likely lithology assessed from the surrounding rocks therefore form the basis for the classifications.

In the area south of Ennis, the rocks are classed as **regionally important karst aquifers** which have good developmental potential (**Rk^d**) as the rocks are likely to be similar to the adjacent Burren and Tubber limestones of the East Clare Syncline. There is also one good well recorded at Dromoland although there is no specific capacity value.

To the west of the Fergus estuary where the lithology is likely to change to the deeper water, dark grey shaly limestones similar to the Finlough, Parsonage and mudbank Limestones, the rocks are classed as **locally important aquifers** which are **moderately productive only in local zones (Ll)**;

The Visean rocks in southeast Clare around Parteen are classed as **locally important aquifers** which are **generally moderately productive (Lm)** as they are equivalent to the Clean Shelf Limestones in Limerick. This classification was adopted there on the basis of limited well records, the lithology of the rock and the likely extent of karstification (Deakin et al., 1998).

Volcaniclastic Rocks (v)

These rocks are very small in outcrop and hydrogeological data are lacking so they are therefore given the same classification as the surrounding rocks, the southeast Clare undifferentiated Visean rocks: **locally important aquifers** which are **generally moderately productive (Lm)**. This is also the classification given to equivalent nearby volcanic rocks in Limerick (Deakin et al., 1998).

Clare Shales (CS)

There are no well data for the Clare Shale Formation as the rock unit is relatively thin and crops out in a thin band between the rest of the Namurian rocks and the limestones.

Permeabilities will be low however, as the shale content is high and the plasticity of the rocks will reduce fracturing. Surface streams are common and runoff over the Clare Shales is high which is also indicative of a low permeability.

The minerals in the shales give rise to acidic surface runoff which has a high eroding capacity by the time it reaches the adjacent, lower lying Slievenaglasha limestones. The boundary between the two units is typified by an extensive series of swallow holes and collapses where surface waters can get direct rapid access to the limestone groundwater system. A number of the larger limestone cave systems also commence at the boundary, e.g. the Poulelva/Poulnagollum cave which extends several kilometres into the limestones.

These rocks are classed as **poor aquifers** which are **generally unproductive (Pu)**.

Ross Sandstone (RS), Gull Island Formation (GI), Tullig Sandstone (TS), Central Clare Group (CCG)

The Upper Carboniferous Namurian rocks which includes the Ross Sandstone, Gull Island Formation, Tullig Sandstone and the Central Clare Group are all classed together as a single hydrogeological unit as the rocks all have the same lithological characteristics and appear to behave in a similar manner. They occur in a very large area covering most of west Clare and there are a large number of useful well data. The Lisseycasey and the old Kilrush, Kilkee and Kilmihil sources are all located in these rocks.

There are six 'excellent wells recorded in these rocks, three of which have relatively high specific capacities ranging from 35 to 63 m^3/d/m. One of these is the Kilrush supply however, where there may be extra storage in the local gravels. There are also 29 'good' wells with one specific capacity recorded of 17 m^3/d/m. Many of these good wells are the old local creamery wells. There were four low yielding wells recorded: two 'moderate' wells with specific capacities of 4 and 10 m^3/d/m and three 'poor' wells with very low specific capacities of <2 m^3/d/m. Of the not so useful data, there seem to be a relatively high number of moderate yielding wells, more so than in other parts of the county. This may indicate that slightly higher yields were obtainable than would normally be expected, or perhaps just that the demand was greater in the west due to a higher number of farms relative to domestic houses.

Permeabilities in these rocks are highly variable due to the range of bedrock lithologies present. While there is a degree of reasonable permeability in the upper few metres of rock, the higher permeabilities are usually in the more competent sandstone units at depth. In many of the wells the water is confined, probably by overlying lower permeability shale units, and the wells are often overflowing. Permeable zones are met at deeper levels than in other rocks. In a 3 km deep exploration borehole drilled by Ambassador Oil near Doonbeg, for example, water was struck at 107 m and then intermittently until a depth of 610 m.

Well development is often down to random drilling in these rocks due to the variations in lithologies and presence of confining layers. Groundwater travel times are relatively slow and the bacteriological quality is usually good if the well is properly sealed in the upper few metres. There is a high risk of potential contaminants moving through the upper few metres of rock, perched on top of a low permeability layer, and then travelling down the outside of the well. The shaly nature of the rocks however, often gives rise to high iron and manganese and this can pose problems for domestic users.

The Upper Carboniferous Namurian rocks, including the Ross Sandstone, the Gull Island Formation, the Tullig Sandstone and the Central Clare Group are all classed as **locally**

important aquifers which are **moderately productive only in local zones**. The rocks of the Ross Sandstones, the Gull Island Formation, the Tullig Sandstones may be slightly more productive due to their higher percentage of sandstones and siltstones rather than shales but it would not be justifiable to class these rocks in a higher category on the basis of the relatively poor drainage characteristics of the areas.

Sand/Gravel Aquifers

None of the sand/gravel deposits in Co. Clare is large enough, or clean enough, to be considered a regionally important aquifer. There is however, one area between Broadford and Bridgetown in the Glenomra River valley which may have potential for development as a locally important aquifer. There are no borehole records for the area and therefore the saturated thickness is not known. The deposits are clean, washed sands and gravels which are more than 10 m thick, and with the high permeability and relatively high rainfall in the area it is expected that the throughput may be great enough to provide adequate local supplies.

Site investigation may also prove other sand/gravel deposits to be aquifers, but in the absence of more detailed information, the smaller deposits, those of unknown thicknesses or suspected thin saturated zones, those mapped as morainic sand/gravel and those which are interfingered with glacial tills are not included here. Some of the larger morainic deposits may prove, on further investigation, to have lenses of cleaner gravel within them which meet the classification criteria.

Summary of Aquifer Categories

The aquifers in County Clare are summarised in Table 4.4.

Table 4.4 Aquifer Classifications

Aquifer Category	Subdivision	Geological Unit
Regionally important (R)	Sand/gravel (**Rg**)	n/a
	Karst (**Rk**) **Rk**[c] Development potential limited by concentration of flow **Rk**[d] Good development potential	Slievenaglasha, Burren and Tubber Lsts (Burren to Ennis area). Slievenaglasha, Burren and Tubber Lsts (East Clare Syncline area). Undifferentiated Visean Lsts (S Ennis)
	Fissure flow (**Rf**)	n/a
Locally important (L)	Sand/gravel (**Lg**)	Glenomra River Valley gravels
	Bedrock which is generally moderately productive (**Lm**)	Undifferentiated Visean Lsts (SE Clare) Volcaniclastic rocks
	Bedrock which is moderately productive only in local zones (**Ll**)	Central Clare Group (Namurian) Tullig Sandstone (Namurian) Gull Island Formation (Namurian) Ross Sandstone (Namurian) Finlough Lst Parsonage Lst and mudbank lst Undifferentiated Visean Lsts (SW Clare) Lough Gur Lst Ballycar Lst Cregmahon Lst Waulsortian Lst Old Red Sandstone (Slieve Bernagh)
Poor (P)	Bedrock which is generally unproductive except for local zones (**Pl**)	Ballysteen Lst Ballymartin Lst Lower Lst Shales Old Red Sandstone (Slieve Aughty) Silurian
	Bedrock which is generally unproductive (**Pu**)	Clare Shales Ordovician

5 Groundwater Vulnerability

Introduction

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 (DELG/
EPA/GSI, 1999).

The vulnerability of groundwater depends on the time of travel of infiltrating water (and contaminants), on the relative quantity of contaminants that can reach the groundwater and on 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 type and permeability of the subsoils that overlie the groundwater;
(ii) the thickness of the unsaturated zone through which the contaminant moves; and
(iii) the recharge type – whether point or diffuse.

Details on the hydrogeological basis for the vulnerability assessment can be obtained from the DELG/EPA/GSI publication on Groundwater Protection Schemes (DELG/EPA/GSI, 1999). In summary, the entire land surface is divided into four vulnerability categories: extreme (**E**), high (**H**), moderate (**M**) and low (**L**), based on its geological and hydrogeological characteristics. The vulnerability 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. The map is intended for use as a guide to indicate the likelihood of contamination of groundwater if a contamination event occurs. It does not replace the need for site investigation. The characteristics of individual contaminants are not considered.

Outside the areas where point recharge is occurring, e.g. swallow holes, the vulnerability depends on the type, permeability and thickness of the subsoils. Each subsoil type as described in Chapter 3, is assessed here in terms of its permeability. The vulnerability map is then derived by overlaying the permeability categories with the depth to rock. There are three subsoil permeability categories: high, moderate and low; and four depth to rock categories: <3 m, 3–5 m, 5–10 m and >10 m. The resulting vulnerability classifications are shown in Table 5.1.

Sources of Data

Specific vulnerability field mapping and assessment of the data collected during the subsoils mapping programme were carried out. The field work was focused on assessing the permeability of the different deposit types, as depicted on the subsoils map, so that they could be subdivided into the three permeability categories. This involved the following:

Table 5.1 Geological and Hydrogeological Conditions Determining Vulnerability Mapping Categories

Subsoil Thickness	Hydrogeological Requirements				
	Diffuse recharge Subsoil permeability and type			Point Recharge	Unsaturated Zone
	high permeability (*sand/gravel*)	moderate permeability (*sandy subsoil*)	low permeability (*clayey subsoil, clay, peat*)	*(swallow holes, losing streams)*	(*sand & gravel aquifers only)*
0–3 m	**Extreme**	**Extreme**	**Extreme**	**Extreme (30 m radius)**	**Extreme**
3–5 m	**High**	**High**	**High**	**N/A**	**High**
5–10 m	**High**	**High**	**Moderate**	**N/A**	**High**
>10 m	**High**	**Moderate**	**Low**	**N/A**	**High**

Notes: (i) N/A = not applicable.
(ii) Permeability classifications relate to the material characteristics as described by BS5930.
(iii) Release point of contaminants is assumed to be 1–2 m below ground surface.

(adapted from DELG/EPA/GSI, 1999)

- describing selected exposures/sections according to the British Standard for Site Investigations (BS5930:1981), taking account of the new draft revised standard (Norbury, 1998).
- taking additional samples for full particle size analysis in complex permeability boundary areas. (Hydrometer tests, which separate the silt and clay particles are expensive. Most of the particle size data are therefore sieve analyses, where the silt and clay are grouped together as total percentage fines.)
- assessing the recharge characteristics of selected sites using drainage, vegetation and other secondary indicators;
- specific work at Kilnamona in association with two concurrent joint GSI/TCD MSc. research projects on vulnerability mapping. This work used various geophysical techniques to delineate the permeability boundary across the limestone/shale boundary; and
- specific work at Newtown near Bodyke, also in association with the two MSc projects, where a borehole was drilled to carry out some permeability measurements, and recharge assessments were made in the surrounding area.

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

- the subsoils data and maps, and the contoured depth to bedrock data produced during the 3 year mapping programme (see subsoils chapter);
- the soils map produced by An Foras Talúntais (1971);
- the bedrock geology map (see bedrock chapter);
- the GSI karst database;
- the GSI well database; and
- experience gained from the two MSc research projects both of which included parts of Co. Clare in the study areas (Lee, 1999; Swartz, 1999).

Permeability of the Subsoils

The permeability categories, and resulting vulnerability categories depicted on the vulnerability map (Map 6), are qualitative regional assessments of the subsoils based on how much potential recharge is infiltrating and how quickly potential contaminants can reach groundwater. The permeability of subsoils is largely a function of (a) the grain size distribution; (b) the amount (and occasionally type) of clay size particles present; and (c) how the grains are sorted and packed together. It can also be influenced in places 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. In poorly sorted sediments, which are the most common subsoils in Clare, these characteristics also determine the engineering behaviour of the materials (Swartz, 1999) as described using the British Standard for Site Investigations BS5930:1981 and the draft revision (Norbury, 1998). This standard is therefore used to assess the permeability of the subsoils at each exposure, but is supported by recharge and drainage observations in the surrounding area for a regional, three dimensional classification.

Each of the approaches used in assessing the permeability is discussed briefly here. Some of these are described in more detail in the research theses (Lee, 1999 and Swartz, 1999):

1. *BS5930.* Using BS5930, subsoils described as sandy CLAY or CLAY have been shown to behave as low permeability materials. Subsoils classed as Silty SAND and sandy SILT, on the other hand, are found to have a moderate permeability (Swartz, 1999). In general, sands and gravels which are sorted and have a low fines content are considered to have a high permeability. In some instances it was found that subsoils described as 'clayey SAND' or 'clayey GRAVEL' had a high enough proportion of clay to behave as low permeability materials.
2. *Particle size analyses.* The particle size distribution of the sediments describes the relationships between the different grain sizes present. Evaluation of the 400 grain size analyses for the county have shown that each of the glacial till types have a number of distinct grain size characteristics which have in turn influenced the permeability. Samples with less than 35% silt and clay for example have a moderate permeability. Samples with more than 35% fines are more variable and the permeability depends on the amount of clay present and the distributions of the silt and sand grains. Once the general characteristics and variations have been identified, these can be extrapolated to other similar areas where vulnerability observations may be lacking.
3. *Parent material.* The parent material, in this case the bedrock, plays a critical role in providing the particles which have created the different subsoil permeabilities. Sandstones, for example, give rise to a high proportion of sand size grains in the deposit matrix, clean limestones provide a relatively high proportion of silt, while shales, shaly limestones and mudstones break down to the finer clay size particles. A good knowledge of the nature of the bedrock geology is therefore critical. It is also useful to know the direction of movement of the glaciers and the modes of deposition of the sediments as these will dictate where the particles have moved to, how finely they have been broken down, and what the relative grain size make up and packing are. Understanding the processes at work enable predictions to be made where observations are lacking.
4. *Recharge characteristics.* Examining the drainage and recharge characteristics in an area gives an overall representative assessment of the permeability. Poor drainage and vegetation suggest low permeability subsoils once iron pans, underlying low permeability

bedrock, high water tables, and excessively high rainfall can be ruled out. Well drained land on the other hand suggests a moderate or high permeability once artificial drainage is taken into consideration (Lee, 1999).

5. *Soils map.* The soils map of Co. Clare was used to assess drainage characteristics where specific site recharge observations were not available. Poorly drained soils such as gleys can often be related to underlying low permeability subsoils, while the more free draining soils such as the brown earths and grey brown podzolics are more typical of the sandy and silty moderate permeability subsoils.
6. *Quantitative analysis.* In quantitative terms, the boundary between moderate and low permeability deposits is estimated from limited piezometer data over the country to be in the region of 10^{-9} m/s at the field scale (Swartz, 1999). The moderate to high boundary has not yet been looked at in detail and there are no equivalent measured data available. 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. A qualitative assessment incorporating the engineering behaviour of the subsoils and recharge characteristics is more appropriate for regional vulnerability mapping, 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. Each subsoil type and the range in permeabilities in Co. Clare is discussed, and is summarised at the end in Table 5.2.

5.1.1 Tills

Till deposits in County Clare have a widespread distribution and are derived from a number of different bedrock types. As tills are poorly sorted sediments, often with a high percentage of fines (silt and clay), they usually fall into either the moderate or the low permeability category. The permeabilities of each till type are briefly discussed.

Limestone Tills

The wide variation in parent material, from clean limestones such as those in north Clare to the darker, more shaly limestones in the East Clare Syncline and west of the Fergus Estuary, and the Clare Shales in the Kilnamona and Kilfenora areas, has resulted in a range of permeabilities within the limestone tills. These are briefly discussed here with reference to the subsoils chapter (Section 3.3.1.1).

Deposits derived from the clean limestones of the Slievenaglasha, Burren and Tubber rocks are characterised by a high proportion of silt relative to clay, as there is little shale material present in the rocks to provide the clay. Drainage in these areas is usually good and the predominant soils are well drained brown earths and rendzinas. Using BS5930, the subsoils are classed as firm to stiff, pale brown to light grey, sandy SILT which equates to a moderate permeability. Good examples can be seen in the cliff section next to the river in the Caher Valley in north Clare.

Subsoils overlying the more shaly limestones, such as the Ballysteen rocks, are less well exposed and are consequently less well understood. The rocks are also of relatively limited areal extent and being located in the low lying areas adjacent to the Old Red Sandstone hills (e.g. in the Scarriff area), it is probable that the subsoils in these areas are influenced by both Ballysteen Limestone and ORS derived material. This gives rise to a complex subsoils make up and an absence of extensive areas, such as in the Burren, where the subsoils have a relatively uniform composition. Close to the shaly bedrock, the clay particles from the shales and shaly limestones have been incorporated into the tills creating a dark coloured, plastic, clayey deposit which is categorised as BS5930 sandy CLAY and has a low permeability. Borehole records show that these low permeability subsoils are often relatively thin in places directly overlying the shaly bedrock, and are overlain by a slightly different, more permeable material. Where subsoils reach more than 10 m thick, they are usually overlain by the relatively well drained grey brown podzolics of the Elton Series which indicates better drainage and a slightly higher permeability overall. In some areas, however, recharge observations suggest that there are also thicker areas of low permeability material present. These subsoils are complex and may straddle the boundary between moderate and low permeability. The differentiation and distribution of the two permeability types is not well understood and therefore they are conservatively categorised as moderate permeability where appropriate observations are lacking.

Limestone tills located in the Kilfenora and Kilnamona valleys, and west of the limestone/Clare Shales bedrock margin, have been heavily influenced by the underlying soft Clare Shales which have contributed a relatively high percentage of clays to the deposit matrix. The predominant soils in these areas are poorly drained gleys, and moderately drained grey-brown podzolics with a high clay content (An Foras Talúntais, 1971). Drainage and vegetation indicate that there is relatively low recharge and the BS5930 descriptions are typically sandy CLAY or CLAY. These deposits are classed as low permeability.

The shallow coarse, sandy gravelly limestone tills are classed as BS5930 sandy GRAVEL. The associated soils are usually free draining brown earths and grey brown podzolics, and the drainage and vegetation suggest well drained conditions. These deposits are classed as moderate permeability as they are poorly sorted and contain sufficient fines that on the whole, they can not be classed as high permeability, although there may be occasional pockets of high permeability material present. Examples are found overlying much of the clean limestone bedrock where the subsoils are relatively thin, for example in the area west of Drumcliff Spring.

Devonian Tills

The Devonian Old Red Sandstone bedrock also comprises a number of different lithologies which are, in part, reflected in the overlying tills. The mode of deposition of the deposits which is highlighted by the density and compaction of the materials, is also important. The primary constituent of the tills is sand, derived from the sandstones, but there is also a high percentage of clay in places from the mudstones and the more shaly layers. There are two permeability categories in these deposits corresponding to the two deposit types as described in Section 3.3.1.2.

The clayey sandstone tills are common in east Clare on the southern sides of the mountains where the sandstones are located, particularly in the drumlins. These subsoils are classed as very stiff, very sandy CLAY, sandy CLAY and clayey SAND using BS5930, and are associated with poorly drained gleys and peats. The clay contents are significantly high enough that the deposits behave as low permeability materials. The valley south of Knockaphunta in southeast Clare for example, is underlain by these deposits.

The looser, more free draining sandy deposits are described as soft SAND or silty SAND using BS5930 and are considered to be moderate permeability. These deposits are associated with free draining brown earths and brown podzolics, but also, in places, with the poorly drained gleys mentioned above. Where the gleys are present, borehole records and sections have shown that the sandier deposits are often only a few metres thick and are draped over underlying low permeability sandy CLAY. The overall composite or three-dimensional permeability is determined by the recharge conditions at the site, which in these cases indicate a low permeability category. This is a consequence of the thicker, more clayey deposits at depth restricting recharge.

Lower Palaeozoic Tills

The Lower Palaeozoic tills are also subdivided into two permeability classes which may be due to both the differing bedrock lithologies and the mode of deposition. The thicker more mature deposits, which are found in the southern sides of the mountains and in valleys (such as the River Graney valley), are often clayey with overlying poorly drained soils and peats. The BS5930 descriptions are typically sandy CLAY and the drainage and recharge conditions suggest that the permeability is low.

The second Lower Palaeozoic till type is described using BS5930 as SAND or silty SAND. There is significantly less clay in these deposits and this has impacted on the permeability to give a moderate classification. This is supported by the overlying free draining soils which are often brown earths. The area inland of Tinarana Bay on Lough Derg for example has more than 10 m of these deposits, although they are usually thinner, and directly overlying bedrock.

Namurian Tills

The Namurian bedrock has broken down easily with glacier movement over it giving rise to two main types of sediment materials, each with their own distinct permeability characteristics. It appears from initial investigations that the permeability in tills derived from these rocks in Clare may also be indirectly related to the thickness of the deposit.

In general, tills greater than 10 m thick which are derived from Namurian rocks, are well broken down, clay rich tills. The most common morphological expression of these is drumlins and there are many examples present in a wide band from west of Ennis to Kilfenora, e.g. around Kilmaley and in Inagh. Similar deposits occur in a more topographically subdued till sheet to the southwest of the county between Carrigaholt and Kilkee. The BS5930 description shows the deposits to be firm to stiff CLAY or sandy CLAY and they are usually associated with poorly drained gley soils, both of which indicate a low permeability. In a limited number of areas throughout these tills, it was found that there were small areas of well drained brown earths present on the tops of the drumlins. These are usually small, are likely to be associated with natural drainage on the tops of the hills and are therefore not assumed to give any indication of the composite permeability. In some instances they may also be due to the presence of rock cored drumlins which have been mistaken for thick tills. Time restrictions prevented us from resampling in these areas but they should be considered in future site investigations.

In areas where the deposits are between 1.5 and 10 m thick, usually between the drumlins, the permeability was found to vary significantly. In general, the subsoils in these areas comprise broken up rock and immature tills with a variable clay content. In some cases there has been enough grinding down of the materials to produce sufficient clay such that the behaviour of the material is that of a low permeability deposit. In other areas, the grinding processes were minimal and moderate permeability deposits remain. These areas are highly complex. The soils map shows variations from poorly drained gleys to well drained brown earths and brown podzolics. Field investigations have shown the BS5930 descriptions to include GRAVEL, clayey GRAVEL and coarse sandy CLAY with abundant gravel. As these areas are usually less than the critical 10 m thickness they have not been studied in detail. This serves as a reminder that site investigation is necessary on a site to site basis.

The thick deposits of coarse grained broken up bedrock in the hills in the Ennistymon-Lahinch area (described in Section 3.3.1.4) were found to be well drained but of limited areal extent. They are associated with brown podzolic soils and are classed as moderate permeability as they have sufficient percentage of total fines and high enough clay content to prevent a high permeability classification being applied. A similar process has occurred in the vicinity of Lickeen Lake but these deposits are not differentiated as they are not thick enough to impact on the vulnerability map.

5.1.2 Sand/Gravel

Sand/gravel deposits are variable across the county and have associated variable permeabilities. The well rounded, washed and sorted gravels with sand (refer to Section 3.3.2), such as those found in the Broadford Valley around the Ballyquin quarry, have few, if any, fines, are well drained and are overlain by brown earths. These characteristics are indicative of a high permeability deposit. These deposits are also mapped as a potential aquifer provided further investigation can prove the presence of a sufficient saturated zone (refer to Section 4.19).

The morainic sand/gravel deposits are much more complex due to the chaotic nature of their deposition. There are two categories of permeability within these deposits which are related to the underlying bedrock geology and source material, and are these are found in two distinct geographical locations.

The deposits located in East Clare around Mountshannon and southwest Killaloe are comprised of a mixture of mainly Old Red Sandstone and Lower Palaeozoic derived sediments. While there is a higher percentage of fines in these deposits which will reduce the permeability to moderate in places, significant pockets of high permeability subsoils may still remain such that potential contaminants could make their way into the underlying aquifer relatively quickly. These deposits are therefore classed conservatively on the regional maps as high permeability. Site investigation may prove specific sites to be more appropriately considered as moderate. These deposits are not likely to be of aquifer quality due to the presence of the silts and clays and the variability in permeabilities.

The morainic sand/gravel in west Clare, overlying the Namurian sandstones and shales, generally have a much higher percentage of clay particles due to the high proportion of shales in the Namurian rocks. They also have low permeability tills interbedded with them in places. Sand and gravel particles were often found to be coated with fines (probably with a relatively high proportion of clay), in contrast to the slightly cleaner subsoils found in east Clare. The overlying soils are usually relatively well drained brown podzolics with occasional gleys in places. These Namurian derived morainic sand/gravel deposits are therefore mapped as moderate permeability due to the higher clay content.

5.1.3 Till with Gravel

Till with gravel deposits are complex subsoils comprising intermixed tills and sand/gravel and they therefore often have a wide range in grain size distribution. In Clare they are present in a small area northeast of Mountshannon where they are principally derived from Devonian sandstones. They are typically thin, unconsolidated loose, sandy materials which are draped over the Devonian tills in places. The overlying soils are predominantly peats and podzols.

These deposits were not studied in detail so they are classed tentatively as moderate permeability, due to the mixture of grain sizes present. They are also often thin, overlying the moderate or low permeability Devonian tills and therefore the composite permeability is often more important for the vulnerability map. Site specific investigations may prove high or low permeability classifications would be more appropriate in places.

5.1.4 Alluvial Deposits

Alluvial deposits are variable ranging from high permeability sandy gravelly deposits to low permeability clayey silty deposits. In most instances in Clare there is minimal information to enable this distinction to be made based on field observations. In general, the alluvial deposits are relatively thin so detailed investigations were not carried out. As there are no major river flood plains in Clare (excluding the estuarine areas), areas with subsoils greater than 10 m thick which contain alluvial deposits are likely to comprise relatively thin alluvial deposits overlying another subsoil type, often till. In these cases, the permeability of the surrounding tills is taken to dictate the overall permeability of the area.

5.1.5 Lake Bottom Deposits

Lake clays and silts are laid down in well sorted layers of interbedded clays and silts. They are overlain by gleys and peats on the soils maps and comprise some of the lowest permeability deposits in Clare.

5.1.6 Peat

Peat permeabilities depend on the degree of peat decomposition (humification) and the effects of subsidence. Apart from the upper layer of intact bogs, peat has a relatively low permeability.

In many lowland parts of Clare, the peat is underlain by lake clay and silt. This usually has a low permeability, although the permeability will increase somewhat approaching the boundary of the lake clay/silt, where the proportion of clay decreases.

Although peat has a relatively low permeability, each peat deposit is considered separately as in places it is just a thin cover over another underlying subsoil deposit or is located where the water table is high. The soils map was used in these instances to determine the type of peat and to give an indication of the hydrogeological situation present. The underlying/surrounding subsoils in this instance determine the composite or three-dimensional permeability.

5.1.7 Marine Deposits

The marine deposits are of limited extent around the coastal beaches. They are usually comprised of loose, sorted, coarse sands and are overlain by thin, if any, excessively well drained soils (regosols).
They are therefore classed as high permeability deposits.

5.1.8 Estuarine Deposits

The estuarine deposits are predominantly silts and muds which are overlain by poorly drained gleys

Table 5.2 Permeability and distribution of subsoils in County Clare

Subsoil	Assumed Permeability	Distribution
Limestone till	Moderate Low	Overlying clean limestone bedrock in north and central Clare. Inter-drumlin areas where subsoils are thin and not well developed. Overlying Ballysteen shaly limestones and where influenced by the Namurian Clare Shales
Devonian till	Moderate Low	Where subsoils are shallow in upland areas. Where influenced by sandstone rich Devonian bedrock. In drumlins and often where thick (>10 m) and on southern sides of mountains. Where influenced by shale and mudstone rich Devonian bedrock.
Silurian till	Moderate Low	Tuamgraney to Ogonello area. Immature deposits in upland areas. Thicker deposits on the southern sides of mountains.
Namurian till	Moderate Low	Ennistymon to Lahinch area. Often in inter-drumlin areas where subsoils are <10 m thick. Drumlins. Where influenced by the Clare Shales. Area around Carrigaholt.
Sand/gravel	High Moderate	Broadford valley. Deposits southwest of Killaloe and Mountshannon area. Deposits between Cooraclare and Kilrush.
Till with gravel	Moderate	Northeast Mountshannon area.
Lake deposits	Low	Scattered small patches in low lying areas.
Alluvium	variable	Where thick, usually depends on the surrounding deposits.
Peat	Low	West Clare, upland areas in east Clare, small scattered patches in central lowlands.
Marine deposits	High	Sandy beach deposits along the coast.
Estuarine Sediments	Low	Shannon and Fergus estuaries.

In the low-lying areas close to the coast, these gleys may be related to high groundwater levels which impede the drainage, but on the whole, the interbedded muds and predominance of sorted fine material suggest a low permeability.

Thickness of the Unsaturated Zone

The thickness of the unsaturated zone is only relevant in vulnerability mapping in the case of sand/gravel aquifers, which in Co. Clare applies solely to the deposits in the valley east of Broadford where the Ballyquin quarry is located. The depth to water table in this area is unknown. Where it is found from site investigation to be greater than 3 m below the surface, the vulnerability classification will be high, while where it is less than 3 m below the surface, e.g. close to the river, it will be extreme. As the deposit lies in a valley with relatively steep sides it is likely that the water table will be more than 3 m below surface in most instances and the deposit is therefore shown on the map as high vulnerability.

Karst Features

Karstification (the enlargement of fractures by chemical solution) of limestones in Clare has given rise to the development of various karst features including swallow holes, collapses, caves, dry valleys, turloughs and sinking streams (refer to Section 4.5.4). All of these features can provide easy access to groundwater for potential contaminants. The karst features are shown on Map 4 (the hydrogeology data map), and on Map 6 (the vulnerability map), where they represent points of 'extreme' vulnerability.

Depth to Bedrock

The thickness of the subsoils (the depth to bedrock) is a critical factor in determining groundwater vulnerability to contamination. A brief description of the variations in subsoils thicknesses is given in Section 3.4.

For the purposes of compiling the vulnerability map, the whole land surface was contoured into three of the four depth to rock categories: <3 m, 3–10 m and >10 m. This was done using extensive aerial photo interpretation, in conjunction with the available depth to rock information from boreholes which are shown in Map 3.

The DELG/EPA/GSI vulnerability classification requires a 5 m depth to rock contour in areas of low permeability subsoils to distinguish between high and moderate vulnerability (see Table 5.1). There were insufficient data to enable this contour to be drawn on the Clare regional maps and this distinction is therefore not made. The 3–10 m depth to rock interval in low *permeability* deposits (e.g. clayey subsoils) is all shown as high *vulnerability* on the maps and there is no moderate *vulnerability* category. In reality, most of the low permeability deposits occur in steep sided drumlins, where the 5 m and 10 m depth to rock contours would have appeared on top of each other on the regional maps, leaving a minimal, if any, area of moderate permeability visible on the map. This distinction has not affected the moderate or high *permeability* deposits, as the 5 m depth to rock contour is not relevant to the classification scheme.

The depth to rock contour data were also interpreted at a less detailed scale than the permeability mapping. The process relied heavily on aerial photo interpretation as borehole data were scarce. This procedure is difficult, particularly in complex areas such as in Clare where there are so many small

drumlins, some of which are rock cored. The regional map is our best estimate of the vulnerability with the available information and should always be supported by site investigation in specific areas.

The Vulnerability Maps

The vulnerability map (Map 6) is derived from combining the contoured depth to bedrock data, the subsoil permeabilities and the identified karst features (see Table 5.1). The general classification scheme is outlined in Table 5.3.

In County Clare there are large areas of rock outcrop and subsoil thicknesses are often <3 m. This gives rise to a vulnerability category of 'Extreme' over a significant proportion of the county of the area. Within this area, rock outcrop and shallow rock (i.e. where the soil and subsoil is usually <1 m) is specifically delineated and shown on Map 6 to assist Clare County Council in decision-making.

It is emphasised that the boundaries on the vulnerability map are based on the available data and local details have been generalised to fit the map scale. Evaluation of specific sites and circumstances will normally require further and more detailed assessments, and will frequently require site investigations in order to assess the risk to groundwater. The regional map is useful as a guide to highlight the type of hydrogeological conditions present, and the likely variations.

Limitations

Considerable new insight into the permeability of subsoils was gained from the work carried out by the MSc. students which ran concurrently with the protection scheme. As the understanding and permeability assessment methodologies advanced, every effort was made to make the appropriate amendments to the approach to vulnerability mapping taken in Clare. However, due to extra work involved and the resulting time constraints which could not have been foreseen at the beginning of the project before the research began, it was necessary in some areas to restrict the assessment of permeability only to the areas where it would influence the vulnerability map; i.e. areas of subsoil deposits greater than 10 m thick. The *permeability* classifications in areas where subsoils are less

than 10 m thick are not always accurate. This has implications only for the digital GIS *vulnerability* map in that the *permeability* code attached to polygons in areas <10 m will not

Table 5.3 Summary of Vulnerability Classification Scheme

Vulnerability Rating	Hydrogeological Setting
Extreme	Areas where rock is at the ground surface. Areas where the subsoil is known or is interpreted to be <3m thick. In the vicinity of karst features. Sand/gravel aquifers where the unsaturated zone is interpreted to be <3 thick.
High	Areas where *high* permeability subsoil is known or is interpreted to be >3m thick. Areas where *moderate* permeability subsoil is known or is interpreted to be 3–10m thick. Areas where *low* permeability subsoil is known or is interpreted to be 3–5m thick. Sand/gravel aquifers where the unsaturated zone is interpreted to be >3 m thick
Moderate	Locations where *moderate* permeability subsoil is known or is interpreted to be >10m thick. Locations where *low* permeability subsoil is known or is interpreted to be 5–10m thick.*
Low	Locations where *low* permeability subsoil is known or is interpreted to be >10m thick.

*Not differentiated from 'High' on the map (refer to Section 5.8) always be correct. The resulting *vulnerability* polygons and codes (i.e. permeability + depth to rock), however, are correct as intended. Site investigations should be carried out in areas with between 3 and 10 m of subsoils, to assess both the permeability and the depth to rock, and thereby determine whether the *vulnerability* classification should be High or Moderate (refer to Table 5.1). These areas are all conservatively mapped as High vulnerability at present due to the absence of both 5 m depth to rock contours and permeability assessments in all areas less than 10 m thick.

The vulnerability map is a useful tool, which combines the best available permeability and depth to rock information. The regional map will be used as a guide in land-use planning and is not intended to be prescriptive. The vulnerability classification framework however, can be applied on a site to site basis following appropriate site investigation and this is to be recommended to potential developers.

6 Hydrochemistry and Water Quality

Introduction

An assessment of the quality of groundwater in County Clare is given in a report to Clare County Council by the Geological Survey of Ireland (Cronin & Deakin, 1999). This chapter gives the main conclusions of that report.

Overall Assessment

- The hydrochemistry of groundwater in County Clare is primarily influenced by the nature of the subsoil and bedrock that it passes through. The groundwater in the limestone areas (north and central Clare, and the lowlying areas of east Clare) is hard and can be classed as calcium bicarbonate ($Ca(HCO_3)_2$) type water. Softer waters are found in the remaining areas (west Clare and the upland areas of east Clare), where the bedrock comprises mainly sandstones, siltstones and shales.
- The main groundwater quality problems in County Clare are as follows:
  (a) high iron (Fe) and manganese (Mn);
  (b) bacteriological pollution;
  (c) high turbidity in some spring supplies;
  (d) high lead (Pb) levels in the Mountshannon area.
- The high iron (Fe) and manganese (Mn) concentrations are caused mainly by the natural conditions in the ground and the natural chemistry of the groundwater. This may occur in areas underlain by peat, muddy limestones, the Old Red Sandstone and the Namurian rocks, where reducing conditions result in solution of Fe and/or Mn from the geological materials. This causes taste and aesthetic problems. High manganese levels may also occur from pollution by silage effluent. High Fe concentrations are sometimes associated with high turbidity in karst springs. Two large springs – Elmvale and Kileany – had high Fe concentrations in the samples analysed for the GSI by the State Laboratory, and one – Kilrush – had high Mn. Ennis UDC report occasional high Fe levels at Drumcliff spring.
- The most important groundwater quality issue in County Clare is the presence of faecal bacteria in public and private water supplies. A significant proportion of the public groundwater supplies (10 out of 15) contained faecal bacteria during GSI sampling of raw waters. In certain areas, a high proportion of private wells (>50%) are also likely to be polluted, at least intermittently. The presence of faecal bacteria is not only a problem in itself, but is an indicator of the possible presence of viruses and, in exceptional circumstances, Cryptospiridium.
- The bacteriological pollution of a relatively high proportion of groundwater supplies in Clare is due to the following:
  (e) the ‘extremely’ vulnerable conditions in large areas, where either bare rock or thin subsoils provide only limited protection;
  (f) the karstic nature of much of north and mid-Clare, where groundwater flow velocities are rapid, purification in the limestone is minimal and microbes can be carried large distances;
  (g) poorly designed, located and constructed septic tank systems and farmyards;

(h)landspreading of organic wastes;
(i) poor siting and construction of wells.

- In some springs and boreholes in karst areas, high turbidity occurs after heavy rainfall. This is caused where (a) sediment that has collected in fissures and cavities is washed out at the start of recharge events, and (b) where there is a direct link between the source and a swallow hole into which surface water containing sediment is flowing. For example, runoff from the Namurian shales and sandstones in the Drumcliff catchment infiltrates into the karst limestones through swallow holes and travels rapidly through the groundwater system to the spring. In contrast, Pouladower spring has less problems with turbidity as the lakes in the catchment allow sediment to settle out before the spring is reached.
- Lead (Pb) problems occur in the Mountshannon area. However, only 3 out of 24 supplies in the area had high Pb concentrations (Jones, 1998). The indications are that new artesian supply had low Pb concentrations and sampling is ongoing.
- Nitrate concentrations are generally low in County Clare. Nitrate levels were less than the EU MAC (50 mg/l NO_3) in all public supply wells monitored apart from Bridgetown PWS and Crusheen PWS. The latter had high nitrate in 1991, however since then levels have been low. Public supply for the area is now taken from the Ennis PWS and not from this borehole. Both Crusheen and Bridgetown are included in the ongoing programme of raw water monitoring (see Section 6.3 below). All the other supplies, apart from Montpelier, had less than 25 mg/l in all samples analysed. Nitrate contamination is likely to be caused by point sources, such as septic tank systems.

Future Actions

- As a good database on groundwater quality is required to enable an improved and continuing assessment:
  (j) analyses of raw water in the public supplies rather than treated water will be carried out on a regular basis (at least twice a year until the background situation and trends in each source are defined).
  (k)full analyses (including all major ions) will be carried out on at least some of the samples from each source to enable a fuller picture of groundwater quality and contaminant movements to be obtained.
  (l) where there is evidence of significant contamination, the sampling frequency will be increased.
- Disinfection will be maintained at all public supplies to provide protection against microbial contamination of the supply. A recommendation to provide for adequate disinfection will be made to private group schemes, particularly in areas identified as extremely vulnerable.
- The existing programme of delineating groundwater protection zones around public and group scheme supplies, using the DELG/EPA/GSI guidelines, will be continued.
- Routine checking of sanitary protection at the well head of Council sources and any other sources investigated will take place. This is to address the potential contamination of sources by storm waters and spillages at ground level.

7 Groundwater Protection

Introduction

In Chapter 1, with reference to Appendix A, the general groundwater protection scheme guidelines were outlined 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. Subsequent chapters describe the different geological and hydrogeological land surface zoning elements as applied to County Clare. This chapter draws these together to give the ultimate elements of land surface zoning – the groundwater protection scheme map and the source protection maps. It is emphasised that these maps are not intended as 'stand alone' elements, but must be considered and used in conjunction with the groundwater protection responses for potentially polluting activities. Two such responses have been published: **Groundwater Protection Responses for Landfills** (DELG/EPA/GSI, 1999) and **Groundwater Protection Responses for Landspreading of Organic Wastes** (DELG/EPA/GSI, 1999), and further responses will be prepared in the future.

The Groundwater Protection Maps

The groundwater protection map (Map 7) was produced by combining the vulnerability map (Map 6) with the aquifer map (Map 5). Each protection zone on the map is defined by a code which represents both the vulnerability of the groundwater to contamination and the value of the groundwater resource (aquifer category). The codes are shown in the general groundwater protection scheme matrix in Table A.3. Not all of the possible hydrogeological settings are present in County Clare; those which are present are given in Table 7.1.

Table 7.1 Matrix of Groundwater Resource Protection Zones

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

Groundwater Source Protection Reports and Maps

Source protection zones have been delineated around five local authority wells in County Clare: Drumcliff Spring, Pouladower Spring, Ballyvaughan (Newtown borehole), Whitegate Springs and Mountshannon (new artesian borehole). These have been produced as separate source reports.

Conclusion

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

In considering a scheme, it is essential to remember that: (a) a scheme is intended to provide guidelines to assist decision-making in County Clare 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. Clare

County Council will apply the scheme in decision-making on the basis that the best available data are being used. The maps have limitations because they generalise (with the degree of generalisation depending on data availability) variable and complex geological and hydrogeological conditions. The scheme is therefore not prescriptive and needs to be qualified by site-specific considerations and investigations in certain instances. The investigation requirements depend mainly on the degree of hazard provided by the contaminant loading and, to a lesser extent, on the availability of hydrogeological data. The onus is 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.

The scheme has the following uses for Clare 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;
- it helps ensure that the pollution acts are not contravened;

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Appendix A

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 Schemes, Groundwater Protection Responses for Landfills** and **Groundwater Protection Responses to the 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,

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.

which have a significant potential to contaminate, to be located in areas of lower vulnerability.

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

Source Protection Zones

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

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

These elements are integrated to give the source protection zones.

Delineation of Source Protection Areas

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

In delineating the inner (SI) and outer (SO) protection areas, there are two broad approaches: first, using arbitrary fixed radii, which do not incorporate hydrogeological considerations;

and secondly, a scientific approach using hydrogeological information and analysis, in particular the hydrogeological characteristics of the aquifer, the direction of groundwater flow, the pumping rate and the recharge.

Where the hydrogeological information is poor and/or where time and resources are limited, the simple zonation approach using the arbitrary fixed radius method is a good first step that requires little technical expertise. However, it can both over- and under-protect. It usually over-protects on the 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

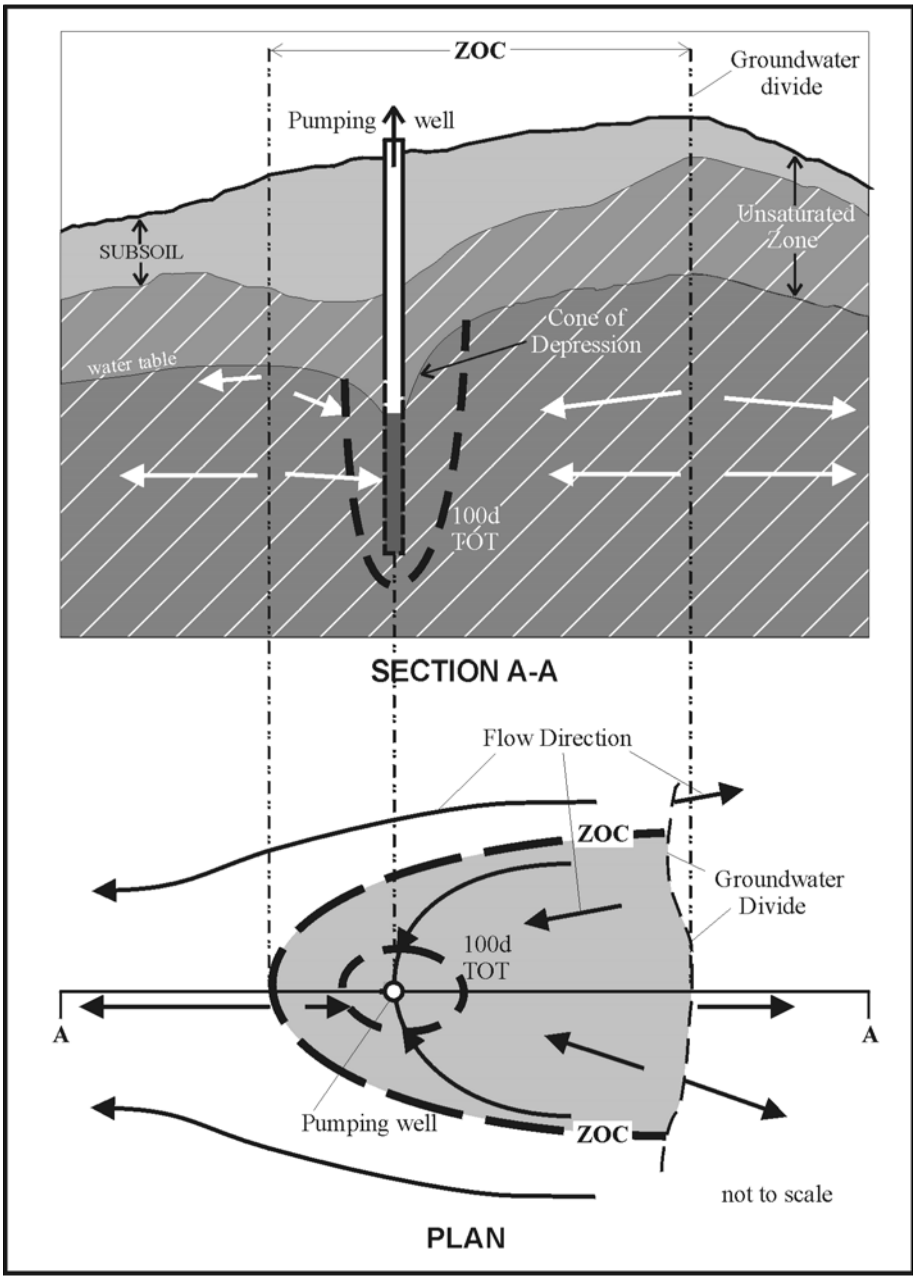

Fig. A.1 Conceptual model of the zone of contribution (ZOC) at a pumping well (adapted from US EPA,

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

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

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.

Delineation of Source Protection Zones

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

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

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.

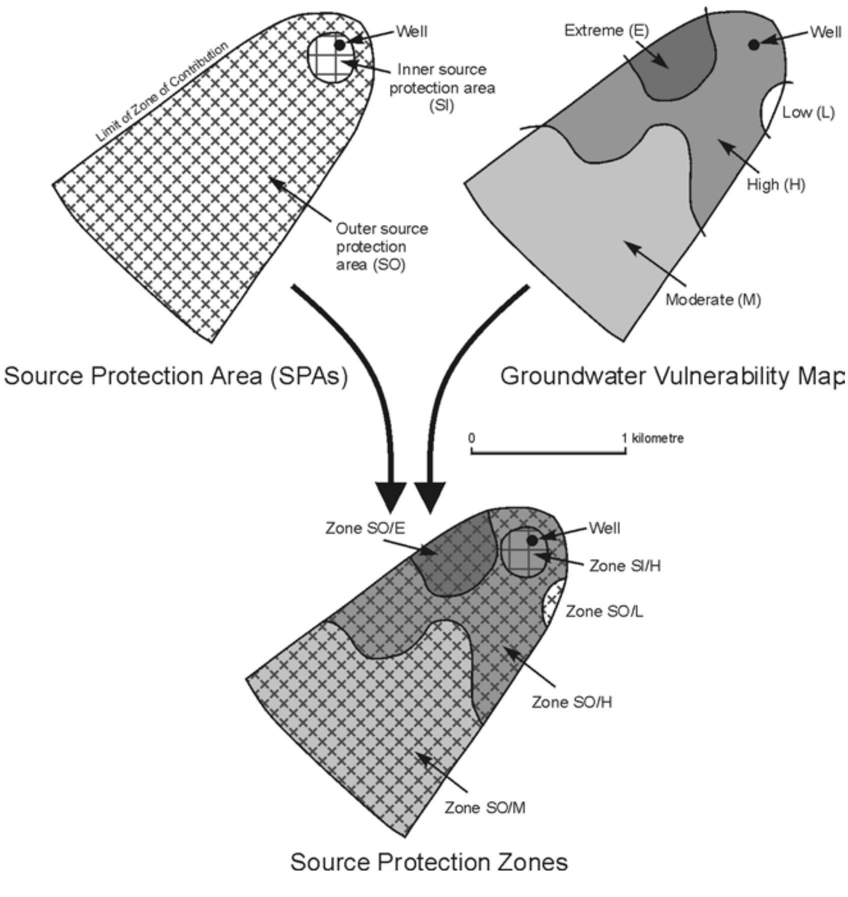

Fig. A.2 Delineation of Source Protection Zones Around a Public Supply Well from the Integration of the Source Protection Area Map and the Vulnerability Map

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.

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

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

be necessary for that development. The groundwater protection responses are a means of ensuring that good environmental practices are followed.

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

R1 Acceptable subject to normal good practice.

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

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

R4 Not acceptable.

Integration of Groundwater Protection Zones and Response

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

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

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

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

In considering a scheme, it is essential to remember that: (a) a scheme is intended to provide guidelines to assist decision-making on the location and nature of developments and activities

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) 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.