THE VULNERABILITY TO POLLUTION AND HYDROCHEMICAL VARIATION OF ELEVEN SPRINGS (CATCHMENTS) IN THE KARST LOWLANDS OF THE WEST OF IRELAND

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DECLARATION

I declare that this is entirely my own work except where otherwise stated. I agree to allow the Library to loan or copy this thesis on request.

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ABSTRACT

DOAK, M. J. (1995) The vulnerability to pollution and hydrochemical variation of eleven springs (catchments) in the karst lowlands of the west of Ireland.

The vulnerability to pollution and hydrochemical variation of groundwater in the mid-west karstic lowlands of Ireland were investigated from October 1992 to September 1993, as part of an EU STRIDE project at Sligo Regional Technical College. Eleven springs were studied in the three local authority areas of Co. Galway, Co. Mayo, and Co. Roscommon. Nine of the springs drain locally or regionally important karstic aquifers and two drain locally important sand and gravel aquifers. The maximum average daily discharge of any of the springs was 16,000 m^3/day.

Determination of the vulnerability of groundwater to pollution relies heavily on an examination of subsoil deposits in an area since they can act as a protecting or filtering layer over groundwater.

Within aquifers/spring catchments, chemical reactions such as adsorption, solution-precipitation or acid-base reactions occur and modify the hydrochemistry of groundwater (Lloyd and Heathcote, 1985). The hydrochemical process(es) that predominate depend on the mineralogy of the aquifer, the hydrogeological environment, the overlying subsoils, and the history of groundwater movement.

The aim of this MSc research thesis was to investigate the hydrochemical variation of spring outflow and to assess the relationship between these variations and the intrinsic vulnerability of the springs and their catchments. If such a relationship can be quantified, then it is hoped that the hydrochemical variation of a spring may indicate the vulnerability of a spring catchment without the need for determining it by field mapping. Such a method would be invaluable to any of the three local authorities since they would be able to prioritise sources that are most at risk from pollution, using simple techniques of chemical sampling, and statistical analysis.

For each spring a detailed geological, hydrogeological and hydrochemical study was carried out. Individual catchment areas were determined with a water balance/budget and groundwater tracing. The subsoils geology for each spring catchment were mapped at the 1:10,560 scale and digitised to the 1:25,000 scale with AutoCad™ and ArcInfo™. The vulnerability of each spring was determined using the Geological Survey's vulnerability guidelines. Field measurements and laboratory based chemistry analyses of the springs were undertaken by personnel from both the EPA Regional Laboratory in Castlebar, Co. Mayo, and the Environment Section of Roscommon Co. Council. Electrical conductivity and temperature (°C) were sampled fortnightly, in the field, using a WTW microprocessor conductivity meter.

A percentage (%) vulnerability was applied to each spring in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low) which occurred within the confines of each spring catchment. Hydrochemical variation for the springs were presented as the coefficient of variation of electrical conductivity. The results of this study show that a clear relationship exists between the degree of vulnerability of each catchment area as defined by the subsoil cover and the coefficient of variation of EC, with the coefficient of variation increasing as the vulnerability increases. The coefficient of variation of electrical conductivity is considered to be a parameter that gives a good general reflection of the degree of vulnerability occurring in a spring catchment in Ireland's karstic lowlands.

ACKNOWLEDGEMENTS

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The Geological Survey of Ireland, for the use of its large earth science database and various maps, and in particular Mr. D. Daly and Dr. W. Warren for their support and advice during the year of field work. The 'gang' at the GSI and in particular those on the 4th floor.

The EU STRIDE project and the Department of the Environment for funding my research and allowing me the use of the regional water laboratories at Castlebar (EPA) and Roscommon.

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CHAPTER 1

INTRODUCTION

1.1 STUDY BACKGROUND

The European Union and the Department of Environment under the STRIDE Environment Sub Programme (Measure III) awarded a contract to Sligo RTC in 1992, to manage a project on groundwater studies in the west of Ireland. This project was entitled 'Groundwater Vulnerability Assessments, Groundwater Studies, and the Development of Aquifer Protection Plans for Counties Galway, Mayo, and Roscommon' (herein after referred to as the 'STRIDE' project).

The STRIDE project had four objectives:

1. The production of aquifer protection plans for Counties Galway, Mayo, and Roscommon.
2. The quantification of the relationship between hydrochemical variability at a spring and spring catchment vulnerability, so as to provide a rapid means of prioritising groundwater sources as to their vulnerability.
3. The evaluation and use of Geographic Information Systems (GIS) for groundwater protection studies, and the application of GIS in the production of groundwater vulnerability maps.
4. The determination of the most appropriate means of delimiting source protection areas for karstic springs and borehole wells.

The STRIDE project involved three research groups, several government and local government agencies, and was completed in April 1994. The Environmental Science Unit and the Natural Resources Development Centre, Trinity College undertook objective 3 and part of objective 1 (see above). The Department of Civil, Structural and Environmental Engineering, Trinity College undertook objective 4. The Department of Environmental Science, Sligo RTC undertook objective 2 and part of objective 1. The Environmental Protection Agency Laboratory (Western Region), Galway Co. Council, Mayo Co. Council, and Roscommon Co. Council carried out a programme of groundwater sampling and analysis, and provided data to the STRIDE project. The Geological Survey of Ireland gave technical advice, archival data and drilling time to all three groups, and supervised the geological mapping undertaken by the Sligo RTC research group.

1.2 STATEMENT OF PROBLEM

In the mid-west lowlands of Ireland a high proportion of groundwater is used for drinking water, and most of it is stored in unconfined karstic limestone aquifers. The three local authorities involved in the STRIDE project have varying dependancies on groundwater; Galway - *c.* 27%, Mayo - *c.* 18%, and Roscommon - *c.* 86%. In each local authority area many small springs are utilised for public water supply. Commonly, the groundwater-tables of the springs are relatively close to the surface with an inadequate natural subsoil protection and are therefore very susceptible to pollution. Over recent years with the intensification of agriculture, pollution of such springs is frequent particularly during the silage making season.

Subsoils (Quaternary deposits) are regarded as the single most important natural feature in influencing groundwater vulnerability to pollution. They can act as a protecting or filtering layer over groundwater (Daly and Warren, 1994). Subsoil maps and data are lacking or of poor quality in the three counties, as the only information available are the old Geological Survey of Ireland (GSI) 6 inch 1840s geology maps. The local authorities would require the expertise of a geologist or an earth scientist and monies for field mapping of subsoil deposits, trial pitting, and augering in order to determine the vulnerability of a groundwater source. Basic geohydrological work such as mapping karstic features and tracing would also be needed. Clearly, it is not practical for each county to map the vulnerability of all their public supply sources to the standard set out in the GSI's guidelines (Daly and Warren, *op. cit.*) and therefore, they must prioritise their groundwater sources.

Within aquifers/spring catchments, chemical reactions such as adsorption, solution-precipitation or acid-base reactions occur and modify the hydrochemistry of groundwater (Lloyd and Heathcote, 1985). The hydrochemical process(es) that predominate depend on the mineralogy of the aquifer, the hydrogeological environment, the overlying subsoils, and the history of groundwater movement. Thus, if the hydrochemistry is influenced by aquifer conditions then it is reasonable to assume that information about the aquifer environment, including its vulnerability to pollution, can be deduced from the hydrochemistry.

1.3 AIMS AND OBJECTIVES

The aim of this MSc research thesis is to investigate the hydrochemical variation of spring outflow and to assess the relationship between these variations and the intrinsic vulnerability of the springs and their catchments. If such a relationship can be quantified, then it is hoped that the hydrochemical variation of a spring may indicate the vulnerability of a spring catchment without the need for determining it by field mapping. Such a method would be invaluable to any of the three local authorities since they would be able to prioritise sources that are most at risk from pollution, using simple techniques of chemical sampling, and statistical analysis.

Eleven springs were selected for the study (Table 1.1) and their locations are shown in Figure 1.1.

TABLE 1.1
The eleven springs selected for study

Co. Galway	Co. Mayo	Co. Roscommon
Barnaderg Belmont	Ballindine Ballyhaunis Crossmolina Kilkelly	Ballinagard Ballinlough Killeglan Mount Talbot Rockingham

The aim of this study was achieved by meeting the following objectives:

- The execution of a 44 week Quaternary (subsoils) reconnaissance field mapping programme around eleven springs, in the three local authority areas.
- The determination of a catchment boundary for each spring, and its confirmation using water balance methods.
- The designation of a vulnerability to the spring catchments using recent vulnerabilty rules devised by the Geological Survey of Ireland.
- The completion of source reports presenting the geological, hydrogeological and vulnerability details of each spring catchment.
- An examination of the relationship between the hydrochemical variation of spring outflow and the intrinsic vulnerability of the spring catchments.

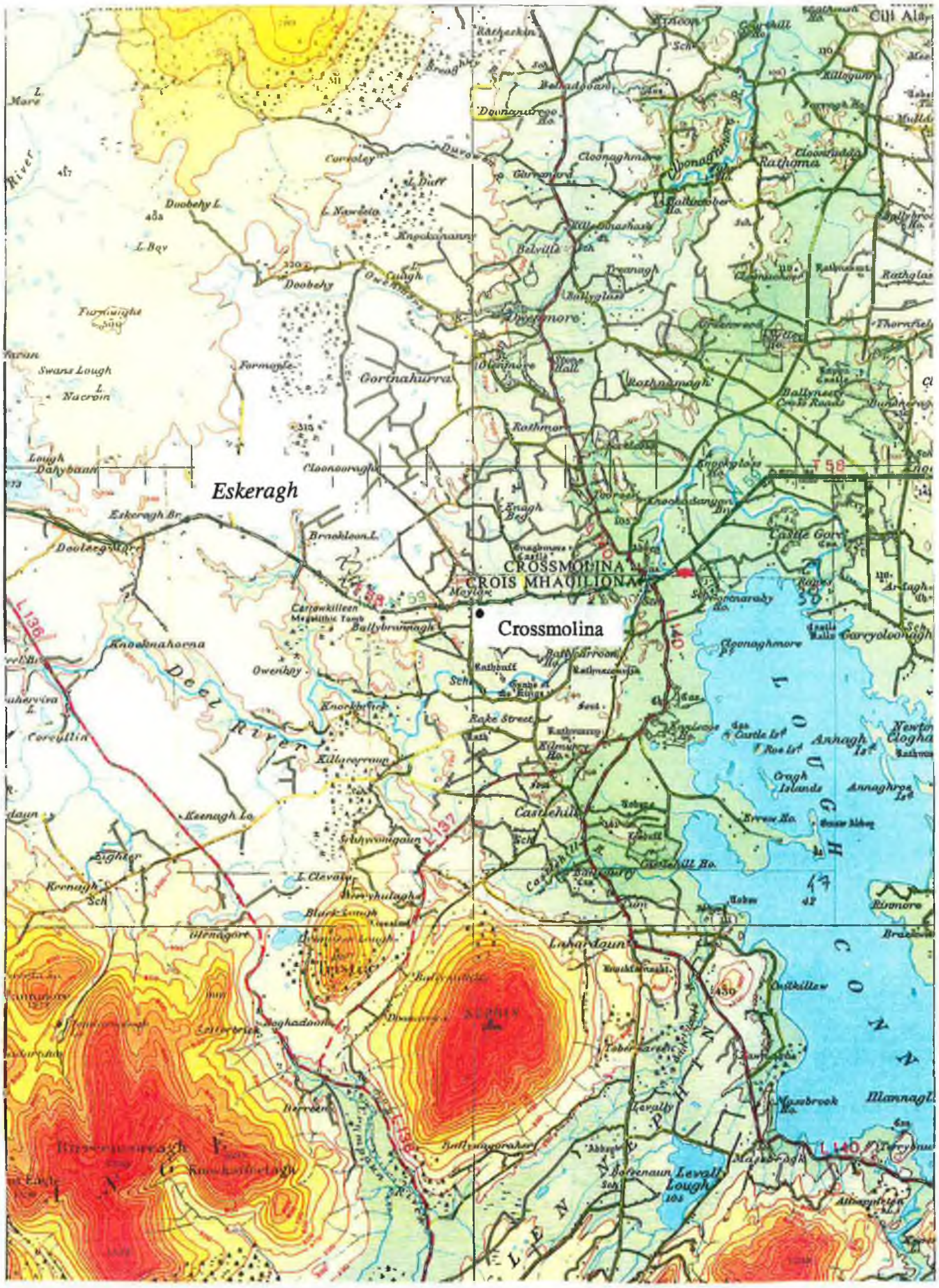


FIGURE 1.1 a
Location of Crossmolina Spring and Eskeragh Rainfall Station
[Extract of OS Sheet 6]

Scale 1:126,720 ↑ **North**

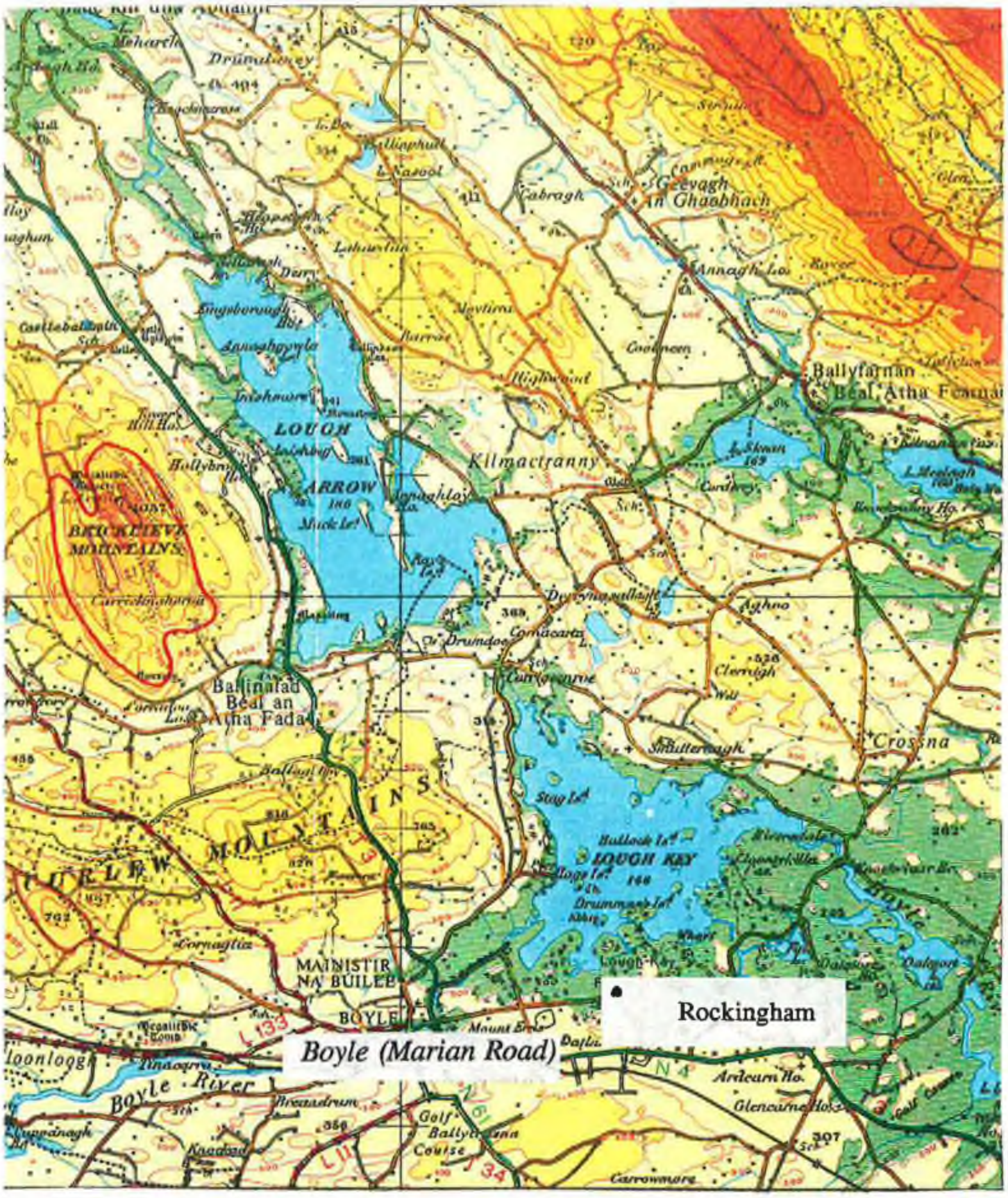


FIGURE 1.1 b
Location of Rockingham Spring and Boyle Rainfall Station
[Extract of OS Sheet 7]

Scale 1:126,720 **North**

FIGURE 1.1 c
Location of the Ballinagard, Mount Talbot, and Killeglan Springs, and Ballygar and Roscommon Town Rainfall Stations

[Extract of OS Sheet 12]

Scale 1:126,720 **North**

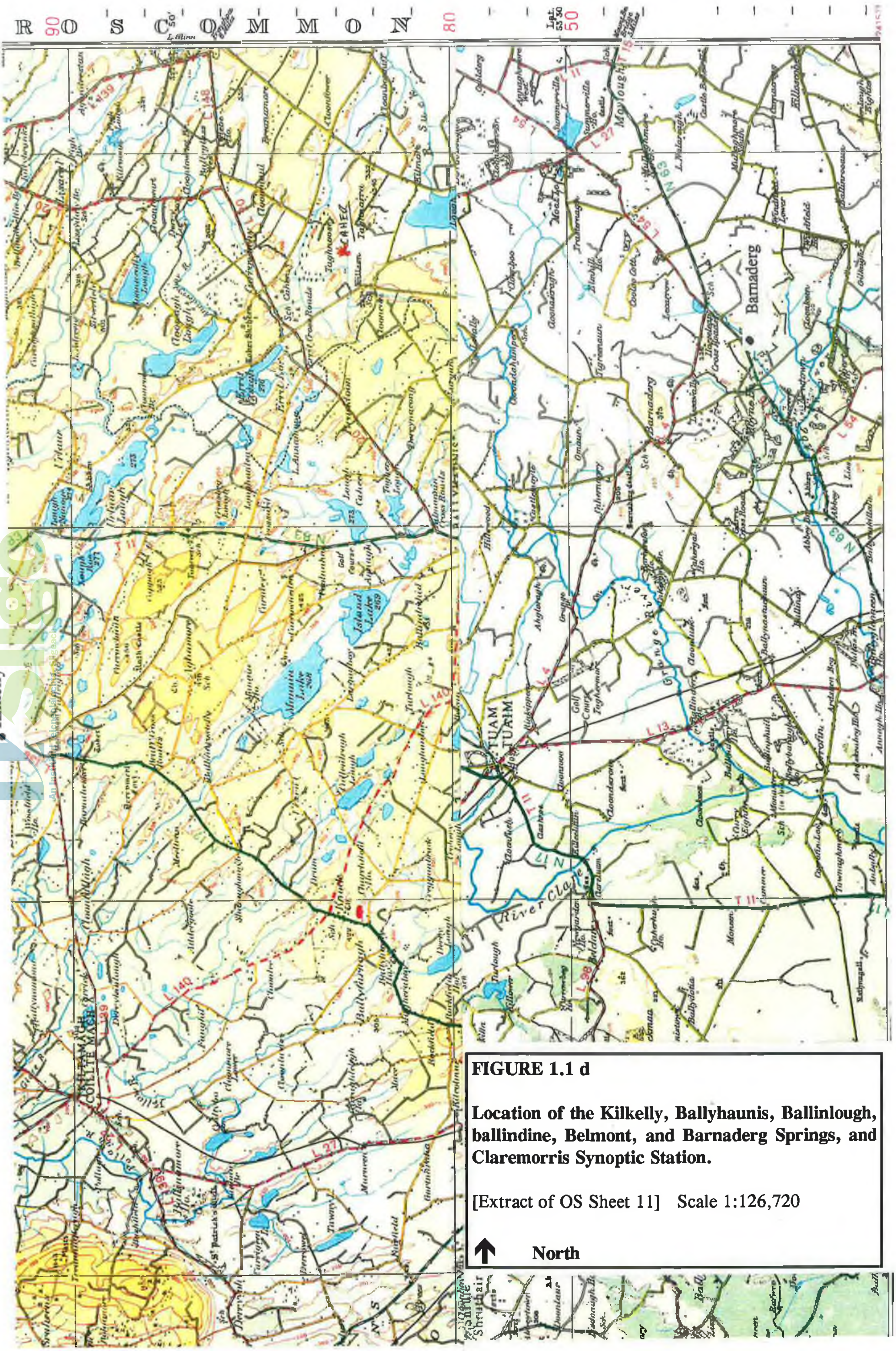


FIGURE 1.1 d

Location of the Kilkelly, Ballyhaunis, Ballinlough, ballindine, Belmont, and Barnaderg Springs, and Claremorris Synoptic Station.

[Extract of OS Sheet 11] Scale 1:126,720

North

1.4 THESIS LAYOUT

This thesis is divided into five separate but interelated chapters:

- Subsoils Geology (Chapter 2)
  This chapter presents the methods that were used to map the subsoils in large areas surrounding each spring in order to complete reconnaissance subsoils (Quaternary) maps. These subsoil maps form the basis for determining the vulnerability of groundwater in the vicinity of the springs.

- Hydrogeology and Spring Catchment Delineation (Chapter 3)
  This chapter presents the methods that were used to determine the catchment areas which supply water to each spring. It also details the climate of the study area and the parameters which were necessary to carry out a spring water balance.

- Vulnerability (Chapter 4)
  This chapter details the guidelines that were used to determine the vulnerability of groundwater in each spring catchment. The vulnerability of each spring is presented as a series of maps determined from the subsoils maps completed in chapter one.

- Hydrochemistry (Chapter 5)
  This chapter presents the data from the one year sampling programme carried out by the Castlebar EPA Regional Water Laboratory, Co. Mayo and Roscommon Co. Council. It also investigates the relative usefulness of a range of parameters for determining the hydrochemical variation of groundwater.

- Conclusions (Chapter 6)
  A summary of the previous four chapters is presented as a synoptic table, with results and conclusions.

CHAPTER 2

SUBSOILS GEOLOGY

2.1 INTRODUCTION

The availability of reliable Quaternary maps were important to the three research groups within the STRIDE project. Detailed subsoils information were essential within the confines of the well head or at the spring for the source protection group at TCD, and in larger areas surrounding springs for this study, and the GIS group at TCD.

In order to avoid confusion at this point, it should be stated that the terms Quaternary, quaternary deposits, drift, subsoils and overburden, are synonymous with the terms *subsoil* or *subsoils*. The terms subsoil or subsoils, shall be used throughout this thesis when describing such deposits.

Of the eleven springs selected for this study only two had recent subsoils data, the Killeglan and Ballinagard spring areas in Co. Roscommon (Quinn, 1988). The other nine springs had no modern subsoils information whatsoever, since the only data available were those in the Geological Survey 6" field sheets, which were mapped in the last century (1840s). As part of this author's STRIDE contract, and in order to provide enough information for the determination of groundwater vulnerability at each spring, detailed reconnaissance subsoils mapping was undertaken in all spring areas. The field mapping programme was conducted under the supervision of the Quaternary Section, Geological Survey of Ireland (GSI).

2.2 RECONNAISSANCE MAPPING AREAS

At the start of this study in October 1992, it was decided by the GSI that field mapping should cover the relevant 1:25,000 scale sheet (150 km^2) for each source, in order to include the recharge or catchment areas of each spring, which were not yet known. This involved mapping ten 1:25,000 scale sheets, since two springs occur on the same sheet. The location of these sheets appear in Figure 2.1.

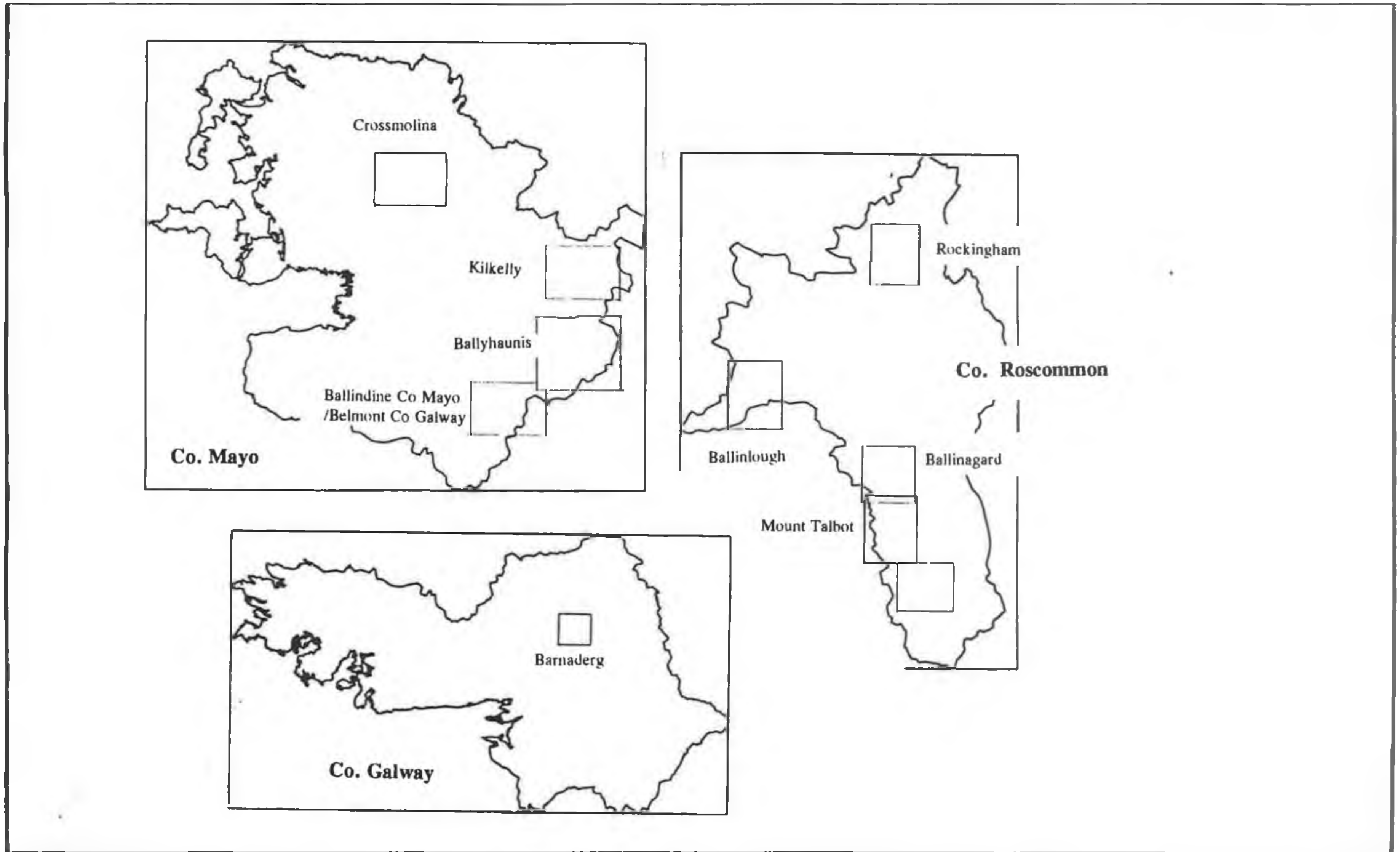


FIGURE 2.1

Location of the ten 1:25,000 scale mapping zones

2.2.1 Mapping Methods and Progress

The four 1:25,000 scale sheets for the Ballindine, Ballyhaunis, Crossmolina, and Kilkelly springs were reconnaissance mapped during the first five months of the project. Field mapping nearer the springs was carried out at a detailed 6" scale (1:10,560) and additional techniques included trial pitting, recording of geological sections and drilling, in order to determine the permeabilities and depths of the surrounding subsoils. Outside the 6" mapping zones, but within the confines of the relevant 1:25,000 scale sheet, subsoil geology was compiled from the 1840s geology 6" field sheets (GSI), aerial photograph interpretation, and some ground truthing.

The field sheets were transferred manually to the 1:25,000 scale and were then digitised by this author over April 1993 using ArcInfo™, a GIS package at TCD. For the remaining six springs smaller field mapping areas were selected because of time constraints. Areas closer to each spring but within a radius of 10km were mapped at the 6" scale, ensuring that their catchments which were not yet decided would be included. It was also determined, that further digitising of field maps should be carried out by staff at SRTC, and not by this author.

The field and digitised subsoil geology maps for each spring area appear in Appendices A - K, as part of separate source reports.

2.2.2 Subsoil Types

The different subsoil types used as mapping units are described below and appear in Table 2.1, as they occur on the 1:25,000 scale map legend.

Alluvium

Alluvial deposits are post-glacial unconsolidated materials which have been deposited by streams or rivers, both past and present. They cover a range of sediment sizes, from gravels to fine muds.

Peat

Peat is a post-glacial organic soil, or deposit. Raised bogs are usually greater than 5m deep, and are underlain by relatively low permeability sediments such as clayey till or lake clays. Blanket bog is very different; it is often less than 2m deep, forming in areas where there is high rainfall and high altitude. Within the Peat group, six categories of bog were identified by the GIS group at TCD, using the Ireland Peat Map (Cross, 1988), the CORINE Land Cover Project [CORINE (1993)] and this author's field sheets.

TABLE 2.1
Subsoil Legend on the 1:25,000 Maps

ALLUVIUM	
PEAT	Raised Bog Undifferentiated
	Blanket Bog Undifferentiated
	Raised Bog Intact
	Raised Bog Cutover
	Blanket Bog Intact
	Blanket Bog Cutover
TILL	Undifferentiated Till
	Clayey Till
	Silty Till
	Sandy Till
	Gravely Till
	Stoney Till
	Till with Gravel
GRAVELS	Sands and Gravels
	Esker (Sand and Gravel)
	Gravel Pit
UNDIFFERENTIATED SUBSOIL (> 3m deep to rock) **SHALLOW UNDIFFERENTIATED SUBSOIL** (> 1m < 3m to rock)	
BEDROCK NEAR SURFACE	
OUTCROP	

Till

Till is a collective term for the group of sediments laid down by the direct action of glacial ice without the intervention of water.

Undifferentiated Till, is a category found where less detailed mapping took place. Here it was possible to determine if a deposit was till or sand and gravel but not possible to discern the type of till, without widespread trial pitting or section data.

The remaining categories of till were used to classify the more detailed mapping areas, nearer to each spring or within a radius of 10km. They are organised in terms of particle size and are subdivided into different till types depending on the percentages of different sized particles present in the till matrix. Geological sections or trial pitting were needed in order to classify the tills in this way. The subdivisions are: *clayey till, silty till, sandy till, gravely till, stoney till,* and *till with gravel.* A clayey till, for example, has a high percentage of clay particles present, and a silty till has a high percentage of silt in its matrix, and so on. Till with gravel is an intermediate deposit type and is used to describe subsoils which contain intermixed tills and gravels, to such an extent that they cannot be mapped separately (Deakin, 1993). They are glacial in origin, and are generally formed in ice marginal moraines.

In all cases, apart from the Kilkelly and Crossmolina spring areas, the dominant lithology of the tills is limestone. Sandstone till is found in Kilkelly and Crossmolina.

Gravels

Sands and gravels were dominantly deposited in the interlobate areas of advancing or retreating ice domes. Some were deposited as river gravels (glaciofluvial) and others in ice dammed lakes (glaciolacustrine deposits).

Eskers, are sinuous sand and gravel ridges laid down as sub-glacial tunnels underneath ice sheets or between ice walls. They often stand proud of otherwise flat lying areas.

Gravel pits, are extraction sites in gravel areas. They are marked for information and groundwater vulnerability matters. These pits are often regarded as potential dumping sites, and can be zones of extreme vulnerability in gravel bodies that are known to be aquifers, since depth to watertable would obviously be shallower in the more deeply excavated pits.

Undifferentiated Subsoil

Undifferentiated subsoil, is a category found in some of the maps. It is an equivalent term of the now outdated 'Drift' and 'Shallow Drift' phraseology, used by the Irish and British

Geological Surveys. The term 'Drift' was introduced by C. Lyell (1797-1875), who suggested that glacial deposits were laid down by melting icebergs which ***drifted*** across an ice-age sea. 'Drift' was used widely in the old geology maps carried out in the 1840s, to cover all types of glacial deposit, from tills to sands and gravels. Therefore, use of the old data did not allow the separation of drift, into till or sand and gravel, and so the term undifferentiated subsoil was used.

Bedrock near surface

Bedrock near surface, is an area where bedrock is less than 1m from the surface.

Outcrop

Where outcrop is marked, bedrock is outcropping, or is exposed to the surface.

2.4 SUBSOILS GEOLOGY OF THE ELEVEN SPRING AREAS

The subsoil characteristics of the eleven spring areas covered by the ten 1:25,000 scale sheets (Appendices A - K) are very variable in both texture and thickness.

Sand and gravel deposits are common in six sheets along a NW/SE axis, which include the Crossmolina, Kilkelly, Ballyhaunis, Ballinlough, Barnaderg, and Killeglan springs. The depths to rock in these areas are often greater than 5m. This axis is coincident with the zone of convergence (Warren and Ashley, 1994) of two ice domes, the northern dome and central dome, which occurred in the last glaciation ~18,000BP. During deglaciation the ice domes at the zone of convergence separated forming an interlobate area flooded by a lake system. Ridges of coarse ice-marginal lacustrine sediments accumulated in the interlobate area as the ice margins retreated to their respective centres. Almost all of the many sand and gravel ridges that this author encountered in these six areas are related to the interlobate lacustrine sediments.

The other four sheets which include the Ballindine, Belmont, Rockingham, Ballinagard and Mount Talbot springs, are outside the interlobate area. They have thinner subsoil deposits and a lack of sands and gravels, but limestone tills and limestone bedrock outcrop are more common.

A summary description of the subsoils mapped within a 10km radius of each spring appears in Table 2.2. Detailed subsoil descriptions appear in Appendices A - K, as part of the separate source reports.

TABLE 2.2
Summary Description of the Subsoils Mapped Within a 10km Radius of Each Spring

SPRING	SUBSOILS a) Type/texture of Subsoil b) % Areal extent of the subsoils within a 10km radius of each spring c) Depth to rock
1 KILKELLY	a) Eskers, sand and gravel of glacio-lacustrine origin. High permeability (k). b) 100 % areal extent. c) > 5m, often > 15m.
2 CROSSMOLINA	a) Sand and gravels of glaciolacustrine origin (High k). Blanket peat overlies thick deposits of low k limestone till, to the north of the spring. b) 100 % areal extent. c) 3 - 5m, except at spring.
3 BARNADERG	a) Eskers, sand and gravel. Stoney till. Medium to high k subsoils. b) 100 % areal extent. c) > 3m, except at spring.
4 BALLINLOUGH	a) Eskers, sand and gravel. Clayey limestone till. Medium to high k subsoils. b) 98% areal extent. Outcrop in high ground to south-west. c) > 3m to 10m. ~ 6m at source.
5 BALLYHAUNIS	a) Esker sand and gravel ridges adjacent to spring. Clay/silt limestone till in 50% of area. Medium to high k subsoils. b) 80 % areal extent, 20% is outcrop. c) > 3m, often > 15m in gravel areas.
6 BALLINAGARD	a) Clayey limestone till. Medium to low k subsoils. b) 70 % subsoil areal extent, 30% of catchment is outcrop/subcrop. c) < 3m in places.
7 BALLINDINE	a) Clayey limestone till and raised peat (low k). Stoney till with sandy matrix (medium k). b) 95% subsoil areal extent, 5% is outcrop. c) < 3m in places.
8 MOUNT TALBOT	a) Clayey limestone till. Sandier near rockhead. Raised bog in inter-drumlin areas. Low k subsoils overall. b) 65% areal subsoil extent, 35% extent is outcrop; limestone ridge 150m OD to east. c) > 3m in subsoil area, except at spring.
9 KILLEGLAN	a) Sandy limestone till. Medium to low k subsoils. Esker sand and gravels (non-aquifer) in places. b) 90% areal subsoil extent, 5% of catchment is outcrop, 5% is subcrop. c) < 3m in places.
10 BELMONT	a) Clayey limestone till. Sandier near rockhead. Low k subsoils. b) 70% areal subsoil extent, 30% extent of outcrop; limestone ridge 150m OD. c) < 3m in subsoil area, except at spring.
11 ROCKINGHAM	a) Outcrop, Bedrock near surface. b) 15% areal subsoil extent, 85% extent of outcrop. c) < 3m.

CHAPTER 3

HYDROGEOLOGY AND SPRING CATCHMENT DELINEATION

3.1 INTRODUCTION

Springs are the main natural discharge outlets for groundwater in unconfined karstic aquifers. Topographic low spots provide the simplest mechanism for their formation where a change in topography or a break in slope intercepts the groundwater-table. The spring is the pulse of a karstic aquifer; its flow regime may reflect the hydrogeological characteristics of an aquifer or smaller spring catchment area. The spring catchment is the total area, both underground and surface that may contribute recharge or flow to a spring. Catchments are separated by divides or boundaries. The terms 'groundwater basin', 'zone of contribution', and 'source protection area' are synonymous with the term spring catchment.

Nine of the springs in this study drain locally or regionally important karstic aquifers and two drain locally important sand and gravel aquifers. The latter two (Crossmolina and Kilkelly), non-karstic springs were included to compare their hydrogeological and hydrochemical characteristics to those of the karstic limestone springs. The maximum average daily discharge of any of the springs is 16,000 m^3/day.

Before this study there was little geological or hydrogeological data for many of the springs, and none of their catchment boundaries were known. Three of the Co. Roscommon springs, Killeglan, Ballinagard, and Rockingham had some miscellaneous hydrogeological documentation such as local borehole records and results of pumping tests.

Determination of the eleven spring catchments and their boundaries were essential to the main aim of this study in order to relate the hydrochemical variation of spring discharge to the vulnerability of its catchment.

This chapter introduces the concepts associated with a karstic aquifer, describes the meteorology and hydrogeology of the study area, and focuses on the methods used in determining the catchment boundaries of the eleven springs.

3.2 THE KARSTIC AQUIFER - A Review

A karstic aquifer is an aquifer in which the flow of water is or can be appreciable through one or more of the following: joints, faults, bedding planes, and cavities - any or all of which have been enlarged by the dissolution of bedrock (Quinlan *et al.*, 1991). Karstic aquifers are in general extremely heterogeneous in character. A fundamental characteristic that differentiates water flow in porous aquifers from that in karstic ones is that in the latter, the velocity of flow in both the saturated and unsaturated zones is closely related to a network of high velocity drains (quickflow) within a slow velocity matrix (baseflow, or diffuse flow); (White, 1991).

According to Sokolov (1965) various zones can be distinguished in a karstic aquifer:

- An unsaturated zone, in which suspended water may be retained at certain times.
- A zone of fluctuating piezometric level, corresponding to the highest level reached by surface water and the lowest one (this zone may be highly karstified).
- Below the zone of fluctuating piezometric level lies a saturated zone similar in texture to that of a granular medium, but possibly containing some preferential circulation conduits.

Mangin's scheme (1975) is simpler to some extent, allowing for an epikarstic aquifer, which would be equivalent to Sokolov's suspended karstic water or conventional saturated zone, both being connected to a series of fractures which function during periods of recharge. As far as a conceptual model of karst aquifers is concerned Padilla *et al.* (1994) propose one of a fissured aquifer made up of large, barely permeable blocks, which constitute the body of the karstic mass and form the water retaining element, separated by highly permeable fractures and/or conduits, which form the transmissive element (Figure 3.1).

Diffuse flow, as used in describing karst aquifers, should not be interpreted to be the laminar dispersed flow common in granular Darcian flow aquifers. The term *diffuse* (Quinlan *et al., op. cit.*) means slow, both laminar and slightly turbulent flow of water, through a system of small discrete fissures and fractures that are being dissolutionaly enlarged, albeit extremely slowly. *Conduit* flow is used to refer to flow through dissolution passages with diameters of centimetres to meters as described by Shuster and White (1971) and Smart and Hobbs (1986). Velocities are commonly high and flow is frequently turbulent.

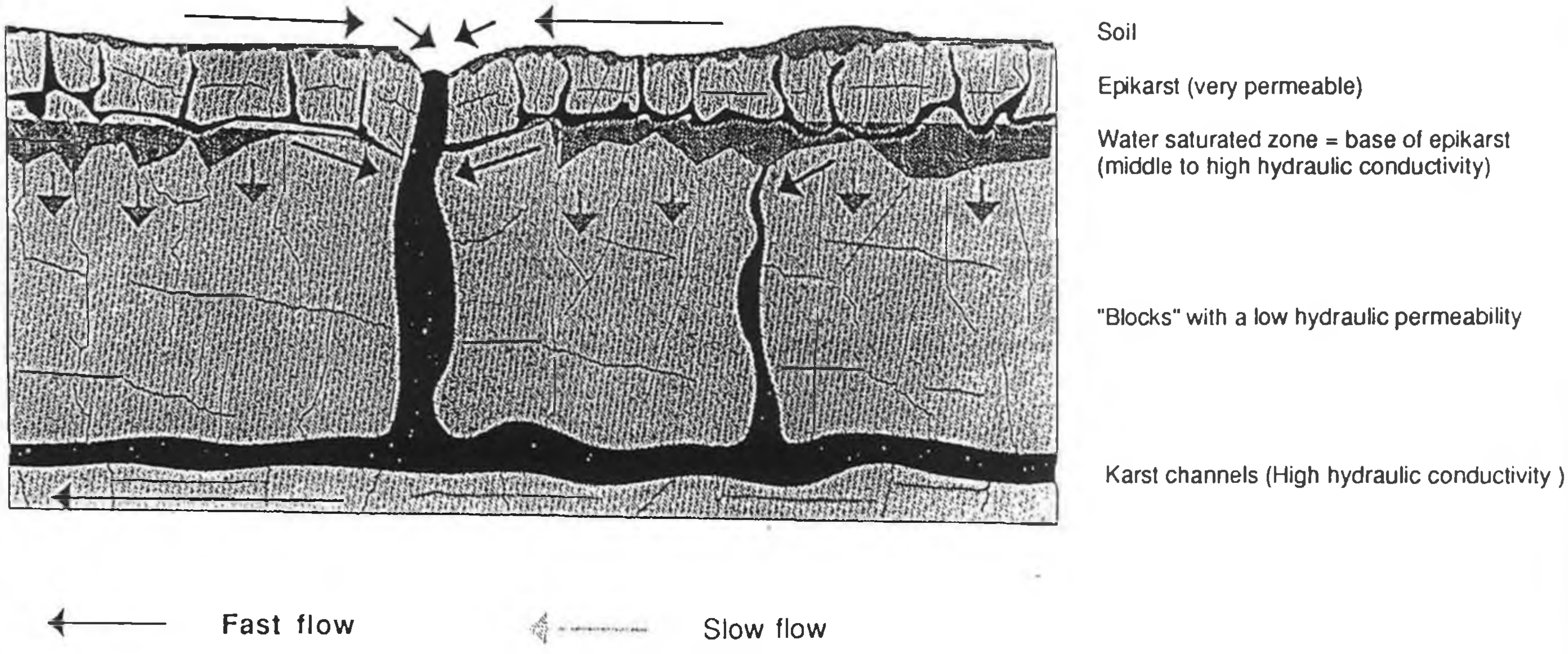


FIGURE 3.1
Outline of 'blocks' and epikarst in a Karstic Aquifer

Recharge in a karstic area may range from point to diffuse. Point recharge is characterised by sinking and losing streams, or closed depressions where drainage is often via a shaft system (Smart and Friedrich, 1986).

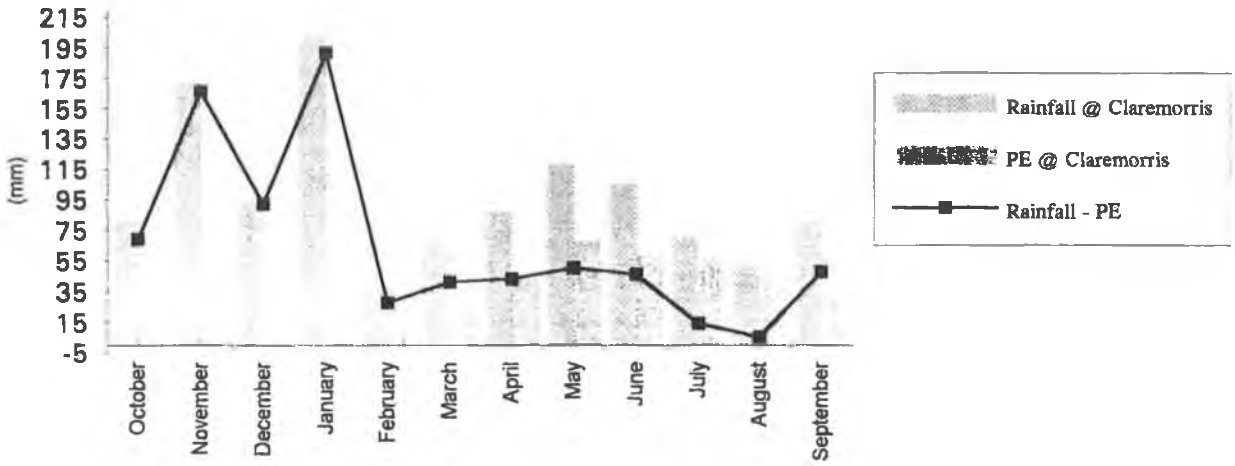
3.3 CLIMATE OF THE STUDY AREA

Table 3.1 presents data for the meteorological service synoptical station at Claremorris, which characterises the climate of the study area. On average (1951-1981) rainfall is spread relatively evenly over each year, and evaporative demand shows a maximum in summer when it exceeds rainfall in May and June. However, climatic conditions were unusual for the October 1992 to September 1993 field period since rainfall amounts exceeded evapotranspiration each month. A diagram for Claremorris during this period, appears in Figure 3.2.

TABLE 3.1
Climatic data at the Claremorris synoptic weather station for the October 1992 to September 1993 field year, with 30 year averages for precipitation and PE, based on the Monthly Weather Bulletin and Climatological Note No. 7, both of the Meteorological Service.

MONTH	Average Temp. (°C)	Daily Mean Sunshine (hrs/d)	Rain Days	PE ('51-81)	PE	Precipitation ('51-81)	Precipitation
October	7.5	2.53	21	15.3	12	115	80.9
November	7.3	1.4	28	1.2	6.2	117	172.9
December	4.1	0.79	21	-2.3	-1.3	124	92.0
January	5.9	0.86	28	-1.5	11.7	116	203.5
February	6.8	1.01	14	10.9	8.5	77	36.3
March	6.5	2.29	16	28.9	23.9	81	64.9
April	9.0	3.66	19	54.0	43.2	62	86.3
May	10.5	5.21	21	75.9	68.1	72	118.4
June	13.5	2.81	18	82.0	58.6	74	104.6
July	14.1	2.73	25	69.7	56.1	75	70.2
August	13.5	3.35	17	57.8	46.7	93	52.3
September	11.6	3.39	14	36.2	31.8	107	79.8
TOTAL			**242**	**428.1**	**365.5**	**1113**	**1244.6**

FIGURE 3.2
1992-93 Meteorology for the Claremorris Synoptic Station



3.4 THE HYDROLOGICAL, GEOLOGICAL AND HYDROGEOLOGICAL CHARACTERISTICS OF THE 11 SPRING AREAS

3.4.1 Hydrology of the study area

The eleven springs are situated in five surface water basins. They are:

(1) Lough Conn (part of River Moy)
Crossmolina spring and Kilkelly spring (Trimoge River)
(2) River Shannon
Rockingham spring and Ballinagard spring (Hind River)
(3) River Clare
Barnaderg spring (Abbert River) and Ballyhaunis spring (Dalgan River)
(4) Lough Mask
Ballindine spring (River Robe) and Belmont spring
(5) River Suck
Ballinlough, Mount Talbot and Killeglan springs.

3.4.2 Mapping Method

As discussed in Chapter 2, a comprehensive subsoils mapping programme was carried out at the relevant 1:25,000 scale sheet for each spring. Similarly, hydrogeological mapping was carried out in order to determine the geology of the eleven spring catchments and their catchment boundaries. This fieldwork predominantly took place in the Summer of 1993 and included the mapping of rivers and drains, and their direction of flow. Wells were dipped for static water level. Karstic features were also mapped. Underground tracing was carried out where possible using an optical brightener, Leucophor STA.

3.4.3 Geology and Hydrogeology of the Eleven Springs

A summary of the geology and hydrogeology for the eleven spring areas may be found in Table 3.2. Hydrogeological details for each individual spring appear in Appendices A - K, as part of the separate source reports. All nine karstic springs and the sand and gravel spring at Crossmolina are underlain by Lower Carboniferous Dinantian Limestone. The Kilkelly spring is underlain by Carboniferous sandstone and drains both the sandstone and overlying sands and gravels.

An extensive body of data has been compiled on the hydrogeology of the karstic lowlands which fall within large parts of the study area (Daly, D., 1980; Drew and Daly, 1994; and Thorn and Coxon, 1989). The lowlands have many features typical of carbonate rock terranes, such as groundwater recharge via sinkholes, losing streams, turloughs (seasonal lakes),

TABLE 3.2 Summary of Spring Aquifer Geology and Hydrogeology

SPRING	AQUIFER GEOLOGY	SPRING DETAILS (i) Estimated Avg. Spring Output (ii) minimum flow (iii) maximum flow (iv) catchment size	WELL DETAILS if within 10m of the spring (1) Depth (5) Abstraction Rate (2) Diameter (6) Specific Capacity (3) Depth to Rock (7) Inflows (4) Static Water Level	KARSTIC FEATURES
1 KILKELLY	Sand and Gravel /Sandstone	(i) 3,300 m^3/d (ii) 1,700 m^3/d (iii)3,900 m^3/d (iv) 1.6 km^2		None
2 CROSSMOLINA	Sand and Gravel	(i) 1,560 m^3/d (ii) 850 m^3/d (iii)4,800 m^3/d (iv) 0.85 km^2		None
3 BARNADERG	Pure Limestone	(i) <2,000 m^3/d (ii) - (iii) - (iv) < 1 km^2		None evident
4 BALLINLOUGH	Pure Limestone. Sand and Gravels near/at spring.	(i) 3,000 m^3/d (ii) 2,950 m^3/d (iii) - (iv) 2.5 km^2	Trial well No. 1 (1) 61 m (2)150 mm (3) 7.5 m (4) - (5) 5,000 m^3/d (6) - (7) (a) 8 m. b.s.* (b)10 m. b.s. Pump. well No. 1 (1) 12.5 m (2) 200 mm (3) 6.2 m (4) 1 m. b. s. (5) 3,036 m^3/d (6) 1,128 $m^3/d/m$ (7) (a) 8 m. b. s. (b)10 m. b. s.	Cavities in borehole
5 BALLYHAUNIS	Muddy (Impure) Limestone. Sand and Gravel Aquifer near source	(i) 12,000 m^3/d (ii) 2,500 m^3/d (iii)45,000 m^3/d (iv) 6.0 km^2		Swallow Hole. Positive trace to the spring; 440m/hr over 3.2 km. Dolines, often subcrop.
6 BALLINAGARD	Pure Limestone	(i) 16,000 m^3/d (ii) 10,000 m^3/d (iii)80,000 m^3/d (iv) 7.9 km^2		Several swallow holes, all with positive trace to spring. Dolines. Turloughs to the south.
7 BALLINDINE	Pure Limestone	(i) 3,000 m^3/d (ii) 2,000 m^3/d (iii) 3,500 m^3/d (iv) 4.3 km^2	(1) 15 m (5) - (2) 150 mm (6) - (3) 7.7m (7) - (4) -	Turlough, dolines. Suspected collapse features overlain by till.
8 MOUNT TALBOT	Pure Limestone	(i) 6,500 m^3/d (ii) 4,000 m^3/d (iii) - (iv) 7.3 km^2		Turlough. 2 Swallow holes. Several Dolines.
9 KILLEGLAN	Pure Limestone	(i) 6,910 m^3/d (ii) - (iii) - (iv) 6 km^2		Two main swallow holes, with positive trace to spring. 10's of swallow holes in the area. Dolines and turloughs.
10 BELMONT	Muddy (Impure) Limestone	(i) 185 m^3/d (ii) 182 m^3/d (iii) 310 m^3/d (iv)< 0.1 km^2		Turlough. Losing river. Several Dolines.
11 ROCKINGHAM	Pure Limestone	(i) > 13,100 m^3/d (ii) - (iii) - (iv) > 8 km^2	(1) 19.2 m (5) 6,200 m^3/d (2) 300 mm (6) - (3) 1 m (7) 7.6 m. b. s. (4) 4 m. b. s.	Dolines. Cavities in several local boreholes. Turlough nearby.

* m. b. s. is metres below surface

caves, large extremes in transmissivity, and lack of surface drainage. The Rivers Clare, Robe, Shannon and Suck -the four main rivers- have considerable interchange between river flow and groundwater.

Borehole records, tracing results and geology indicate that each limestone spring (nos. 3-11, Table 3.2) drains a shallow unconfined karstic aquifer, although at springs 3, 4 and 5, sand and gravel is present beneath the water table at and, in the vicinity of the springs. Of the nine limestone springs, seven are in an area that is underlain by Pure Limestone which is considered to be a regionally important aquifer (Drew and Daly, *op. cit.*). They are the Ballinagard, Ballindine, Ballinlough, Barnaderg, Killeglan, Mount Talbot, and Rockingham springs. Pure Limestone is a pale to grey, bedded, fossiliferous, coarse to medium grained limestone. It is widespread in outcrop, and is the limestone in which is developed the greatest degree of karstification. The Ballyhaunis and Belmont spring areas, are underlain by Muddy Limestone, which is considered to be a local moderately productive aquifer. The Muddy Limestone is dark grey to black, and well bedded. It may have a clayey lithology but is often interbedded with black calcareous shales and cherts at the base (Drew and Daly, *op. cit.*). Karstification often occurs in the cleaner units and beds of the muddy limestone.

Seven of the limestone spring catchments (nos. 5-11, Table 3.2) show point recharge and karstic features that indicate the dissolution of bedrock, whereas two spring areas (3 and 4) have no obvious karst morphological features at the surface since their catchments have substantial areal extents and depths of subsoil. However, at Ballinlough (4) two sets of cavities in limestone at 8 metres below surface (m.b.s.) and 10 m.b.s., have been recorded in recent boreholes adjacent to the spring. Tracing carried out at springs 5, 6 and 9 may indicate that conduit flow conditions predominate in the aquifers of these areas. Overall, conduit/fissure flow conditions are believed to occur in all nine of the limestone aquifers/catchments.

3.5 ESTIMATION OF SPRING CATCHMENT AREAS BY A WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed within the ten 1:25,000 scale sheets, it became evident that the determination of the spring catchment boundaries would be difficult. However, an understanding of the size of each spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies was to occur within the spring recharge zones. It was decided that, as an initial step, each spring catchment area would be *estimated* by a water balance. Hydrogeological techniques and water tracing were carried out later to confirm the estimated catchment areas. This work is described in Section 3.6.

In equation form, a water balance for a spring consists of:

$$\text{Discharge from spring} = (\text{Recharge})\text{Catchment Area} \; +/- \; \text{Change in Storage} \quad \text{(i)}$$

It is normal practice to assume for Irish conditions that the net catchment storage change (ΔS) is on the annual scale negligible, as the climatic cycle is generally of a yearly period (Cawley, 1990). As a result, the annual water balance equation can be expressed simply as:

$$\text{Discharge from spring} = (\text{Recharge})\text{Catchment Area} \quad \text{(ii)}$$

Thus the area required to supply the annual discharge from a spring may be estimated by:

$$\text{Discharge/Recharge} = \text{Catchment Area} \quad \text{(iii).}$$

Apart from spring discharge which is the dominant outflow component of a catchment, there can be other minor outflows such as abstraction of water from wells, and flow to other aquifers. Similarly there are often several types of recharge to a groundwater system, such as precipitation or direct recharge, river recharge, inter-aquifer flow and urban recharge. Therefore, the simple equation above, (iii), should be represented in full by:

$$\text{Outflows/Inflows} = \text{Catchment Area} \quad \text{(iv)}$$

OR

$$\left(\begin{array}{c} \textbf{Outflows} \\ \text{Total Spring Output} \\ + \text{ Abstraction} \\ + \text{ Flow to other} \\ \text{aquifers} \end{array} \right) / \left(\begin{array}{c} \textbf{Inflows} \\ \text{Direct Recharge} \\ + \text{ Indirect Recharge} \\ + \text{ Flow from other aquifers} \\ + \text{ Urban Recharge} \end{array} \right) = \begin{array}{c} \textbf{Catchment} \\ \textbf{Area} \end{array}$$

The generalities of the water balance calculations for all springs appear below. The detail of individual spring water balance calculations appear as part of the source reports, in Appendices A - K.

3.5.1 Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

3.5.1.1 Total Spring Output

The total output of a spring may consist of two elements, water abstracted from the spring and pumped to the public water supply (reservoir tank), and the overflow, which continues on its natural course into the stream network, usually over a weir or via an overflow pipe.

Spring abstraction pumping rates were available from daily caretaker records or meters installed at the pumps.

Overflows at the Ballinagard and Crossmolina springs were determined with existing thin-plate weirs, as heights of water at a stage, on the upstream side of the weir and converted to flow using British Standard tables. For most of the other springs, a staff gauge had to be placed upstream of non-standard spring weirs or in an overflow channel, in order to estimate the spring overflow. Water levels were converted to discharge with rating curves, developed over the October 1992 to September 1993 period, by a midget current meter (velocity-area method), or by dye/salt dilution gauging using a constant rate injection method. The overflows at the Barnaderg, Ballinlough and Belmont springs were often minute and were estimated directly by a current meter. Apart from these last three springs, overflow was estimated every two weeks by the reading of stage heights, with the co-operation of local authority personnel. Details of each of the flow measurement methods used in this thesis, may be found in Shaw (1988).

The estimated total spring outputs and the minimum and maximum total outputs for certain springs appear in Table 3.2, and may be analysed in detail in the source reports, Appendices A - K.

3.5.1.2 Abstraction

This is a small outflow component which consists of abstraction from other wells or sources within a spring area. Often the water that is extracted by such methods finds its way back to the spring via septic tanks, run-off or effluent works (D. Daly, pers. comm.).

3.5.1.3 Flow to other aquifers

Flows to other aquifers were disregarded for this thesis for the reasons stated in section 3.5.2.3, below.

3.5.2 Inflow Calculations

- Direct recharge
- Indirect recharge
- Flow from other aquifers
- Urban recharge

3.5.2.1 Direct Recharge

Direct Recharge is the dominant inflow component and consists of the proportion of rainfall which percolates to the groundwater body of a spring catchment and may be represented as:

Direct Recharge = Rainfall - Evapotranspiration - Runoff

OR

Actual Recharge = Potential Recharge - Runoff.

where Potential Recharge = Rainfall - Evapotranspiration

Rainfall

In water balance calculations, individual rain gauges are assumed to be representative of a considerable area surrounding them. Rainfall station choice for this study was limited since the data needed were for the relatively recent October 1992 to September 1993 period, without any gaps, and certain stations found in Climatological Note no. 7 (Meteorological Service, 1981) have since been closed down. Certain rainfall stations were located at towns near to a spring and so rainfall was taken directly from the station. Where springs were some distance from a rainfall station the Theissen method was used to determine rainfall. The rainfall stations used for this study appear in Table 3.3 and Figure 1.1.

TABLE 3.3
Rainfall stations used for this study

Co Mayo	*Co Galway*	*Co Roscommon*
Eskeragh	Ballygar	Boyle (Marian Road)
Claremorris S.W.S		Roscommon Town (Vocational School)
Horan International (Knock) Airport		

Evapotranspiration

The direct transfer of water to the atmosphere from the ground or from vegetation is by evaporation. When water moves from the soil, from an open water surface or from a wet surface of vegetation the process is evaporation, but when the water in the soil moves into the plant roots, through the plant, and from the plant to the atmosphere the process is called transpiration. The combination of the two processes is commonly called evapotranspiration (Keane, 1986). Actual evapotranspiration (AE) is usually estimated from standard meteorological measurements by working with a conceptual quantity called potential evapotranspiration (PE), determined by the Penman formula. The Penman equation is based on variables such as wind speed and solar radiation, and calculates the value of PE as the amount of water transpired by a green crop which completely covers the ground and is never short of water [at field capacity] (Keane, *op. cit.*). Monthly PE values for all spring areas, during the October 1992 to September 1993 period, were taken from the Claremorris and Birr Meteorological Service synoptic stations since they were the nearest data points for PE.

The availability of soil water will determine the amount of AE. When water is freely available and the soil is at field capacity the PE rate can be met. As a soil dries out the remaining water is more tightly held and plants experience increasing difficulty in extracting water. When a critical soil moisture deficit (SMD) of about 30 mm is reached, known as the root constant, the soil can no longer sustain evaporation at the potential rate. The plant responds by closing the leaf stomata and so evapotranspiration is checked. At an SMD of 60 mm, AE can be reduced to less than 65% of its potential value in grass (Keane, *op. cit.*).

Taking these factors into account, it was decided that the annual AE should be the same as the annual PE at all springs, since climatic conditions were unusual for the October 1992 to September 1993 field period when rainfall amounts exceeded evapotranspiration each month.

Actual Recharge

Actual recharge is the water that reaches the water table, and potential recharge is the water that is available but which may go to another destination (Lerner, 1990). Groundwater rarely receives 100% potential recharge, unless it is point recharge via a swallow hole or diffuse via bare limestone blocks. Some rainfall may be lost to surface runoff depending on the infiltration rates of the overlying soils and subsoils. Also at depth below the soil surface, rainfall may exceed the infiltration capacity of a soil layer, causing lateral sub-surface flow (or throughflow) to occur above the less permeable soil layer. Such through flow may never reach the underlying aquifer but may move through the upper soil horizons towards stream channels. The amount of potential recharge that eventually does reach the groundwater body can be anything from 0% to 100%. For example, groundwater in the Crossmolina area (no. 2, Table 3.2) that is hosted in high permeability sands and gravels, may receive up to 100% potential recharge. However, where clay till with a thick impermeable iron pan overlays an aquifer, little potential recharge may reach the water table (E. Daly, pers. comm.).

3.5.2.2 Indirect Recharge

Where streams, rivers and lakes have a permeable substrate, water can percolate into an aquifer when the water table levels are lower.

3.5.2.3 Flow from other aquifers

Inflows from other bedrock aquifers/catchments were disregarded for this thesis since there was no available hydrogeological information. Inflow is unlikely, in any case, since all of the aquifers in this study are shallow, highly permeable and are likely to have water tables that mirror surface topography, and so not exchange water with other underground catchments. The flow from small superficial sand and gravel aquifers should be estimated.

3.5.2.4 Urban Recharge

This is an artificial type of inflow caused by storm runoff from concrete areas or by leakage from water pipes and sewers, resulting from their damage or deterioration.

3.6 DELINEATION OF THE CATCHMENT BOUNDARIES OF A SPRING

Both the water balance approach and the spring recession analysis technique adopted by Price and Johnston (pers. comm.), one of the other STRIDE groups, only estimate the area of a spring catchment. These methods do not indicate or delineate the catchment boundaries of a spring. In order to demarcate physically the estimated spring catchment area an understanding of the hydrogeological characteristics of karst aquifers and spring catchments in general is needed.

3.6.1 Defining the Limits of the System

The conceptual distinctions between spring catchments and aquifers are blurred in karstic regions because of the integrated system of conduits that carry water to the subsurface. There are three components to karst hydrologic systems.

- The aquifer
- The patchwork of surface catchments
- The patchwork of groundwater catchments. (White, 1991)

Unconfined groundwater catchments are often closely related to the overlying surface catchments (watersheds) because the flow paths through the conduit system are alternative routes of flow to the system of surface channels. In certain cases, particularly where the aquifer is shallow and the boundaries of the surface and subsurface basins are identical, the conduit system merely serves as an underground bypass to the surface stream (Ford and Williams, 1989). Underground, the difference in elevation between the spring and the water table upstream determines the head in the system and thus the energy available to drive a circulation. Where unconfined groundwater is deeper, subsurface catchments may not be precisely congruent with surface catchments due to conduits that cross present surface catchment divides, which may have been formed when the water table was at a lower stand than present. Fissures may also cross the catchment boundaries of springs at any depth, and the frequency of fissure occurrence within the rock mass can vary over several orders of magnitude (Skinner, 1985). Fissure elucidation is difficult unless there are adequate data, which can only be obtained by a network of observation boreholes or by tracer tests.

The lower boundary of an unconfined karstic aquifer is commonly an underlying impermeable formation, but should the rocks be very thick, the effective lower limit of the aquifer occurs where no significant permeability has developed. This may be because the rocks have only recently been exposed to karstification, or because lithostatic pressure at depth is so great that there is no penetrable fissuring and consequently groundwater is precluded. The lower boundaries of the aquifer/catchments of springs 4 and 11 (Table 3.2), were taken to be in the range of 10 m.b.s. and 8 m.b.s. respectively, since these were the depths of the only inflow zones in boreholes greater than 50m deep, and within 10m of the springs. The relatively fast flowing tracing results at springs 5, 6 and 9, (described in section 3.6.2.3), may indicate that their catchments have shallow flow. The presence of turloughs in the vicinity of springs 6-11, indicates that groundwater is also shallow in these areas, since the water-table is at surface. Generally the maximum depth of any of the karst aquifers/catchments in this thesis were taken to be 50m below the surface, since karstification in the lowlands of Ireland is believed to only occur to this depth (D. Drew, pers. comm.).

Information such as groundwater levels, groundwater flow direction, and the travel time of flow, are essential in determining the physical boundaries of a spring catchment. Generally, hydrogeological information was sparse in the study area as there were few borehole records and only three spring areas had water-table maps. The only information available in most cases were the measured discharges of the springs or underground tracing results, compiled by this author over the October 1992 to September 1993 period.

3.6.2 Spring Catchment Delineation

The physical boundaries of the estimated spring catchment areas were principally determined by:

- mapping topographic/piezometric contours and thus establishing regions of divergence of flow (groundwater divides); and
- water tracing using an optical brightener - Leucophor STA.

Details and maps of the individual spring catchment boundary demarcations may be found in Appendices A -K (source reports), but the generalities appear below.

3.6.2.1 Contour Maps

Groundwater levels may be used to determine the direction of groundwater flow by constructing contour maps and flow nets. A minimum of three observation wells are needed to determine a flow direction, which must be levelled to Ordnance Datum. Only three of the eleven spring areas have water table maps, devised previously by others at the Geological Survey of Ireland, and K. T. Cullen & Co. (hydrogeological consultants). They are Ballinagard, Killeglan and Rockingham; all are in Co. Roscommon. The other eight springs had either less than three wells/boreholes in their area, or had more than three wells but with no known Ordnance Datum, and so no contour maps could be completed.

3.6.2.2 Other Groundwater Information

In most of the nine karstic spring areas, there were fewer groundwater level measurement points than the hydrogeologist would like due to the lack of boreholes/wells, and so indirect information on groundwater levels had to be used. Hydrogeological information was supplemented with data on the position and elevation of other springs/seepages, topography, and height of influent rivers. Several 1:126,700/1:10,560 scale Ordnance Survey topographic maps were used to help construct a spring catchment map.

The two non-karstic springs in Crossmolina and Kilkelly drain shallow unconfined sand and gravel aquifers and so their catchments were demarcated by topography alone.

3.6.2.3 Groundwater Tracing

One of the most fundamental items of information about the karstic aquifer is the direction of flow confirmed by water tracing. This choice of method is often dictated by the subsoil cover of a catchment. Tracing is dependant on accessible input points which are often point recharge features such as swallow holes or dolines. Four successful water traces were conducted in three of the nine limestone spring catchments (nos. 5, 6, 9, Table 3.2) using an optical brightener, Sodium Leucophor STA. The fluorescent dye was introduced into swallow holes at medium to high water levels where it disappeared below ground with the flow of a sinking stream. All possible outflow points were monitored for the tracer using a fabric detector constructed of sterile unbleached cotton gauze. Evaluation of the presence of the dye on the detector was visual, with a hand-held ultraviolet source. A velocity of 440m/hr was recorded for the trace at Ballyhaunis. Tracing experiments enabled part of the catchments of springs 5, 6 and 9, to be delineated by the definition of the surface catchments of the sinking streams.

CHAPTER 4

VULNERABILITY

4.1 INTRODUCTION

The European Commission (1991) has recognised that "groundwater is a natural resource with both ecological and economic value.........is limited and should therefore be managed and protected on a sustainable basis". In Ireland it is an offence to pollute groundwater under the Local Government (Water Pollution) Acts of 1977 and 1990. The Geological Survey of Ireland (GSI) have recently completed several county groundwater protection schemes using the technique of vulnerability mapping in order to meet such directives and laws, to prevent groundwater pollution in general and to protect groundwater sources such as springs and boreholes.

Recently the entire subject of vulnerability from its definition to the examination of the vulnerability mapping procedure was re-evaluated at the GSI by Daly and Warren (1994), ending in the publication of a comprehensive set of vulnerability guidelines which appear in Appendix L. This author and several co-workers in the STRIDE project contributed to the vulnerability debate and some of our views were included in the guidelines. The definition of groundwater vulnerability utilised for this thesis was that of the above publication, which is:

> "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".

This chapter describes the factors which influence groundwater vulnerability, and in particular the vulnerability of a karstic spring catchment, and outlines the methods that were used in order to assign a vulnerability rating to the subsoils of the catchments.

4.2 VULNERABILITY

Subsoils are regarded as the single most important natural feature in influencing groundwater vulnerability to pollution. They can act as a protecting or filtering layer over groundwater (Daly and Warren, *op. cit.*). The basic characteristics of subsoils which influence vulnerability are:

- Particle size distribution
- Degree of consolidation and fracturing
- Degree of weathering
- Clay content
- Thickness of subsoils and the unsaturated zone.

(adapted from Deakin, 1993)

Particle size distribution

A well sorted homogenous deposit such as gravel, will have large interconnected pore spaces (interstices) allowing relatively free passage of water (and contaminants) through it. A matrix supported deposit, such as a till, may contain particles of a range of sizes, such as clay, silt, or gravel. These poorly sorted subsoils are generally of a lower permeability and will attenuate contaminants.

Degree of consolidation and fracturing

In general consolidated subsoils such as lodgement till are the product of compaction by the weight of glacier ice and are of a lower permeability than the more loosely packed, porous unconsolidated subsoils such as eskers or alluvium. Glaciotectonics or stress release can cause fracturing in consolidated and over consolidated subsoils. The fractures can be horizontal or vertical, or both. Small solutional conduits may initiate at the site of fractures, allowing a free passage for water or contaminants, providing little attenuation.

Degree of weathering

Weathering of limestone parent material subsoil may cause limestone clasts to decalcify, leaving behind cavities which would increase the permeability of the subsoil.

Clay content

Clay particles aid the attenuation capacity of a subsoil. They may modify the chemistry of incoming recharge or the contaminant, since they offer sites for adsorption, ion exchange, and the degradation of bacteria, or micro-organisms. Clays cause subsoils to have a low permeability since their minute particle size can readily occupy subsoil interstices.

Thickness of subsoils and the unsaturated zone

The thickness of both the unsaturated zone and the subsoils above the water table are of special importance, since they represent the first line of natural defence against groundwater pollution (Foster, 1987). In this zone voids in the subsoils or rock are only partially occupied by water, except after heavy rain when some fill completely. Water percolates downwards in this zone by a multiphase process, with air and water co-existing in the pores and fissures of soils or rock. More significant impediments to downwards flow are sometimes provided, by localised impermeable layers, such as bands of clayey till in an overall sandy till succession, or shale/chert bands in a limestone sequence.

Groundwater is most vulnerable to pollution where the subsoil is absent or very thin. This is particularly common in the karstic lowlands where point recharge via swallow holes or diffuse recharge via bare fissured rock occurs, allowing water or contaminants to enter the water table with minimal attenuation. Each of the springs under study drain shallow unconfined aquifers with thin unsaturated zones. These aquifers are in direct hydrogeological connection with the surface, and hence are generally more vulnerable to contaminants originating at or near the surface than confined aquifers.

Shallow wells, abandoned quarries, and pits are sometimes used for the disposal of storm water, household rubbish and other unwanted material. Commonly the holes intercept the water table or permeable zones and allow the direct feeding of contaminants into aquifers.

4.3 VULNERABILITY MAPPING PROGRAMME

4.3.1 Vulnerability of the Ten 1:25,000 scale Subsoil Reconnaissance Maps

As discussed in Chapter 2, the subsoils of the eleven spring areas were mapped onto ten 1:25,000 scale sheets. Four of the sheets were digitised by this author (Co. Mayo sheets) using ArcInfo™, a GIS package, and six were digitised by SRTC personnel onto Autocad™. Any available depth-to-bedrock data for each sheet were extracted from wellcards on file at the GSI, and entered into a computer database by SRTC personnel. Records of detailed trial pitting and section logging carried out by this author for the Ballyhaunis, Barnaderg, and Crossmolina spring areas were entered onto a DBase III™ template, devised by this author and Ms. S. Pipes of the TCD GIS group.

All ten maps, the depth to rock records, and the DBase III™ data, were sent on discs to the TCD GIS group, for cleaning and reclassification. The TCD GIS group decided that up to three sets of vulnerability rules would have to be used in order to generate the ArcInfo™ vulnerability maps from this digital data set. Certain areas of each of the ten 1:25,000 scale subsoil sheets lacked depth to rock data, but other areas had depth to rock data or had details of trial pit sections. Table 4.1 outlines the rules used by the GIS group for the areas which had no depth to rock information whatsoever. Where both the subsoil type and depth to bedrock were known in certain parts of a 1:25,000 scale sheet the improved and achievable

TABLE 4.1
Vulnerability rules used by the GIS team for the areas that had no depth to rock information whatsoever.

Extreme vulnerability:	Bedrock outcrop, bedrock near surface
High vulnerability:	Sands and Gravels, Esker
Low vulnerability:	Bog
Unknown vulnerability:	Undifferentiated till, Drumlins, Alluvium.

TABLE 4.2
GSI Improved and Achievable Guidelines for Vulnerability mapping.

Vulnerability Rating	Hydrogeological Setting
Extreme	1. Outcropping bedrock or where bedrock is overlain by shallow (3m or less) subsoil. 2. Sand and gravel aquifers with a shallow (3m or less) unsaturated zone. 3. Within 30m of karstic features (including along the area of loss of losing or sinking streams) and within 10m on either side of losing or sinking streams up flow of the area of loss to the source. (In certain circumstances, for instance, where overland surface runoff is likely, greater distances may be needed).
High	1. Bedrock overlain by > 3m of high permeability sand and gravel, or 3-10m of intermediate permeability subsoil such as sandy till or 3-5m of low permeability subsoil such as clayey till, clay or peat. 2. Unconfined sand and gravel aquifers with an unsaturated zone > 3m.
Moderate	1. Bedrock overlain by > 10m of intermediate permeability subsoil such as sandy till or 5-10m of low permeability subsoil such as clayey till, clay or peat. 2. Sand and gravel aquifers overlain by > 10 m of moderate permeability subsoil such as sandy till or 5-10m of low permeability subsoil such as clayey till, clay or peat.
Low	1. Bedrock overlain by > 10m of low permeability subsoil such as clayey till, clay or peat. 2. Confined gravel aquifers overlain by > 10 m of low permeability subsoil such as clayey till or clay.

TABLE 4.3
Steps taken in preparing a vulnerability map for the Lez springs, France.

1. Determine the inventory of the karst system in the area.
2. Determine the limits of each system - tracers, hydrochemistry *etc.*
3. Look at recharge zones, point and diffuse, map soils and subsoils.
4. Look at the circulation zones in karst.
5. Look at fractures, using aerial photographs.
6. Look at geomorphology.

(after Avias, 1994)

GSI vulnerability mapping rules (Table 4.2) were used, whereas in areas with poorer information, the minimum standard GSI vulnerability rules were used (Appendix L).

In total ten vulnerability maps at the 1:25,000 scale were generated with ArcInfo™ by the GIS group. These maps were incorporated into three 'county' maps at the 1:126,720 scale for use with the synthetic Stride report (Thorn, 1994).

4.3.2 Vulnerability of the Eleven Spring Catchments

In considering spring vulnerability, the catchment area of the spring or zone of contribution (ZOC) must first be delineated as was done in Chapter 3, and the subsoils for the area are mapped at a detailed level with trial pitting, Chapter 2. In addition, further items can be taken into account when determining the vulnerability of a spring catchment such as the residence time of groundwater in the aquifer, potential linkages of swallow holes to source, transport rates, dilution, and the attenuation potential of the limestone. Such additional factors (Table 4.3) were carried out by Avias (1994) who determined a 1:25,000 scale vulnerability map for the karstic Lez Springs, in France.

Spring catchment vulnerability maps for the 11 springs were determined with the GSI improved and achievable vulnerability mapping rules (Table 4.2) at either the 6" or 1:25,000 scale depending on catchment size. In addition, the steps set out by Avias (apart from step 4) were considered for the nine limestone springs.

The vulnerability maps for each spring catchment are enclosed in Appendices A - K, as part of the separate source reports.

The mapped vulnerabilities for the springs are further presented as a percentage (%) vulnerability, in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), which occur within the confines of each spring catchment. These % values appear in Table 4.4.

TABLE 4.4	
SPRING	**% Vulnerability of Catchment Area as Defined by Subsoils Mapping**
1 KILKELLY	1 % Extreme 99 % High
2 CROSSMOLINA	0.1 % Extreme 99.9 % High
3 BARNADERG	100 % High
4 BALLINLOUGH	10 % Extreme 90 % High
5 BALLYHAUNIS	26 % Extreme 69 % High 5 % Moderate
6 BALLINAGARD	33 % Extreme 67 % High
7 BALLINDINE	10 % Extreme 90 % High
8 MOUNT TALBOT	47 % Extreme 53 % High
9 KILLEGLAN	50 % Extreme 50 % High
10 BELMONT	100 % Extreme
11 ROCKINGHAM	100 % Extreme

CHAPTER 5

HYDROCHEMISTRY

5.1 INTRODUCTION

In any aquifer situation, chemical reactions such as adsorption, solution-precipitation or acid-base reactions may be occurring and thus modifying the chemistry of groundwater (Lloyd and Heathcote, 1985). Which hydrochemical process dominates at the time may depend on certain aquifer features or intrinsic parameters such as the mineralogy of the aquifer, the hydrogeological environment, the type and thickness of overlying subsoils, or the history of groundwater movement. In this dependence lies the usefulness of hydrochemistry; the inverse can be solved, that is information about the aquifer environment can be deduced.

"The probability of a randomly drilled monitoring well intercepting the trunk conduit which drains a groundwater catchment is similar to the probability of a dart randomly thrown at a wall map of Ireland, hitting the River Shannon! Therefore springs rather than wells are the most logical, efficient, reliable, and economical places to monitor the hydrochemistry of limestone aquifers" (adapted from Quinlan and Ewers, 1985).

5.2 WATER CHEMISTRY ANALYSIS

Water chemistry at each spring was assessed over the October 1992 to September 1993 period. Field measurements and laboratory based analyses of the springs were undertaken by personnel from both the EPA Regional Laboratory in Castlebar, Co. Mayo, and the Environment Section of Roscommon Co. Council. Electrical conductivity (EC) and temperature (°C) were sampled fortnightly, in the field, using a WTW microprocessor conductivity meter. EC values were measured within about +/-1% error, and automatically corrected to 25°C. Water samples of 500ml, were taken at the same time in order to determine total hardness (mg/l $CaCO_3$) and pH in the laboratory. Full chemical analyses were carried out four times over the year in order to allow a proper hydrochemical interpretation of the springs and the calculation of an ion balance error. The main parameters sampled for the full analyses appear in Table 5.1.

Coxon and Thorn (1989a) have demonstrated clearly that frequent sampling of more than once a fortnight is necessary to study the hydrochemical variation of a karstic aquifer, since any chemical changes occurring are usually short term and are often related to rainfall events and changing flow conditions. Flood peak related sampling (Quinlan & Alexander, 1987) at the hourly level, is thought to be more useful than regular sampling for a karstic aquifer.

Monetary and organisational constraints did not allow such a sampling regime and so the level of sampling in this study may be inadequate, causing any conclusions that are formed in the later chapters to be tentative. A more detailed sampling regime is required before the conclusions of this study can be verified.

TABLE 5.1
List of chemical and physical parameters sampled for a full chemical analysis.

Electrical Conductivity (μS/cm)	Total coliforms/100ml	Ca (mg/l $CaCO_3$)
pH	Faecal Coli/ E.Coli	Mg (mg/l $CaCO_3$)
Temperature (^oC)		Na mg/l
Total Hardness (mg/l $CaCO_3$)		K mg/l
Alkalinity (mg/l $CaCO_3$)		Cl mg/l
Fe mg/l		SO_4 mg/l
Mn mg/l		NO_3 mg/l

When investigating hydrochemistry for a base study (Coxon and Thorn, *op. cit.*) it would be reasonable to exclude springs with a history of pollution since the hydrochemical variation at a spring may not only be due to the natural properties of the catchment or aquifer, but it may also be due to a contaminant pulse. A contaminant pulse may be seasonal as is often the case with certain pollutants such as nitrate, when it builds up in the drier soils of the summer months and is released to the water table after heavy winter rains, or due to the wastes themselves being seasonal, such as silage effluent in May and June. However, where an aquifer is karstic with a lack of overlying subsoils or a predominance of point recharge features, the contaminant pulse will tend to move to the water table during shorter periods, and consequently will have a diminished influence on the hydrochemical variation of the spring catchment or aquifer.

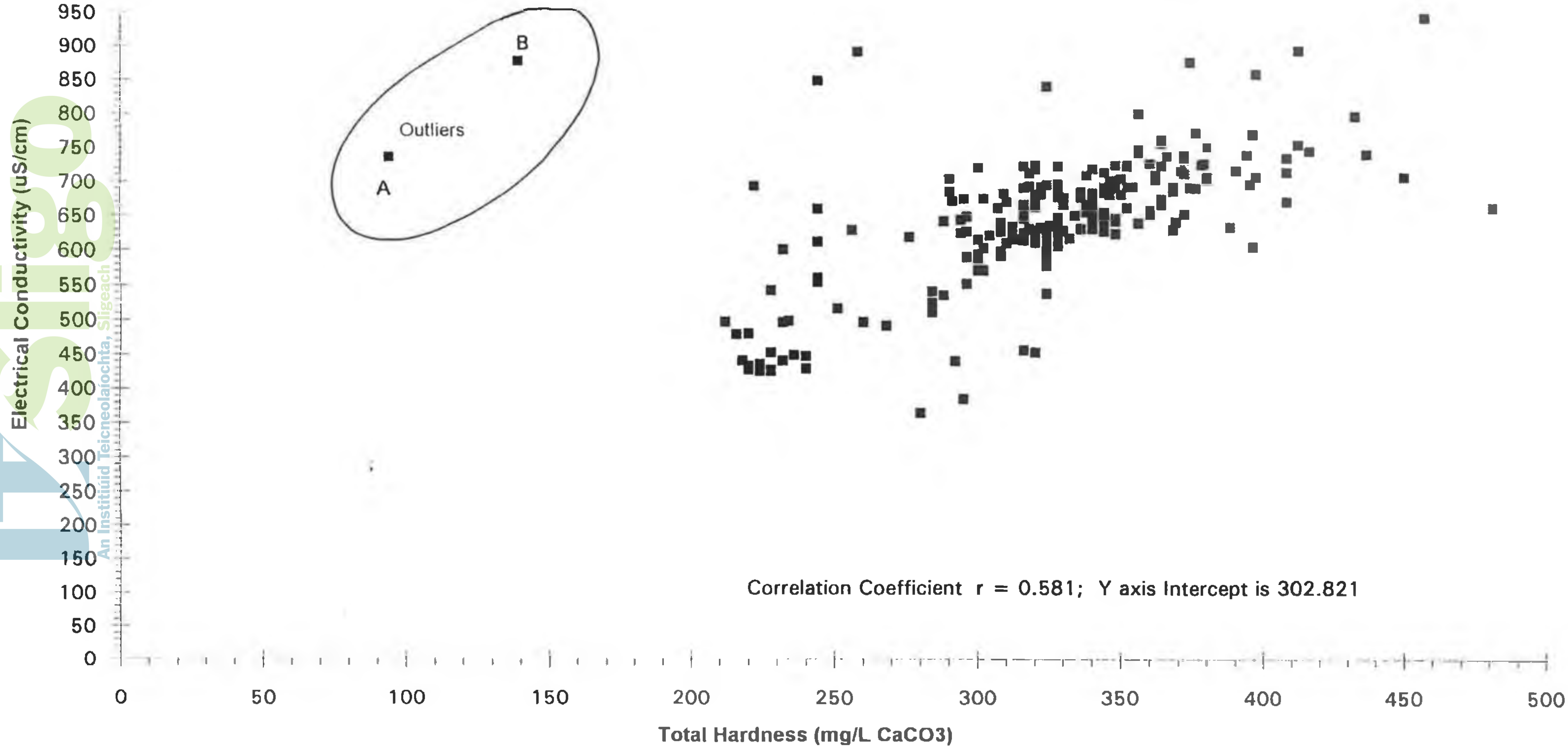
5.3 HYDROCHEMICAL VARIATION

5.3.1 Inspection of Raw Data

Appendix M, presents the raw data for the parameters sampled at each spring, with summary statistics of EC and Hardness.

The most obvious feature of the chemical data in Appendix M, is the poor relationship between the total hardness data sets and the EC data sets, as depicted when comparing the coefficients of variation of EC and hardness, and by a correlation analysis of the complete set of EC and hardness values, which is graphed in Figure 5.1. The coefficient of variation is the standard deviation divided by the sample mean; it is a statistical parameter that was originally used by Shuster and White (1971), and is examined in detail in Chapter 6.

FIGURE 5.1 **Correlation Analysis of Electrical Conductivity and Total Hardness readings for all 11 Springs**



The correlation coefficient in Figure 5.1, between the complete set of EC and hardness values is a poor 0.581, with a wide scattering of data points on either side of the best fit regression line. Two outliers on the graph illustrate some of the inconsistencies between the EC and hardness relationship; to the very left of the graph, the samples marked A and B, taken at Ballinlough spring (8/9/93) and Mount Talbot spring (7/9/93) have relatively high EC values of 736 μS/cm and 878 μS/cm respectively, but have extremely low corresponding hardness values of 94 mg/l $CaCO_3$ and 139 mg/l $CaCO_3$. Such low hardness values are not compatible with the high EC levels measured in the field since rather well defined relationships exist for hardness and EC in Ireland. The only way to explain these opposite readings is that the two hardness samples were stored for some time before titration occurred allowing the deposition of calcium carbonate, or that the samples were improperly titrated in the laboratory.

Groundwater contains excess carbon dioxide; when groundwater re-emerges at the surface CO_2 will diffuse out, causing the pH to rise. Major chemical changes may occur after the exposure of groundwater to the atmosphere. The loss of excess CO_2 and a rise in pH may cause the deposition of calcium carbonate (Coxon and Thorn, 1989b). In hindsight, the analysis of total hardness should have been carried out in the field at the same time as EC and temperature, in order to avoid the risk of the deposition of $CaCO_3$. If it is not practical to measure hardness in the field, Langmuir (1971) recommends that samples for HCO_3^- analysis be packed in ice on site and brought to laboratory temperatures just prior to titration, with the bicarbonate titration being carried out within 24 hours of sampling. None of these recommendations were carried out in either the EPA or Roscommon Co.Co. laboratories; in certain cases titration occurred 21 days after sampling.

The poor correlation between EC, sulphate and bicarbonate (total hardness) is a common feature of all groundwaters (Lloyd and Heathcote, *op. cit.*). The poor correlation between EC and hardness in this thesis may simply follow this trend or, it may be that sampling/laboratory techniques added to the trend.

Hardness is a poor overall chemical indicator since it only measures the concentrations of the CO_3^{-2}, HCO_3^-, SO_4^{-2} and Cl^{-2} ions. Tills or subsoils that overlay a karstic aquifer may have strong elements of non-carbonate chemistry, depending on the parent material. The chemistry of groundwater in a karstic aquifer would certainly be influenced by the overlying subsoil deposits; recharge water will achieve equilibrium with the minerals present in a till as it infiltrates to the water table (Spears and Reeves, 1975). Therefore some other indicator is necessary to determine the effect subsoils have on the hydrochemistry of a spring catchment.

EC is usually more related to total dissolved solids (E. Daly pers. comm.) and the major ions such as Cl^-, K^+, Na, and NO_3^{-2}, parameters that would be better measures of the chemistry of a subsoil than hardness alone. EC is highly correlated with the major ionic species and provides an indication of ion concentration (Hem, 1970). It is a quick, extremely inexpensive surrogate for a chemical analysis when it is not necessary to know what specific ions are present.

With this and the sampling problems discussed above, it was decided that electrical conductivity (µS/cm) should be the main parameter used in order to determine the hydrochemical variation of a spring water through time.

5.3.2 Distribution of EC data

Figure 5.2 shows a histogram of EC values for the complete data set of all 11 springs, and a simple statistical analysis of the distribution appears in Table 5.2. The histogram shows that the main cluster is about the EC values of 515 µS/cm - 770 µS/cm, a range typical of water that is hosted in limestone bedrock. The smaller peak of 425 µS/cm - 500 µS/cm is the signature of the Kilkelly spring since it is a sand and gravel based spring where the underlying geology and a certain percentage of the parent material of the gravels is Carboniferous sandstone.

TABLE 5.2 Statistical Analysis of the EC data	
Mean	645.7916667
Median	655.5
Mode	691
Standard Deviation	99.25196336
Variance	9850.952232
Kurtosis	0.925134451
Skewness	-0.288683641
Range	578
Minimum	365
Maximum	943
Sum	154990
Count	240

5.3.2.1 Analysis of Variance of the Limestone Springs (ANOVA)

An ANOVA (Table 5.3) was carried out on the electrical conductivity values of the 9 limestone springs to determine if EC variation between the springs is not larger significantly than the variation of EC within each spring. It was found that F at 8.25, was higher than the critical value of 1.7, and so this statement (Ho) had to be rejected. This ANOVA suggests that EC variation is more dependant on individual real characteristics of a spring such as geology, hydrogeology, subsoils, etc., and not due to sampling error.

FIGURE 5.2 Histogram of Electrical Conductivity values for the 11 Springs

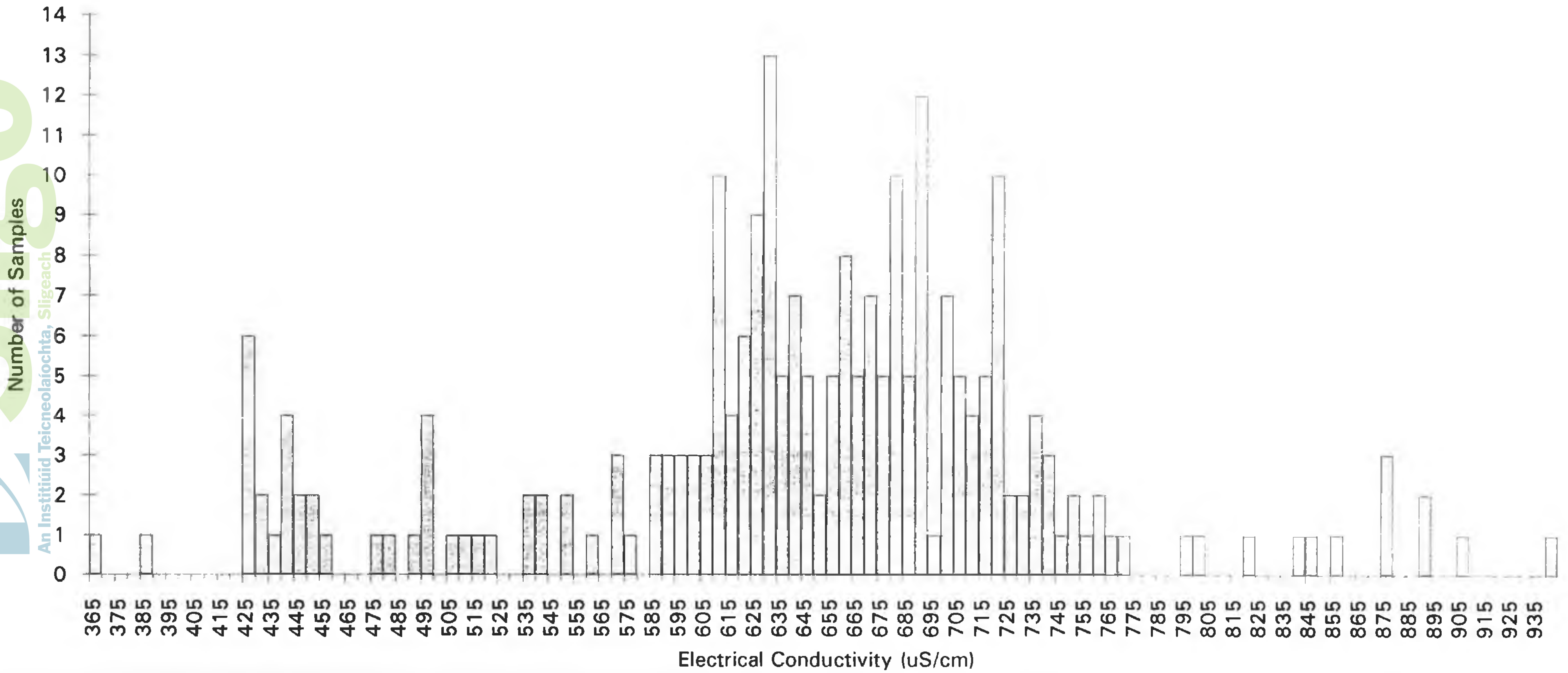


Table 5.3
Anova: Single-Factor

Springs	Count	Sum	Average	Variance
Ballyhaunis	23	13622	592.2609	2930.929
Mt Talbot	23	16407	713.3478	5091.601
Ballinlough	22	15234	692.4545	2968.355
Ballinagard	22	16203	736.5	4623.31
Rockingham	20	12512	625.6	12494.67
Killeglan	24	15619	650.7917	6676.52
Ballindine	21	13397	637.9524	3705.248
Barnaderg	20	13541	677.05	2214.05
Belmont	20	13666	683.3	9557.274

Anova

Source of Variation	SS	df	MS	F	P-value	F crit
Between Springs	363945.7	8	45493.21	**8.258258**	1.49E-09	**1.703468**
Within Springs	1024639	186	5508.814			
Total	1388585	194				

5.3.2.2 Seasonal Variation of EC

The variation of EC values over the October 1992 to September 1993 period in the two sand and gravel springs and five of the limestone springs are graphed in Figures 5.3 and 5.4, respectively.

Figure 5.3 shows that the variation in EC over the year for the two sand and gravel springs was minimal (a relatively smooth graph). These signatures reflect the relatively long residence times groundwater or recharge tends to have in these types of aquifer.

The plot for the five limestone springs, Figure 5.4, shows irregular and non-uniform variation in EC values for the year; signatures that are typical of karstic aquifers. The elevated EC values of the 845 µS/cm - 940 µS/cm peaks are coincident with the late July, August, and early September 1993 period, when recharge levels were at their lowest for the area. The low levels of 450 µS/cm - 550 µS/cm are coincident with the elevated rainfall periods in January 1993.

FIGURE 5.3 EC Variation at the Kilkelly and Crossmolina Springs, with Rainfall

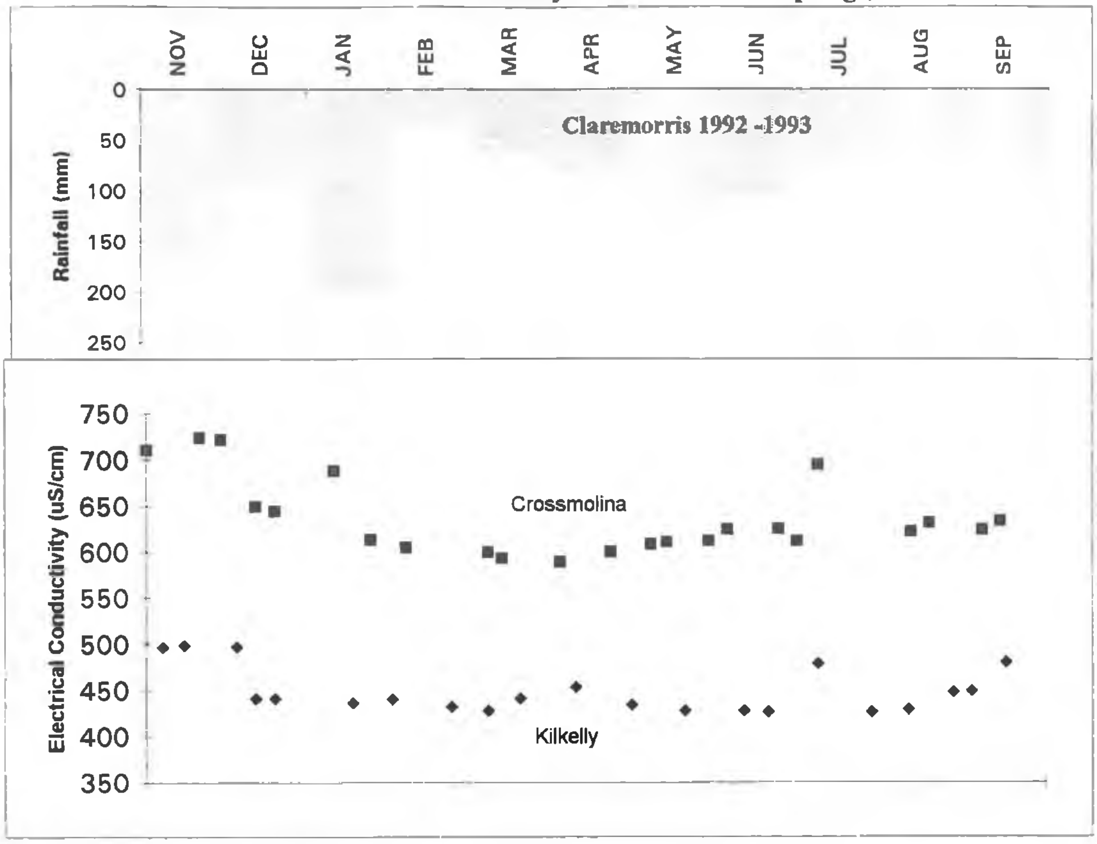
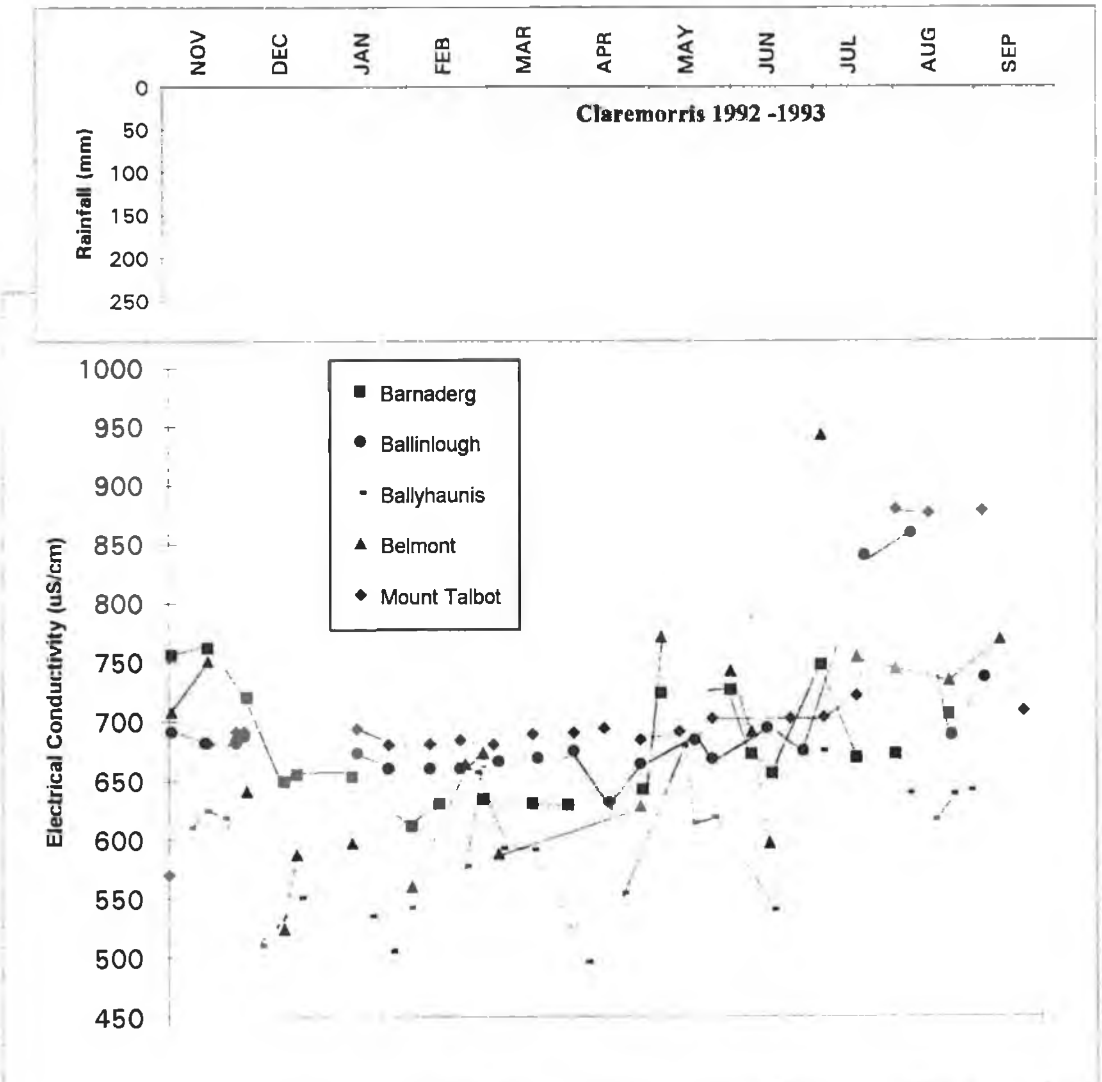


FIGURE 5.4 EC Variation at 5 Limestone Springs, with Rainfall



5.3.2.3 Coefficient of Variation of EC

EC variation for each spring was determined using the coefficient of variation as used by Shuster and White (*op. cit.*), but calculated for a polymodal distribution as stated by Quinlan *et al.* (1991). The coefficients of variation for each spring appear in Table 5.4; the springs are listed in an order defined by the increasing coefficient of variation of EC.

TABLE 5.4
Coefficient of Variation of EC for the 11 Springs under study

SPRING	COEFFICIENT OF VARIATION EC [SD/$\bar{x}$ (%)]
1 KILKELLY	5.6%
2 CROSSMOLINA	6.6%
3 BARNADERG	6.95%
4 BALLINLOUGH	7.9%
5 BALLYHAUNIS	9.1%
6 BALLINAGARD	9.2%
7 BALLINDINE	9.5%
8 MOUNT TALBOT	10.0%
9 KILLEGLAN	12.6%
10 BELMONT	14.3%
11 ROCKINGHAM	17.9%

The characterisation and interpretation of the EC variation at the 11 springs appears in Chapter 6.

5.4 WATER QUALITY

Although the data set for the full chemical analysis was not as comprehensive as was desired, a preliminary attempt was made to investigate the overall water quality of the springs. Tables 5.5 to 5.15 present the main chemical parameters measured at each spring, with summary statistics.

The Irish Drinking Water Standards S.I. No. 81 (Dept. of Environment 1988) were used to provide the maximum admissible concentrations (MAC) of chemical parameters. The guide levels for certain parameters were taken from the EU Directive on Quality of Water for Human Consumption (80/778/EEC). The MAC for bacteria counts were taken from the Official Journal of the EU No. 4229/11.

TABLE 5.5

1. Kilkelly Parameter	No. of Obs (n)	Min.	Max.	Median	Mode	Mean (X)	S.D.	S.D./ X %	*E.U./ Irish MAC, (G.L.)*
Conductivity uS/cm	21	426	498	441	441	449	25	5.6%	*1500*
pH	21	6.4	7.8	7.4	7.3	7.39	0.3		*6.0 -9.0*
Temp °C	21	8.8	19.5	10.4	9.5	11.94	3.4	28.45%	
Total Hardness mg/l $CaCO_3$	20	212	292	228	232	230	16.5	7.19%	
Fe mg/l	1		0.1						*0.2*
Mn mg/l	1		0.05						*0.05*
Total Coliform	3	8	50	20		26	21.6		*0*
Faecal Coliform	3	3	20	8		9.3	10.07		*0*
K mg/l	1		2						*12 (10)*
NO_3 mg/l	2	1.46	2.26						*50 (25)*
Cl mg/l	2	19	22						*250 (40)*

TABLE 5.6

2. Crossmolina Parameters	No. of Obs (n)	Min.	Max.	Median	Mode	Mean (X)	S.D.	S.D./ X %	*E.U./ Irish MAC, (G.L.)*
Conductivity uS/cm	23	589	724	624	612	636.3	41.9	6.6%	*1500*
pH	22	6.7	7.4	7.05	7.1	7.02	0.18		*6.0 -9.0*
Temp °C	23	8.6	12.4	9.6	10.2	9.74	0.85	8.7%	
Total Hardness mg/l $CaCO_3$	21	232	388	324	328	321.5	27.9	8.69%	
Fe mg/l	1		0.002						*0.2*
Mn mg/l	1		0.001						*0.05*
Total Coliform	2	1	316						*0*
Faecal Coliform	1		1						*0*
K mg/l	0								*12 (10)*
NO_3 mg/l	0								*50 (25)*
Cl mg/l	2	27	28						*250 (40)*

TABLE 5.7

3. Barnaderg Parameters	No. of Obs (n)	Min.	Max.	Median	Mode	Mean (X)	S.D.	S.D./ X %	*E.U./ Irish MAC, (G.L.)*
Conductivity uS/cm	20	611	762	662.5	630	677	47	6.9%	*1500*
pH	21	6.5	7.4	6.9	7.1	6.9	0.2		*6.0 -9.0*
Temp °C	22	8.4	16	10.15	9.7	10.4	1.4	13.46%	
Total Hardness mg/l $CaCO_3$	22	244	408	344	364	342.5	32	9.32%	
Fe mg/l	3	0.003	0.1	0.05		0.05	0.04		*0.2*
Mn mg/l	3	0.001	0.05	0.05	0.05	0.03	0.02		*0.05*
Total Coliform	4	3	143	71		72	69.7		*0*
Faecal Coliform	4	1	100	9.5		30	47.2		*0*
K mg/l	2	0	7						*12 (10)*
NO_3 mg/l	5	1.29	3.7	3.27		2.86	0.99		*50 (25)*
Cl mg/l	5	22	26			23	1.73		*250 (40)*

TABLE 5.8

4. Ballinlough Parameters	No. of Obs (n)	Min.	Max.	Median	Mode	Mean (X)	S.D.	S.D./ X %	*E.U./ Irish MAC, (G.L.)*
Conductivity uS/cm	22	631	859	678.5	660	692.4	54.5	7.87%	*1500*
pH	22	6.96	7.57	7.1	7.03	7.1	0.4		*6.0 -9.0*
Temp °C	21	9.3	11	9.5	9.5	9.7	0.5	5.15%	
Total Hardness mg/l $CaCO_3$	21	94	480	340	340	337	68.4	20.28%	
Fe mg/l	4	0.05	0.249	0.1225	0.136	0.136	0.1		*0.2*
Mn mg/l	4	0.02	0.068	0.028	0.02	0.03	0.02		*0.05*
Total Coliform	4	0	2000	94		547	972		*0*
Faecal Coliform	4	0	1200	73		336.5	579		*0*
K mg/l	4	2	6	3.15		3.57	1.7		*12 (10)*
NO_3 mg/l	4	11.4	14.3	12.2		12.5	1.25		*50 (25)*
Cl mg/l	4	24	31			28.25	3.09		*250 (40)*

TABLE 5.9

5. Ballyhaunis Parameter	No. of Obs (n)	Min.	Max.	Median	Mode	Mean (X)	S.D.	S.D./ X %	*E.U./ Irish MAC, (G.L.)*
Conductivity uS/cm	23	496	679	610	618	592.3	54.1	9.14%	*1500*
pH	23	6.6	7.3	7	7	6.9	0.2		*6.0 - 9.0*
Temp °C	23	7.3	10.5	9.5	9.2	9.4	0.7	7.5%	
Total Hardness mg/l $CaCO_3$	19	228	369	300	284	303.9	37.4	12.32 %	
Fe mg/l	4	0.01	0.15	0.0125	0.15	0.102	0.06		*0.2*
Mn mg/l	4	0.001	0.05	0.021		0.023	0.02		*0.05*
Total Coliform	8	46	650	130		188	198.4		*0*
Faecal Coliform	8	0	198	10.5	0	45	71.9		*0*
K mg/l	1		3						*12 (10)*
NO_3 mg/l	4	1.68	2.34	2.2		2.06	0.327		*50 (25)*
Cl mg/l	4	19	21			20.5	1		*250 (40)*

TABLE 5.10

6. Ballinagard Parameters	No. of Obs (n)	Min.	Max.	Median	Mode	Mean (X)	S.D.	S.D./ X %	*E.U./ Irish MAC, (G.L.)*
Conductivity uS/cm	22	674	907	715	715	736.5	67.9	9.23%	*1500*
pH	21	6.9	7.8	7.09	7.05	7.14	0.17		*6.0 -9.0*
Temp °C	21	9.1	11.5	9.8	9.8	9.81	0.6	6.1%	
Total Hardness mg/l $CaCO_3$	20	258	449	365	372	360.4	46	12.71%	
Fe mg/l	4	0.05	0.05	0.05	0.05	0.05	0		*0.2*
Mn mg/l	4	0.02	0.02	0.02	0.02	0.02	0		*0.05*
Total Coliform	4	12	510	138		199.5	221		*0*
Faecal Coliform	4	1	180	63		77	84		*0*
K mg/l	4	1	8	3.4		3.95	2.9		*12 (10)*
NO_3 mg/l	4	8.8	11.1	9.75		9.85	1.2		*50 (25)*
Cl mg/l	4	24	30			27.75	2.63		*250 (40)*

TABLE 5.11

7. Ballindine Parameters	No. of Obs (n)	Min.	Max.	Median	Mode	Mean (X)	S.D.	S.D./ X %	*E.U./ Irish MAC, (G.L.)*
Conductivity uS/cm	21	453	724	634	718	638	60.8	9.5%	*1500*
pH	21	6.4	7.5	7	7.1	6.9	0.26		*6.0 -9.0*
Temp °C	19	6.9	15.3	9.8	10.2	10.4	1.99	19.13%	
Total Hardness mg/l $CaCO_3$	19	244	372	328	320	328.6	27.2	8.28%	
Fe mg/l	2	0.05	0.1						*0.2*
Mn mg/l	2	0.05	0.05						*0.05*
Total Coliform	2	110	609						*0*
Faecal Coliform	2	20	290						*0*
K mg/l	1		4						*12 (10)*
NO_3 mg/l	3	2.06	3.23	3.08		2.79	0.6		*50 (25)*
Cl mg/l	3	21	22						*250 (40)*

TABLE 5.12

8.Mount Talbot Parameters	No. of Obs (n)	Min.	Max.	Median	Mode	Mean (X)	S.D.	S.D./ X %	*E.U./ Irish MAC, (G.L.)*
Conductivity uS/cm	23	570	879	691	691	713	71.3	10.00%	*1500*
pH	23	6.64	7.54	7.11	7.06	7.1	0.16		*6.0 -9.0*
Temp °C	23	8.3	10.8	9.7	10.8	9.82	0.7	7.1%	
Total Hardness mg/l $CaCO_3$	21	139	394	348	362	327.9	55.9	17.05%	
Fe mg/l	4	0.05	0.05	0.05	0.05	0.05	0		*0.2*
Mn mg/l	4	0.02	0.02	0.02	0.02	0.02	0		*0.05*
Total Coliform	4	2	250	78		102	110.4		*0*
Faecal Coliform	4	1	150	35		55	69.3		*0*
K mg/l	4	1.7	10	8	8	6.9	3.6		*12 (10)*
NO_3 mg/l	4	8.9	11	10.1		10	0.92		*50 (25)*
Cl mg/l	4	27	33			29.75	2.75		*250 (40)*

TABLE 5.13

9. Killeglan Parameters	No. of Obs (n)	Min.	Max.	Median	Mode	Mean (X)	S.D.	S.D./ X %	*E.U./ Irish MAC, (G.L.)*
Conductivity uS/cm	24	491	849	638	630	650.8	81.7	12.56%	*1500*
pH	23	6.98	7.83	7.2	6.98	7.2	0.16		*6.0 -9.0*
Temp °C	23	8.1	10.3	9.5	9.2	9.5	0.56	5.9%	
Total Hardness mg/l $CaCO_3$	22	244	396	316	316	312	35.9	11.51%	
Fe mg/l	4	0.05	0.12	0.063	0.05	0.07	0.03		*0.2*
Mn mg/l	4	0.02	0.02	0.02	0.02	0.02	0		*0.05*
Total Coliform	4	2	230	8		62	112		*0*
Faecal Coliform	4	2	50	5	2	15.5	23		*0*
K mg/l	4	1	3	2	2	2	0.8		*12 (10)*
NO_3 mg/l	4	6.5	16.5	14.3		12.9	4.4		*50 (25)*
Cl mg/l	4	27	33			30	2.94		*250 (40)*

TABLE 5.14

10. Belmont **Parameters**	**No. of Obs (n)**	**Min.**	**Max.**	**Median**	**Mode**	**Mean (X)**	**S.D.**	**S.D./ X %**	***E.U./ Irish MAC, (G.L.)***
Conductivity uS/cm	20	524	943	682	597	683.3	97.8	14.3%	*1500*
pH	20	6.5	7.4	7	7.2	6.9	0.2		*6.0 -9.0*
Temp °C	21	7.5	11.5	9.8	8.5	9.8	1.2	12.24%	
Total Hardness mg/l $CaCO_3$	22	244	456	360	324	351	51.7	14.72%	
Fe mg/l	1		0.01						*0.2*
Mn mg/l	1		0.001						*0.05*
Total Coliform	2	0	200						*0*
Faecal Coliform	2	0	200						*0*
K mg/l	1		0						*12 (10)*
NO_3 mg/l	3	0.01	1.67	1.44		1.04	0.9		*50 (25)*
Cl mg/l	3	26	46			33	11.3		*250 (40)*

TABLE 5.15

11.Rockingham **Parameters**	**No. of Obs (n)**	**Min.**	**Max.**	**Median**	**Mode**	**Mean (X)**	**S.D.**	**S.D./ X %**	***E.U./ Irish MAC, (G.L.)***
Conductivity uS/cm	20	365	796	638		625.6	111.7	17.9%	*1500*
pH	21	6.9	7.2	7.05	6.9	7.02	0.09	7.6%	*6.0 -9.0*
Temp °C	21	8.3	11.2	9.4	8.6	9.25	0.7		
Total Hardness mg/l $CaCO_3$	20	280	432	322	302	333.4	40.5	12.14%	
Fe mg/l	4	0.05	0.062	0.05	0.05	0.053	0.006		*0.2*
Mn mg/l	3	0.02	0.02	0.02	0.02	0.02	0.3		*0.05*
Total Coliform	3	6	1060	32		366	601		*0*
Faecal Coliform	2	14	140						*0*
K mg/l	4	1	2	1.9	2	1.7	0.5		*12 (10)*
NO_3 mg/l	4	2.4	11.9	3.85		5.5	4.3		*50 (25)*
Cl mg/l	4	20	32			28	5.7		*250 (40)*

5.4.1 Hardness and Alkalinity

The groundwater in the nine limestone spring catchments is predominantly hard to very hard (Tables 5.7 - 5.15) with total hardness values in the range 228 - 480 mg/l $CaCO_3$. The range in the sand and gravel spring at Crossmolina is 232 - 388 mg/l $CaCO_3$ which is hard (Table 5.6), since the parent material of the gravels is Dinantian limestone. Moderately hard to hard water, in the range of 212 - 292 mg/l $CaCO_3$ occurred at the Kilkelly sand and gravel spring (Table 5.5), where the underlying geology is Carboniferous sandstone. The EC range for this spring is only 426 - 498 µS/cm, which is the lowest range of any of the 11 springs, suggesting that the aquifer has elements of non-carbonate parent material, agreeing well with field evidence since clasts in the gravels consist of up to 20% sandstone.

Alkalinities are generally high for all eleven springs, varying from 206 - 436 mg/l $CaCO_3$. There were three incidents where alkalinity exceeded the hardness values in the Mount Talbot, Ballinlough, and Rockingham springs. Exceedance of the total hardness value by total alkalinity occurs when cation exchange is in operation, caused by the replacement of Ca^{+2} and Mg^{+2} by Na^{+} (Lloyd and Heathcote, *op. cit.*)

5.4.2 Contaminant Indicators

Chloride, Nitrate, Potassium and *E. Coli* are considered to be the main parameters that indicate contamination of a spring (IAH, 1995). Contamination of springs is indicated when levels of these parameters exceed the MAC standards as set out under S.I. No. 81 of 1988, and noted below in Table 5.16. When guide levels (GL) are breached at a spring there should be cause for concern.

TABLE 5. 16 MAC and GLs for Contaminant Indicators.

	MAC	GL	
Chloride mg/l	250	40 or 30	The 40 mg/l GL applies to springs in the west of Ireland since rainfall tends to have relatively high chloride levels here (E.Daly pers. comm.). A GL of 30 mg/l applies to the more mid-central springs.
Nitrate mg/l	50	25	
Potassium mg/l	12	10	
E. Coli. cfu/100ml	0		

Chloride

Of the more western springs only Belmont showed an elevated chloride level of 46 mg/l, slightly above the 40mg/l GL, but very much lower than the MAC. Each of the Co. Roscommon springs (mid-central Ireland [Tables 5.8, 5.10, 5.12, 5.13, 5.15]) occasionally showed levels of chloride above the 30 mg/l GL. These exceedances occurred in summer except for one in Rockingham, which arose in February 1993.

Nitrate

No nitrate exceedances of the GL were recorded at any of the springs.

Potassium

No springs showed an exceedance of the potassium GL of 10mg/l.

E. coli

E. coli is specifically of faecal origin and is the most commonly used indicator of local septic tank or farmyard pollution, which must have occurred sometime in the previous 50-100 days, since 50 days is the lifespan of this bacterium in low permeability subsoils and 100 days in sands. Bacterial contamination is well documented in the karst areas of the west of Ireland (Daly, 1988; Aldwell, 1988; Drew and Daly, 1994). It is endemic where karstic aquifers have poor natural protection, even where the contaminant load is low (Thorn and Coxon, 1992). It is usual for open springs to have a small coliform count due to the presence of birds or animals that may enter the confines of the spring for water, etc..

All of the 11 springs under study showed some *E. coli* contamination; most had levels of less than 200 cfu/100 ml. However, it must be stressed that not enough sampling occurred in any of the springs to determine if such *E. coli* levels are common, and thus a cause for concern. Nevertheless, 3 springs showed very high *E. coli* levels, above a count of 200 cfu/100 ml. They are springs 4, 7, and 10, outlined in Table 5.17, below, although two of these springs showed counts of 0 cfu/100 ml for certain periods.

TABLE 5.17 Summary of *E. Coli* readings for 3 Springs

***E. Coli* cfu/100 ml**	**n**	**Min**	**Max**	
10. Belmont	2	0	200	
4. Ballinlough	4	0	1200	Readings 0; 2; 144; 1200
7. Ballindine	2	20	290	

5.4.3 Other Parameters of Water Quality

Sulphate

No sulphate exceedances over the GL of 25 mg/l were recorded at any of the springs.

Iron and Manganese

Only Ballinlough spring showed elevated levels of iron or manganese with a value of 0.249 mg/l Fe and 0.068 mg/l Mn, occurring on 10/8/1993. Iron is known to attach to sand and gravels and it is common to find high levels of iron in sand and gravels that overlie muddy limestones; the spring Ballinlough, matches such geological conditions.

5.4.4 Synopsis

The chemical analyses agree well with the statement that groundwater pollution in Ireland is mostly microbial, and not chemical (Daly, pers. comm.).

CHAPTER 6

CONCLUSIONS

THE GEOLOGY, HYDROGEOLOGY, VULNERABILITY AND HYDROCHEMICAL VARIATION OF THE 11 SPRING CATCHMENT AREAS

6.1 HYDROCHEMICAL VARIATION - A Review

The characterisation and interpretation of the hydrochemical variation of springs has been the basis for several karstic aquifer studies.

Shuster and White (1971) analysed 14 karstic springs in the Appalachian Mountains, Pennsylvania, U.S.A., at two weekly intervals during 1967-68, in order to determine the variation of hardness, degree of saturation with respect to calcite and dolomite, and the Ca/Mg ratio at each spring. The authors classified the springs into diffuse flow type and conduit flow type mainly by the existence of karstic landforms such as karren, dolines or sinkholes. In this benchmark paper the authors recognised that the conduit flow springs were very variable in hardness throughout the year, whereas the diffuse flow springs had a rather constant hardness. They expressed hardness variation as the coefficient of variation, which is the standard deviation divided by the sample mean ($SD/\bar{X}$ %). The conduit flow springs were discovered to have had a coefficient of variation in the range of 10% - 24%, and the diffuse flow springs had a coefficient of variation of less than 5%. However, in summarising this paper with a view to applying some of their observations to this thesis, two issues arise:

(i) Firstly, the authors unsatisfactorily classified the springs into diffuse flow type and conduit flow type mainly by the existence or absence of karstic landforms. Where there was no evidence of such landforms "none observed", the authors recognised a spring to be diffuse flow type. However, several of their 'diffuse' springs emerge from a cave within a major fault or fracture zone; these springs should have been classed as conduit flow type according to the authors definition of conduit flow, which is ".......water flowing, often turbulently, through solution passages measured in centimetres to meters".

(ii) Secondly, it is not clear the affect subsoil had on the hydrochemical variation of the two spring flow types. The overlying subsoils were dominantly described as thin or lacking, mainly consisting of 'weathered mantle'. No attempt was made to itemise the subsoil extent or texture, yet where no karst features were observed, there must have been a certain extent of subsoil in the area to occlude such features.

In this author's opinion the two ranges of the coefficient of variation of hardness would have been better explained by not just the type of aquifer flow, but also the type of recharge and overlying subsoil cover for each aquifer or spring catchment.

Bakalowicz and Mangin (1980), criticised Shuster and White's use of the coefficient of variation of carbonate hardness for defining the flow type of a karstic aquifer since it is not a valid measure of the complexity of the polymodal distribution of hardness. This is because the accuracy of the standard deviation used to calculate the coefficient of variation is based on the validity of the assumption of a normal distribution. In a discussion of this statement, Quinlan *et al.* (1991), noted that Bakalowicz and Mangin were technically correct, but that the standard deviation can still be calculated for a polymodal distribution, since it is still a measure of dispersion about the mean. However the mean +/- one standard deviation, might include only 50% of the hardness values, rather than 68.27%, which would be expected in a normal distribution. Disregarding the use of the coefficient of variation as an indicator of hardness variation, Bakalowicz and Mangin (*op. cit.*) proposed the use of the frequency distribution of electrical conductivity. They suggest that where frequency distributions are unimodal with high electrical conductivity (EC) values, the aquifers are 'porous' or granular. Unimodal frequency distributions with low EC values indicate a fissured aquifer, and multimodal frequency distributions with a wide range of EC values indicate a well developed karstified aquifer.

The hydrochemical variation of a spring may depend on the following intrinsic factors, which influence the contact time between the recharge water and the host material (Doak *et al.*, 1995):

i) the presence of a subsoil, its permeability and thickness;
ii) the presence of a subsoil (with an intergranular permeability) beneath the watertable, particularly gravel which can sometimes be present at or close to a spring, and which could lower the hydrochemical variation;
iii) the type and rate of recharge - whether point or diffuse;
iv) the flow system in the aquifer - whether conduit, fissure or intergranular, or a combination;
v) the degree of storage, which in certain circumstances could lessen the variation.

All these factors with the exception of (v) were considered in assessing the hydrochemical variation of the eleven springs in this study.

6.2 RESULTS

A synthesis of the subsoils geology, geology and hydrogeology, vulnerability, and hydrochemical variation for the eleven springs (from previous chapters) appears in Table 6.1. The EC values over the October 1992 to September 1993 period at each of the springs are presented as frequency distributions in Figure 6.1, so as to enable interpretation of the data sets as per Bakalowicz & Mangin (*op. cit.*). In both Table 6.1 and Figure 6.1, the springs are listed in an order defined by the increasing coefficient of variation of EC.

Springs 1 and 2 (Table 6.1; Kilkelly and Crossmolina), which have the lowest coefficient of variation, are hosted in sand and gravel aquifers.

Springs 3 - 11, are hosted in limestone aquifers, although at springs 3 - 5 sand and gravel is present beneath the water table at, and in the vicinity of the springs. Three of the limestone springs (3, 4 and 11) have no obvious karst morphological features at the surface, whereas the remainder (5 - 10) have features that indicate point recharge and conduit flow conditions. However, in the catchment areas of springs 4 and 11 (Ballinlough and Rockingham), there is little surface drainage and cavities have been recorded in nearby boreholes.

6.3 DISCUSSION

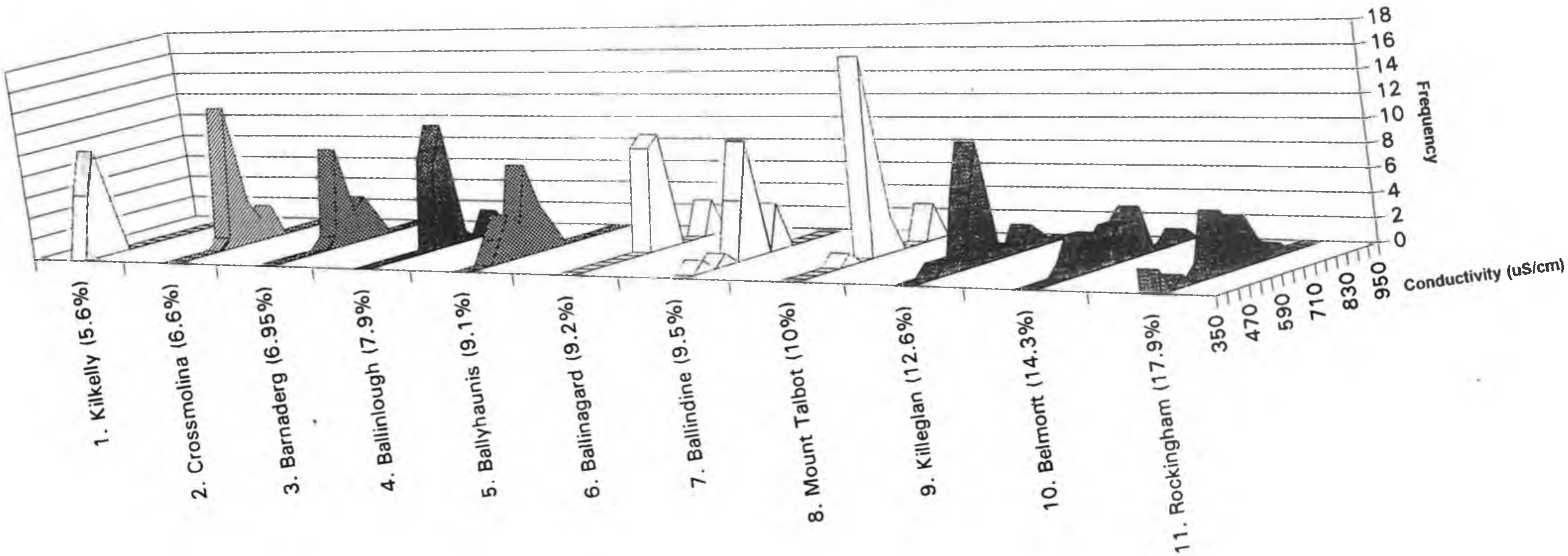
The two sand and gravel springs (1, 2) have a low coefficient of variation of EC and either a unimodal or bimodal frequency distribution in Figure 6.1. This signature reflects the diffuse recharge, the relatively slow intergranular flow and the relatively long residence time for groundwater in the sand and gravel aquifers.

The relationship between the coefficient of variation and the frequency distribution of EC for the nine limestone springs (3 - 11) in Figure 6.1, is not constant or clear-cut, although the springs with higher coefficients of variation have a multimodal distribution and a wider range. Springs 3 and 4, do not show the expected multimodal 'karstified' frequency distribution as indicated by Bakalowicz and Mangin (*op. cit.*). Instead both springs show a bimodal frequency distribution of EC. Two factors may explain this: firstly, the data available in graphing the frequency distribution are not adequate; and/or secondly there is no significant evidence of point recharge. The presence of subsoils over the limestone is thought to buffer the diffuse recharge causing it to have an appreciable total dissolved solids (hence EC) before

TABLE 6.1 Synoptic Table for the Eleven Springs

SPRING	AQUIFER GEOLOGY	SPRING DETAILS (i) Estimated Avg. Spring Output (ii) Minimum flow (iii) Maximum flow (iv) Catchment size	WELL DETAILS If within 1km of the spring (1) Depth (5) Abstraction Rate (2) Diameter (6) Specific Capacity (3) Depth to Rock (7) Inflows (4) Static Water Level	SUBSOILS a) Type/texture b) % Areal extent of the subsoils in the spring catchment c) Depth to rock	KARSTIC FEATURES	RECHARGE TYPE	Frequency Distribution of Electrical Conductivity	% Vulnerability of Catchment Area as Defined by Subsoils Mapping	COEFFICIENT OF VARIATION OF EC
1 KILKELLY	Sand and Gravel	(i) 3,300 m^3/d (ii) 1,700 m^3/d (iii)3,900 m^3/d (iv) 1.6 km^2	-	a) Eskers, sand and gravel of glacio-lacustrine origin. High Permeability (k). b) 100 % areal extent. c) > 5m, often > 15m.	None	Diffuse	Unimodal	1% Extreme 99% High	**5.6%**
2 CROSSMOLINA	Sand and Gravel	(i) 1,560 m^3/d (ii) 850 m^3/d (iii)4,800 m^3/d (iv) 0.85 km^2	-	a) Sand and gravels of glaciolacustrine origin (High k). Blanket peat overlies thick deposits of Low k limestone till. b) 100 % areal extent. c) 3 - 5m, except at source.	None	Diffuse	Uni/bimodal	0.1% Extreme 99.9% High	**6.6%**
3 BARNADERG	Pure Limestone (Diffuse flow)	(i) < 2,000 m^3/d (ii) - (iii) - (iv) < 1 km^2	-	a) Eskers, sand and gravel. Stony till. Medium to High k subsoils. b) 100 % areal extent. c) > 3m, except at source.	None evident	Diffuse	Bimodal	100% High	**6.95%**
4 BALLINLOUGH	Pure Limestone. Sand and Gravels near/at spring. (Conduit flow)	(i) 3,000 m^3/d (ii) 2,950 m^3/d (iii) - (iv) 2.5 km^2	Trial well No. 1 (1) 61 m (2)150 mm (3) 7.5 m (4) - (5) 5,000 m^3/d (6) - (7) 8, 10 m.b.s. Pump. well No. 1 (1) 12.5 m (2) 200 mm (3) 6.2 m (4) 1 m. b. s. (5) 3,036m^3/d (6) 1,128 m^3/d1m (7) 8, 10 m.b.s.	a) Eskers, sand and gravel. Clayey limestone till. Medium to High k subsoils. b) 98% areal extent. Outcrop in high ground at catchment divide. c) > 3m to 10m. ~ 6m at source.	Cavities in borehole	Diffuse	Bimodal	10% Extreme 90% High	**7.9%**
5 BALLYHAUNIS	Muddy (Impure) Limestone. Sand and Gravel Aquifer near source. (Conduit flow)	(i) 12,000 m^3/d (ii) 2,500 m^3/d (iii)45,000 m^3/d (iv) 6.0 km^2	-	a) Esker sand and gravel ridges adjacent to spring. Clay/silt limestone till in 50% of catchment. Medium to High k subsoils. b) 80 % areal extent, 20% is outcrop. c) > 3m, often > 15m.	Swallow Hole. Positive trace to the spring; 440m/hr over 3.2 km. Dolines.	Diffuse and Point	Bimodal	26% Extreme 69% High 5% Moderate	**9.1%**
6 BALLINAGARD	Pure Limestone (Conduit flow)	(i) 16,000 m^3/d (ii) 10,000 m^3/d (iii)80,000 m^3/d (iv) 7.9 km^2	-	a) Clayey limestone till. Medium to low k. b) 70 % subsoil areal extent, 30% of catchment is outcrop/subcrop. c) < 3m in places.	Several swallow holes, which trace positive to spring. Dolines. Turloughs.	Diffuse and Point	Bimodal	33% Extreme 67% High	**9.2%**
7 BALLINDINE	Pure Limestone (Diffuse/conduit flow)	(i) 3,000 m^3/d (ii) 2,000 m^3/d (iii) 3,500 m^3/d (iv) 4.3 km^2	(1) 15 m (2) 150 mm (3) 7.7m (4) - (5) - (6) - (7) -	a) Clayey limestone till and raised peat (low k). Stony till with sandy matrix (med k). b) 95% subsoil areal extent, 5% is outcrop. c) < 3m in places.	Turlough, dolines. Suspected collapse features overlain by till.	Diffuse and Point	Multimodal	10% Extreme 90% High	**9.5%**
8 MOUNT TALBOT	Pure Limestone (Conduit flow)	(i) 6,500 m^3/d (ii) 4,000 m^3/d (iii) - (iv) 7.3 km^2	-	a) Clayey limestone till. Sandier near rockhead. Raised bog. Low k subsoils. b) 65% areal subsoil extent, 35% extent of outcrop; limestone ridge 150m OD. c) > 3m in subsoil area, except at spring.	Turlough. 2 Swallow holes. Several Dolines.	Diffuse and Point. Point at Turlough, Dolines.	Multimodal	47% Extreme 53% High	**10.0%**
9 KILLEGLAN	Pure Limestone (Conduit flow)	(i) 6,910 m^3/d (ii) - (iii) - (iv) 6 km^2	-	a) Sandy limestone till. Medium to low k subsoils. Esker sand and gravels (non-aquifer) in places. b) 90% areal subsoil extent, 5% of catchment is outcrop, 5% is subcrop. c) < 3m in places.	Two main swallow holes, with positive trace to spring. 10's of swallow holes in the area. Dolines and turloughs.	Point and Diffuse	Multimodal	50% Extreme 50% High	**12.6%**
10 BELMONT	Muddy (Impure) Limestone (Conduit flow)	(i) 185 m^3/d (ii) 182 m^3/d (iii) 310 m^3/d (iv) -	-	a) Clayey limestone till. Sandier near rockhead. Low k subsoils. b) 70% areal subsoil extent, 30% extent of outcrop; limestone ridge 150m OD. c) < 3m in subsoil area, except at spring.	Turlough. Losing river. Several Dolines.	Diffuse and Point. Point at turlough, river and dolines.	Multimodal	100% Extreme	**14.3%**
11 ROCKINGHAM	Pure Limestone (Conduit flow)	(i) >13,100 m^3/d (ii) - (iii) - (iv) > 8 km^2	(1) 19.2 m (2) 300 mm (3) 1 m (4) 4 m. b. s. (5) 6,200 m^3/d (6) - (7) 7.6 m. b. s.	a) Outcrop, Bedrock near surface. b) 15% areal subsoil extent, 85% extent of outcrop. c) < 3m.	Dolines. Cavities in several local boreholes. Turlough nearby.	Diffuse	Multimodal	100% Extreme	**17.9%**

FIGURE 6.1 Frequency Distribution of Electrical Conductivity for 11 Springs in the West of Ireland, with their Coefficient of Variation.



it can enter the bedrock aquifer. Consequently care needs to be taken in adapting the Bakalowicz and Mangin approach in karst areas with an appreciable subsoil cover.

A high proportion of recharge to springs 5 - 11, can enter the groundwater system rapidly by direct routes such as swallow holes, bare rock and via shaft systems associated with closed depressions. Opportunity for reactions with the subsoils and bedrock is reduced in high flow conditions and so the groundwater will have relatively low values of EC. During low flow conditions, recharging water, which is well below carbonate saturation, is capable of dissolving more of the limestone rock since it has a longer residence time, so that amounts of ionic species increase rapidly. As the water approaches saturation with respect to the rock, the solution rates decrease (Jacobson and Langmuir, 1974). Hence the coefficients of variation of EC are large for these springs because of the effects of such recharge.

In a study of the Mendip Hills, U.K., Newson (cited in Quinlan *et al*., *op. cit.*) suggested that highly variable springs (high coefficients of variation) were dominated by point recharge at swallow holes and the less variable springs were recharged predominantly by diffuse recharge.

Quinlan *et al*., *op. cit.* inferred the susceptibility of aquifers or springs to groundwater contamination by considering the type of recharge, flow and storage occurring in an aquifer. They introduced four new terms to describe aquifer sensitivity to pollution, discriminating the aquifer type by the coefficient of variation of electrical conductivity. They are: hypersensitive karst aquifer (>10%), very sensitive karst aquifer (5-10%), moderately sensitive karst aquifer (5% or less), and slightly sensitive non-karst aquifer. Hyper/very sensitive karst aquifers are characterised by conduit flow in pipes, point recharge and low/high storage. Moderately sensitive karst aquifers are characterised by diffuse flow, and do not have pipe flow, point recharge or low levels of storage. Slightly sensitive non-karst aquifers are identical in character to clastic aquifers in which flow is via intergranular pores. Although this thesis did not look at storage these terms appear to work for the 11 springs, where springs 5 - 11 with coefficient of variations of EC at 9.1 - 17.9% show characteristics of the hyper/very sensitive karst aquifer type; springs 3 and 4 (6.9 - 7.9%) show features of the moderately sensitive karst aquifer type; and springs 1 and 2 (5.6 - 6.6%) fall into the slightly sensitive non-karst aquifer type. There is some discrepancy between the coefficients of variation in this thesis and those of Quinlan *et al*. However their coefficient of variation boundaries were assumptions, and have yet to be verified.

Table 6.1, shows a clear relationship between the degree of vulnerability of each catchment area as defined by the subsoil cover and the coefficient of variation of EC, with the coefficient of variation increasing as the vulnerability increases. Figures 6.2 and 6.3, present the

FIGURE 6.2

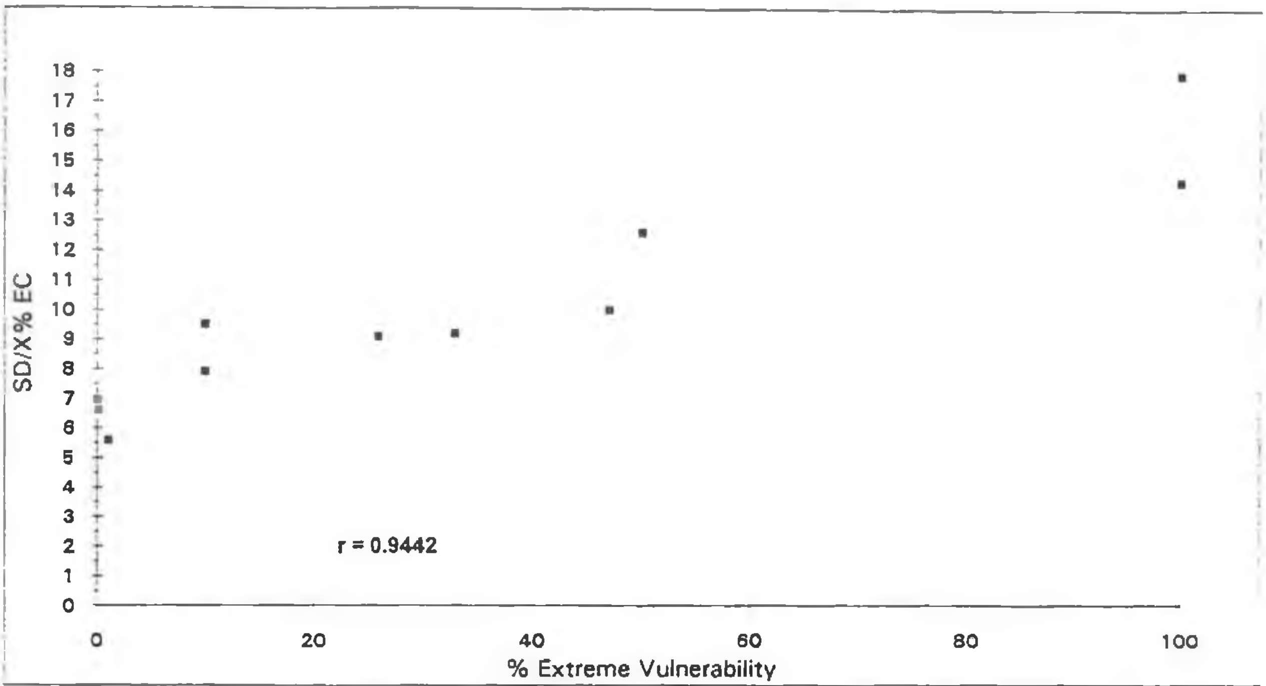
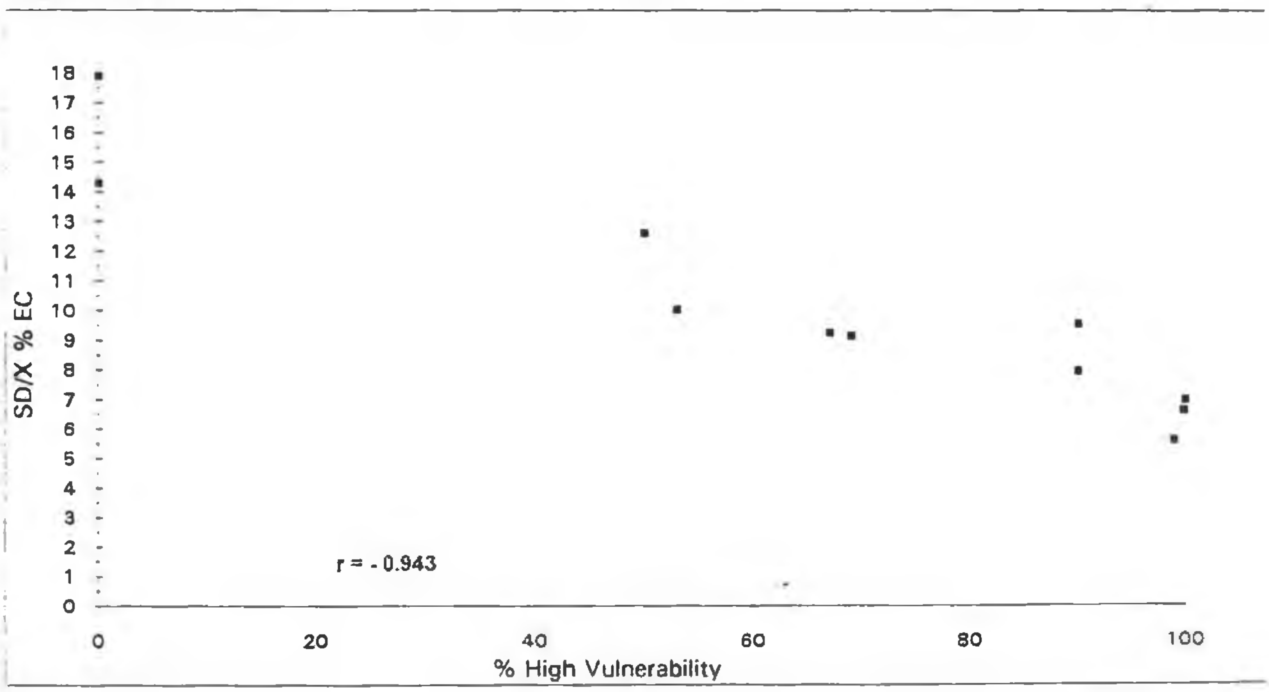


FIGURE 6.3



relationship between the coefficient of variation of EC and the % areal extent of extreme and moderate vulnerability within a spring catchment, as a correlation analysis. These graphs show that there is a high correlation between the coefficient of variation of EC and the % extreme vulnerability, with a value of 0.9442 for r. Similarly there is a high correlation between the coefficient of variation of EC and the % moderate vulnerability, with an inverse value of -0.943 for r.

6.4 CONCLUSIONS

1. The variation, frequency and coefficient of variation in electrical conductivity of spring outflow reflects not only the type of recharge in a spring catchment and the type of flow in the limestone, but also the areal extent, type and thickness of the subsoil cover. This conclusion is particularly important for karst regions in the glaciated areas of northern Europe. However this conclusion assumes that the data available adequately reflect the hydrochemical variation of the spring waters.

2. The coefficient of variation of electrical conductivity is considered to be a parameter that gives a good general reflection of the degree of vulnerability occurring in a spring catchment in Ireland's karstic lowlands.

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APPENDIX M

TABLE OF CHEMICAL DATA FOR THE 11 SPRINGS
October 1992 - September 1993

Date	EC	pH	Temp C	Total Hardness	Fe mg/l	Mn mg/l	Total coliform/100ml	Faecal Coli/ E.Coli	Alkalinity mg/l CaCO3	Alkalinity eq	Ca mg/l as CaCO3	Ca mg/l	Mg mg/l as CaCO3	Mg mg/l	Ca conc m eq/L	Mg conc m eq/L	Na mg/l	Na conc m eq/L	K mg/l	K conc m eq/L	Cl mg/l	Cl conc m eq/L	SO4 mg/l	SO4 conc m eq/L	NO3 mg/l	NO3 conc m eq/L	Sum cations	Sum anions	Ion Balance ERROR
	1 Kilkelly																												
02/11/92	496	7.7	9.9	232																									
10/11/92	498	7.2	9.5	234																									
30/11/92	497	6.4	9.5	212																									
07/12/92	441	7.2	9.5	232																									
14/12/92	441	7.4	10.4	232																									
01/12/93	436	7.2	9.1	224																									
27/1/93	440	7.3	9.5	292			50	20	266		268										22		11		2.26				
18/2/93	432	7.5	9.7	224																									
04/03/93	428	7.1	9.8																										
16/3/93	441	7.5	8.8	218																									
06/04/93	453	7.5	10.4	228																									
27/4/93	434	7.8	19.1	220																									
17/5/93	428	7.8	12.5	228			20	8																					
08/06/93	428	7.4	18.7	220																									
17/6/93	426	7.3	19.5	224																									
06/07/93	479	7.6	11.8	216	1	0.05	8		216		212								2		19		17		1.46				
26/7/93	426	7.7	11.8	228																									
09/08/93	429	7.7	16.5	240																									
26/8/93	448	7.4	11.4	240																									
02/09/93	449	7.3	12	236																									
15/9/93	480	7.3	11.5	220																									
	2 Crossmolina																												
27/10/92	711	7	10.2	318																									
16/11/92	724	7.2	10.2	320																									
24/11/92	722	6.7	10.1	328																									
07/12/92	649	7.1	10	334																									
14/12/92	644	7.1	9.6	348																									
05/01/93	688	7.1	9.1	328																									
19/1/93	613	7.1	8.9	316																									
02/01/93	605	7.4	9	328			1	1	298		284	114	44	10.7	5.68	0.89					28		9						
04/03/93	599	6.8	8.6																										
09/03/93	593	7.1	8.8	300																									
31/3/93	589	7	9	296																									
19/4/93	600	7.4	9.2	232																									
04/05/93	608	7.2	9.3	328	0.002	0.001			302	6.04	284	114	44	10.7	5.68	0.89	0.02	0.00			27	0.76	10	0.36	1.39	0.1	6.572	7.257	
10/05/93	610	7.1	9.8	324																									
26/5/93	612		9.2	328																									
02/06/93	624	7	9.4	316																									
21/6/93	625	6.8	9.4																										
28/6/93	612	7	10.4	320																									
06/07/93	695	7.1	10.4	328			316		316																				
10/08/93	622	6.8	10.1	348																									
17/8/93	632	6.9	10	388																									
06/09/93	624	6.8	12.4	312																									
13/9/93	634	6.9	11	312																									

STATISTICS	EC	Total Hardness
Mean	449.0476	230
Standard Error	5.461762	#N/A
Median	441	228
Mode	441	232
Standard Deviat	25.02894	16.53067
Variance	626.4476	273.2632
Kurtosis	-0.21944	10.96812
Skewness	1.107642	2.934266
Range	72	80
Minimum	426	212
Maximum	498	292
Sum	9430	4600
Count	21	20
CV	5.57%	7.19%

STATISTICS	EC	Total Hardness
Mean	636.3043	321.5238
Standard Error	8.737596	#N/A
Median	624	324
Mode	612	328
Standard Deviat	41.90404	27.94927
Variance	1755.949	781.1619
Kurtosis	0.003661	5.948018
Skewness	1.120042	-1.04218
Range	135	156
Minimum	589	232
Maximum	724	388
Sum	14635	6752
Count	23	21
CV	6.59%	8.69%

Date	EC	pH	Temp C	Total Hardness	Fe mg/l	Mn mg/l	Total coliform/100ml	Faecal Coli/ E.Coli	Alkalinity mg/l CaCO3	Alkalinity eq	Ca mg/l as CaCO3	Ca mg/l	Mg mg/l as CaCO3	Mg mg/l	Ca conc m eq/L	Mg conc m eq/L	Na mg/l	Na conc m eq/L	K mg/l	K conc m eq/L	Cl mg/l	Cl conc m eq/L	SO4 mg/l	SO4 conc m eq/L	NO3 mg/l	NO3 conc m eq/L	Sum cations	Sum anions	Ion Balance ERROR
3 Barnaderg																													
28/10/92	756	7.1	10.3	364																									
11/11/92	762	7.1	9.6	364																									
26/11/92	720	6.8	9.7	300																									
10/12/92	649	6.9	8.4	344																									
15/12/92	655	6.7	10	340																									
05/01/93	653	7.1	9.9	344																									
28/1/93	611	6.7	10.2	244			22	17	206		196										22		9		3.7				
08/02/93	630	7	10.1	340	0.05	0.05	3	1													22		9		3.57				
25/2/93	634	6.7	9.7	325																									
16/3/93	630	7.1	9.7	318																									
30/3/93	629	7.1	9.2	324																									
28/4/93	642	7.4	11.6	340																									
05/05/93	723	7.1	11	348	0.003	0.001			337	6.74	320	128	28	6.8	6.4	0.57	0.01	0			22	0.62	8	0.29	3.27	0.23	6.967	7.879	
24/5/93			10.6	356			120	100																					
01/06/93	726	6.8	10.9	360																									
09/06/93	672	6.8	10.4	364																									
17/6/93	656	6.8	16	360																									
06/07/93	747	7	10.1	356	0.1	0.05	143	2	356		356								7		23		6		2.5				
20/7/93	669	7	10.1	408																									
04/08/93	672	6.7	10.2	320																									
25/8/93	705	6.5	10.5	380																									
09/09/93		6.9	10.4	336																	26				1.29				

STATISTICS	EC	Total Hardness
Mean	677.05	342.5
Standard Error	#N/A	6.809005
Median	662.5	344
Mode	630	364
Standard Deviat	47.05369	31.93707
Variance	2214.05	1019.976
Kurtosis	-1.04013	3.802169
Skewness	0.547715	-1.11141
Range	151	164
Minimum	611	244
Maximum	762	408
Sum	13541	7535
Count	20	22
CV	6.95%	9.32%

Date	EC	pH	Temp C	Total Hardness	Fe mg/l	Mn mg/l	Total coliform/100ml	Faecal Coli/ E.Coli	Alkalinity mg/l CaCO3	Alkalinity eq	Ca mg/l as CaCO3	Ca mg/l	Mg mg/l as CaCO3	Mg mg/l	Ca conc m eq/L	Mg conc m eq/L	Na mg/l	Na conc m eq/L	K mg/l	K conc m eq/L	Cl mg/l	Cl conc m eq/L	SO4 mg/l	SO4 conc m eq/L	NO3 mg/l	NO3 conc m eq/L	Sum cations	Sum anions	Ion Balance ERROR
4 Ballinlough																													
28/10/92	691	7.1	9.5																										
11/10/92	690	7.2	9.6	344																									
10/11/92	682	7.1	9.6	344																									
22/11/92	682	7	9.3	340																									
25/11/92	687	7	9.7	368																									
07/01/93	673	7	9.5	302																									
19/1/93	660	7	9.5	480																									
04/02/93	660	7	9.5	307	.050	<.02			336	6.72		125		4.4	6.25	0.37	10	0.43	2	0.05	28	0.79	7.5	0.27	11.4	0.81	7.103	8.591	-9.48%
16/2/93	660	7.2	9.5	340			186	144																					
03/03/93	666	7.3	9.5	330																									
18/3/93	669	7	9.5	310																									
01/04/93	675	7.6	9.5	330																									
15/4/93	631	7.1	9.5	322																									
27/4/93	664	7.1	9.5	338																									
18/5/93	684	7	9.5	368	0.195	0.037	2000	1200	348	6.96	300	120	68	16.5	6	1.38	10	0.43	6	0.15	30	0.85	10	0.36	14.3	1.02	7.966	9.184	-7.10%
25/5/93	668	7.1	9.5	340																									
15/6/93	694	7.2	11	395																									
29/6/93	675	7.3	9.5	328																									
23/7/93	840	7.1	10.8	324																									
10/08/93	859	7.1	9.5	397	0.249	0.068			340	6.8	307	123	90	21.9	6.14	1.82	11	0.48	3.3	0.08	31	0.87	9.5	0.34	12.4	0.89	8.525	8.898	-2.14%
26/8/93	688	7.3		376	.050	<.02	2	2	332	6.64	272	109	104	25.3	5.44	2.11	9	0.39	3	0.08	24	0.68	11.5	0.41	12	0.86	8.014	8.584	-3.43%
08/09/93	736	7	11	94																									

STATISTICS	EC	Total Hardness
Mean	692.4545	337
Standard Error	11.61573	#N/A
Median	678.5	340
Mode	660	340
Standard Deviat	54.48261	68.35861
Variance	2968.355	4672.9
Kurtosis	5.633631	8.667192
Skewness	2.425703	-1.90139
Range	228	386
Minimum	631	94
Maximum	859	480
Sum	15234	7077
Count	22	21
CV	7.87%	20.28%

Date	EC	pH	Temp C	Total Hardness	Fe mg/l	Mn mg/l	Total coliform/100ml	Faecal Coli/ E.Coli	Alkalinity mg/l CaCO3	Alkalinity eq	Ca mg/l as CaCO3	Ca mg/l	Mg mg/l as CaCO3	Mg mg/l	Ca conc m eq/L	Mg conc m eq/L	Na mg/l	Na conc m eq/L	K mg/l	K conc m eq/L	Cl mg/l	Cl conc m eq/L	SO4 mg/l	SO4 conc m eq/L	NO3 mg/l	NO3 conc m eq/L	Sum cations	Sum anions	Ion Balance ERROR	STATISTICS	EC	Total Hardness
	5 Ballyhaunis																															
04/11/92	610	7	9.2	320			71	16																								
10/11/92	624	6.7	9.6	294																												
17/11/92	618	7	9.1	276																												
01/12/92	510	7	9	284																										Mean	592.2609	303.9474
16/12/92	551	7	9	296			120	1																						Standard Error	11.28856	#N/A
12/01/93	535	7.1	8.4	288																										Median	610	300
20/1/93	505	7.3	7.3		0.15	0.022	140	110													21				1.9					Mode	618	284
27/1/93	542	6.8	9	228					218		204										19		10		1.68					Standard Deviat	54.13805	37.45586
18/2/93	577	7	9.4	324																										Variance	2930.929	1402.942
22/2/93	657	7.2	9.5				230																							Kurtosis	-0.96971	-0.33315
04/03/93	592	6.9	9.5		0.15	0.02															21		12		2.34					Skewness	-0.25134	-0.23476
16/3/93	591	7.1	9.2	308																										Range	183	141
06/04/93	496	7.1	9.2	260																										Minimum	496	228
20/4/93	554	7.2	10	244			650	198																						Maximum	679	369
13/5/93	679	7.1	8		0.01	0.001																								Sum	13622	5775
17/5/93	614	7.3	9.5	300			46																							Count	23	19
25/5/93	618	6.9	9.8	328			49	5																						CV	9.14%	12.32%
17/6/93	540	6.9	10.5	284																												
06/07/93	675	7.1	10.1	336	0.1	0.05	200	32	316		312	125	24	5.83	6.24	0.49			3		21		13		2.33							
09/08/93	639	6.6	10.3	369																												
19/8/93	616	6.7	10	332																												
26/8/93	638	6.7	10.1	356																												
02/09/93	641	6.7	10.4	348																												
	6 Ballinagard																															
28/10/92	724	7.1	10				510	110																								
10/11/92	731	7.2	10.1	372																												
11/11/92	715	7.3	9.8	371																						Mean	736.5	360.4
22/11/92	705	7.2	9.5	397																						Standard Error	14.49657	#N/A
25/11/92	726	7.2	9.8	379																						Median	715	365
07/01/93	692	7.1	9.1	318																						Mode	715	372
22/1/93	705	7.1	9.2	449																						Standard Deviat	67.99492	45.79635
04/02/93	701	7.2	9.2	348	.050	<.02			364	7.28		136		6.8	6.8	0.57	11	0.48	1	0.03	28	0.79	7.5	0.27	11.1	0.79	7.871	9.129	-7.41%	Variance	4623.31	2097.305
16/2/93	680	7.1	9.1	320			76	16																						Kurtosis	2.709413	0.493517
01/03/93	674	7.1	9.1	330																						Skewness	1.961375	-0.15483
18/3/93	689	7.1	9.2	346																						Range	233	191
01/04/93	700	7.8	9.4	346																						Minimum	674	258
19/4/93	713	7.2	11.5	344																						Maximum	907	449
12/05/93	715	7	9.8	390	.050	<.02	12	1	366	7.32	820	328	x		16.4	x	2		8		29		10.5		8.9					Sum	16203	7208
25/5/93	722	7.1	9.8	364																						Count	22	20
24/6/93	738	7.1	10	372																						CV	9.23%	12.71%
07/07/93	737	7.1	10.4	366																								
04/08/93	907		10.3																									
23/8/93	894	7	10.6	412	.050	<.02	200	180	372	7.44	312	125	100	24.3	6.24	2.03	9	0.39	2.8	0.07	24	0.68	16.5	0.59	8.8	0.63	8.728	9.334	-3.35%			
07/09/93	892	7	10.2	258																								
23/9/93	703	7.1	10.1	290																								
07/10/93	740	7.2		436	.050	<.02			386	7.72	366	146	76	18.5	7.32	1.54	8	0.35	4	0.1	30	0.85	12	0.43	10.6	0.76	9.309	9.751	-2.32%			

Date	EC	pH	Temp C	Total Hardness	Fe mg/l	Mn mg/l	Total coliform/100ml	Faecal Coli/ E.Coli	Alkalinity mg/l CaCO3	Alkalinity eq	Ca mg/l as CaCO3	Ca mg/l	Mg mg/l as CaCO3	Mg mg/l	Ca conc m eq/L	Mg conc m eq/L	Na mg/l	Na conc m eq/L	K mg/l	K conc m eq/L	Cl mg/l	Cl conc m eq/L	SO4 mg/l	SO4 conc m eq/L	NO3 mg/l	NO3 conc m eq/L	Sum cations	Sum anions	Ion Balance ERROR	STATISTICS	EC	Total Hardness
	7 Ballindine																															
04/11/92	718	7	10.4	320																												
17/11/92	722	7.1	10.2	316																												
01/12/92	718	6.4	9.8	340																										Mean	637.9524	328.6316
07/12/92	634	7	9.6	344																										Standard Error	13.28309	#N/A
16/12/92	633	6.8	9.9	340																										Median	634	328
12/01/93	627	7.5	6.9	320																										Mode	718	320
27/1/93	614	6.7	9.5	324					318		300										22		7		3.23					Standard Deviat	60.87075	27.20337
08/02/93	626	6.5	9.7	344	0.05	0.05	110	20													22		12		3.08					Variance	3705.248	740.0234
18/2/93	632	7.1	9	344																										Kurtosis	3.68284	4.579315
04/03/93	638	7	9.6																											Skewness	-1.25367	-1.56249
16/03/93	642	7	9.7	340																										Range	271	128
06/04/93	453	7.1	9.5	320																										Minimum	453	244
20/4/93	626	7.1	9.4	296																										Maximum	724	372
27/4/93	615	7.5		316																										Sum	13397	6244
25/5/93	646	7.1	10.6	328																										Count	21	19
17/6/93	537	6.9	12.7	324																										CV	9.54%	8.28%
06/07/93	724	7.1	10.2	352	0.1	0.05	609	290	348			324							4		21		7		2.06							
09/08/93	659	6.9	15.3	244																												
19/8/93	651	7		372																												
26/8/93	633	7.1	14.6																													
02/09/93	649	6.8	12.6	360																												
	8 Mount Talbot																															
27/10/92	570	7.3	9.6				120	64																						Mean	713.3478	327.9048
11/11/92	682	7.3	9.5	346																										Standard Error	#N/A	#N/A
22/11/92	691	7.3	9.2	322																										Median	691	348
25/11/92	691	7.2	9.7	352																										Mode	691	362
07/01/93	693	7.1	9.1	222																										Standard Deviat	71.35545	55.90966
19/1/93	680	7.1	9	350																										Variance	5091.601	3125.89
04/02/93	681	7.1	9.1	309	.050	<.02			352	7.04		130		9.7	6.5	0.81	1	0.04	10	0.26	28	0.79	7.5	0.27	10.5	0.75	7.608	8.847	-7.53%	Kurtosis	2.57637	6.382893
16/2/93	684	7.1	9.2	290			250	150																						Skewness	1.385669	-2.34146
03/01/93	680	7	9.4	322																										Range	309	255
16/3/93	689	7.1	9.3	348																										Minimum	570	139
01/04/93	690	7.5	9.7	316																										Maximum	879	394
13/4/93	694	7.3	8.3	324																										Sum	16407	6886
27/4/93	684	7.1	9.8	336																										Count	23	21
12/5/93	691	7	10.3	354	.050	<.02	2	1	355	7.1	810	324	x			x	2	0.09	8	0.21	33	0.93	9	0.32	11	0.79				CV	10.00%	17.05%
25/5/93	702	7.1	10	362																												
24/6/93	702	7	10.7	362																												
07/07/93	703	7.1	10.8	350																												
20/7/93	721	7	10.8	352																												
04/08/93	879		10.8																													
17/8/93	876	7	10.6	374	.050	<.02	36	6	356	7.12	310	124	64	15.6	6.2	1.3	8.5	0.37	1.7	0.04	27	0.76	19.5	0.7	9.7	0.69	7.909	9.27	-7.92%			
07/09/93	878	6.6	10.5	139																												
23/9/93	706	7	10.5	362																												
07/10/93	738	7.2		394	.050	<.02			382	7.64			34	8.26	7.19	0.69	3	0.13	8	0.21	31	0.87	18	0.64	8.9	0.64	8.214	9.792	-8.76%			

Date	EC	pH	Temp C	Total Hardness	Fe mg/l	Mn mg/l	Total coliform/100ml	Faecal Coli/ E.Coli	Alkalinity mg/l CaCO3	Alkalinity eq	Ca mg/l as CaCO3	Ca mg/l	Mg mg/l as CaCO3	Mg mg/l	Ca conc m eq/L	Mg conc m eq/L	Na mg/l	Na conc m eq/L	K mg/l	K conc m eq/L	Cl mg/l	Cl conc m eq/L	SO4 mg/l	SO4 conc m eq/L	NO3 mg/l	NO3 conc m eq/L	Sum cations	Sum anions	Ion Balance ERROR	STATISTICS	EC	Total Hardness
	9 Killeglan																															
27/10/92	715	7	10.1				230	50																								
10/11/92	624	7.2	9.8	316																												
11/11/92	614	7.3	9.2	314																										Mean	650.7917	312.0909
22/11/92	633	7.4	9.1	327																										Standard Error	16.67898	#N/A
25/11/92	516	7.2	9.6	251																										Median	638	316
07/01/93	643	7.2	9	294																										Mode	630	316
19/1/93	603	7.2	8.8	396																										Standard Deviat	81.70997	35.93236
04/02/93	630	7.3	8.9	340	.050	<.02			312	6.24		120		9.7	6	0.81	10	0.43	1	0.03	28	0.79	7.5	0.27	14.4	1.03	7.269	8.325	-6.77%	Variance	6676.52	1291.134
16/2/93	644	7.2	9.2	316			2	2																						Kurtosis	1.543091	0.56242
01/03/93	665	7.2	9.1	316																										Skewness	0.782637	-0.0326
16/3/93	656	7.2	9.2	316																										Range	358	152
01/04/93	620	7.8	9.2	304																										Minimum	491	244
13/4/93	570	7.3	8.1	300																										Maximum	849	396
27/4/93	625	7.3	9.5	308																										Sum	15619	6866
12/05/93	660	7	9.5	352	.050	<.02	4	2	315	6.3	715	286	x		14.3	x	9		2		33		11		16.5					Count	24	22
25/5/93	664	7.2	9.6	330																										CV	12.56%	11.51%
24/6/93	630	7.2	10	336																												
07/07/93	671	7	9.9	330																												
20/7/93	647	7.1	10.1	296																												
04/08/93	821		10.3																													
17/8/93	800	7.1	10.2	356	0.076	<.02	12	8	305	6.1	284	114	72	17.5	5.68	1.46	9.2	0.4	3	0.08	27	0.76	21.5	0.77	14.3	1.02	7.615	8.65	-6.36%			
07/09/93	849	7.1	10.1	244																												
23/9/93	628	7.3	10.2	256																												
07/10/93	491	7.3		268	0.116	<.02			244	4.88	240	96	28	6.8	4.8	0.57	8	0.35	2	0.05	32	0.9	1	0.04	6.5	0.46	5.766	6.281	-4.28%			
	10 Belmont																															
28/10/92	708	7.2	9.8	338																												
11/11/92	751	7.4	9.8	380																												
26/11/92	641	6.8	9.3	288																										Mean	683.3	351
10/12/92	524	6.9	7.5	284																										Standard Error	#N/A	11.0175
15/12/92	587	7.4	8.5	324																										Median	682	360
05/01/93	597	6.7	8.5	308																										Mode	597	324
28/1/93	560	6.7	8.5	244					244		228										27		8		1.67					Standard Deviat	97.76131	51.67665
18/2/93	664	7.1	8.4	364																										Variance	9557.274	2670.476
25/2/93	673	6.5	8.9	295																										Kurtosis	1.132817	-0.30302
16/3/93		7.2	9.2	345																										Skewness	0.678504	-0.07912
30/3/93	588	7.2	9.4	300																										Range	419	212
28/4/93	628	7.2	10.4	368																										Minimum	524	244
05/05/93	771	7.1	11.1	376	0.01	0.001			364	7.28	348	139	28	6.8	6.96	0.57	0.02	0			26	0.73	10	0.36	1.44	0.1	7.528	8.472		Maximum	943	456
24/5/93			9.9	372																										Sum	13666	7722
01/06/93	742	6.9	10.8	356																										Count	20	22
09/06/93	691	7	10.8	368																										CV	14.31%	14.72%
16/6/93	597		11.5	324																												
06/07/93	943	7.1	11.2	456			200	200	436		400										46				0.01							
20/7/93	754	7	10	412																												
04/08/93	744	6.9		416																												
25/8/93	734	6.8	11.4	408																												
14/9/93	769	6.8	11	396																												

Date	EC	pH	Temp C	Total Hardness	Fe mg/l	Mn mg/l	Total coliform/100ml	Faecal Coli/ E.Coli	Alkalinity mg/l CaCO3	Alkalinity eq	Ca mg/l as CaCO3	Ca mg/l	Mg mg/l as CaCO3	Mg mg/l	Ca conc m eq/L	Mg conc m eq/L	Na mg/l	Na conc m eq/L	K mg/l	K conc m eq/L	Cl mg/l	Cl conc m eq/L	SO4 mg/l	SO4 conc m eq/L	NO3 mg/l	NO3 conc m eq/L	Sum cations	Sum anions	Ion Balance ERROR
	11 Rockingham																												
28/10/92	762	6.9	9.6				1060	140																					
10/11/92	625	7.1	8.8	324																									
17/11/92	614	7.2	8.8	312																									
25/11/92	385	7.1	9.4	295																									
07/01/93	702	6.9	8.6	380																									
19/1/93	602	7.1	8.6	302																									
02/02/93	670	7	8.3	322	.050	<.02			320	6.4		120		7.8	6	0.65	11	0.48	2	0.05	32	0.9	3	0.11	3.7	0.26	7.18	7.673	-3.32%
15/2/93	365	7.2	8.4	280																									
02/03/93	627	7.1	8.6	330																									
15/3/93	570	7.1	8.6	302																									
29/3/93	661	6.9	9	320																									
15/4/93	609	7.1	9.1	310																									
27/4/[illegible]	[illegible]	7.1	9.4	308																									
11/05/93	637	6.9	9.6	328	.050		6		324	6.48	326	130	2	0.49	6.52	0.04	9	0.39	1	0.03	32	0.9	12.5	0.45	2.4	0.17	[illegible]	7.999	-6.82%
27/5/93	679	7	9.4	346																									
30/6/93	796	6.9	10.2	432																									
21/7/93	456	7.1	9.5	316																									
10/08/93	713	6.9	9.8	409	0.062	<.02			361	7.22	352	141	56	13.6	7.04	1.13	9.8	0.43	1.8	0.05	28	0.79	15	0.54	11.9	0.85	8.646	9.394	-4.15%
22/8/93	690	7	11.2	374																									
26/8/93	[illegible]	6.3	9.9	372	.050	<.02	32	14	400	8	328	131	44	10.7	6.56	0.89	9	0.39	2	0.05	20	0.56	11.5	0.41	[illegible]	0.29	7.894	[illegible]	-7.96%

STATISTICS	EC	Total Hardness
Mean	625.6	333.4
Standard Error	24.99467	#N/A
Median	638	322
Mode	#N/A	302
Standard Deviat	111.7796	40.48053
Variance	12494.67	1638.674
Kurtosis	1.163813	0.542031
Skewness	-1.12802	1.06384
Range	431	152
Minimum	365	280
Maximum	796	432
Sum	12512	6668
Count	20	20
CV	17.87%	12.14%

APPENDIX L

GEOLOGICAL SURVEY OF IRELAND VULNERABILITY GUIDELINES

Mapping Groundwater Vulnerability to Pollution - GSI Guidelines
(Donal Daly and William Warren, GSI)

Introduction

Since the late 1960s, groundwater vulnerability maps have played an increasingly important role internationally in the location and operation of potentially polluting activities, and in bringing the groundwater interest to the attention of decision-makers in the planning process. They have become a means of presenting various, sometimes complex, hydrogeological parameters in the form of an easily, but often intuitively, understood term "vulnerability". Vulnerability maps are now becoming an essential part of groundwater protection schemes and a valuable tool in environmental management.

In 1989 the Geological Survey of Ireland (GSI) recommended that groundwater vulnerability assessments should be used as a means of upgrading and improving groundwater protection schemes. As vulnerability mapping is the most important means of carrying out these assessments, guidelines were given which related to typical Irish hydrogeological settings with a four fold vulnerability rating: extreme, high, moderate and low.

In the coming months the GSI, in collaboration with some third-level colleges, will be preparing groundwater protection schemes for three counties - Offaly, Tipperary (SR) and Waterford. Consequently the guidelines are being reviewed, firstly to reflect the quality of both available and readily available geological and hydrogeological data, secondly to include new ideas and thirdly to identify minimum standard vulnerability maps.

This article suggests an appropriate definition of vulnerability for the Irish situation, gives the basis for the guidelines, outlines the background factors influencing the vulnerability ratings and then describes three sets of vulnerability guidelines that vary depending on the data availability.

Definition of Groundwater Vulnerability

Examination of existing vulnerability maps and descriptions of vulnerability in the scientific literature shows considerable variation in the definition and the usage of the vulnerability concept. Up to now there has been no generally accepted definition or methodology for the construction of vulnerability maps. The variation is highlighted in the following points:

1. The definition can be limited to the intrinsic geological and hydrogeological characteristics of an area or can also include land-use and management practices.
2. The aspect of groundwater that is vulnerable can vary. It can be "groundwater" itself; the "groundwater system"; "aquifers"; "groundwater sources", such as karst springs; or "groundwater resources".

3. Groundwater can be taken to be vulnerable to a variety of impacts such as "natural impacts", "human impacts including groundwater abstraction", "contamination caused by human activities", "conservative pollutants", "specific pollutants", "point source pollution" and/or "diffuse pollution".
4. The objectives of the map can be to help in i) preventing groundwater pollution in general, ii) protecting groundwater sources, iii) designing monitoring networks, iv) responding to pollution incidents, v) or creating public awareness/education of the importance and fragility of groundwater.
5. Many vulnerability maps could be titled, depending on their purpose, more accurately as "groundwater sensitivity" maps, "groundwater (or aquifer) response to pollution" maps, "source (spring) response to pollution" maps or "aquifer attenuation capability" maps.

Such considerations affect both the scale of maps, which can range from less than 1:10,000 to greater than 1:500,000, and the data required to compile the maps. For instance, the data required for a vulnerability map, which is part of a regional groundwater protection scheme designed to prevent groundwater pollution from occurring, might consist only of information on the geological materials that are present between the land surface and the groundwater and on details on recharge type, including the locations of point recharge. If the map is a source vulnerability map or is intended for deciding on the response to pollution incidents then, in addition to the above information, the residence time in the aquifer, transport rates, dilution, attenuation within the aquifer, etc., can be taken into account.

For the purpose of its groundwater vulnerability maps and reports, the Geological Survey of Ireland applies the following definition:
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.

Basis for GSI Definition and Usage of Vulnerability Concept
In response to the differences and possible variations, as outlined above, and taking into account of the hydrogeological situation in Ireland, it was decided that:
i) The definition of vulnerability will not include land-use and management practices but will be limited to the inherent geological and hydrogeological characteristics of an area.
ii) It is the vulnerability of "groundwater" that will be mapped and not "aquifers" or "groundwater sources", etc.
iii) Groundwater will be taken to be vulnerable to "contaminants generated by human activities" and not, for instance, "natural impacts". It will be assumed that the contaminants are relatively conservative.
iv) The primary objective of the vulnerability maps will be to give assistance in preventing pollution, as part of groundwater protection schemes. However, they will also help in creating awareness of the sensitivity of groundwater in certain hydrogeological situations.
v) The maps will show the vulnerability of the first groundwater encountered in either sand/gravel aquifers or in bedrock. This groundwater may not be the main resource beneath a site where there is a deep confined aquifer.

The vulnerability of groundwater depends on the time of travel of groundwater (and contaminants) and on the contaminant attenuation capacity of the geological materials. 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 quickly receives water (and contaminants) from the land surface is considered to be more vulnerable than groundwater that receives water (and contaminants) more slowly. the travel time and attenuation capacity are a function of the following natural attributes of any area:

i) the subsoils that overlie the aquifer;
ii) the recharge type - whether point or diffuse; and
iii) in the case of unconfined sand and gravel aquifers, the thickness of the unsaturated zone.

The subsoils are regarded as the single most important natural feature influencing groundwater vulnerability to pollution. They can act as a protecting filtering layer over groundwater, depending on the type, permeability and thickness. So, for instance, the higher the clay content, the lower the permeability and the greater the thickness, the better the protection from contaminants. Groundwater is most vulnerable where the subsoil is absent or very thin.

The type and rate of recharge are particularly important in karstic limestone areas, where point recharge through swallow holes and sinking streams can occur. Attenuation is minimal, flow velocity is fast, and so groundwater is very vulnerable to pollution in these situations.

In sands/gravels, a deep water table reduces the likelihood of contamination because contaminants have to travel farther and are slower to reach the groundwater. This allows the various beneficial physical, chemical and biological processes, that occur in the unsaturated zone, to attenuate the pollutants.

The possible flow rates and attenuation of contaminants once they have entered groundwater in either bedrock or sand/gravel are not taken to be factors in vulnerability mapping because by then the impact has occurred and there is no further capacity to prevent the impact or protect the groundwater. (Obviously the degree of impact is another issue, which depends on a variety of factors including the pollutant loading.) However, they can be taken into account in considering the vulnerability of a specific well or spring. Also, the bedrock hydrogeology is not taken to be a significant factor in defining vulnerability. It is assumed, firstly that once contaminants enter groundwater in bedrock there is, owing to the fissure permeability that characterises Irish bedrock, little attenuation, other than by (usually relatively limited) dilution, and secondly that an unsaturated zone in bedrock is not a significant factor. Consequently, it is assumed that, with the exception of karst morphological features that indicate rapid recharge (swallow holes, for instance), the only factor determining the vulnerability of groundwater in bedrock is the nature (type, permeability and thickness) of overlying subsoils or Quaternary deposits. It is considered that the hydrogeology of different bedrock types can be taken into account when the aquifer map is linked with the vulnerability map in preparing the groundwater protection map and code of practice. For instance, regionally important bedrock aquifers that are karstified can be so indicated on the aquifer map.

Background Factors Influencing the Vulnerability Ratings

In proposing guidelines, the following factors have been taken into account:

i) The main threat to groundwater in Ireland is posed by point sources - farmyard wastes, septic tank effluent, pollutants in sinking streams and to a lesser extent leachate from waste disposal facilities, leakages and spillages. Consequently, in defining groundwater vulnerability to pollution the safest assumption is that the contaminants are being released from point sources below the ground surface at depths of 1-2m.

ii) Detailed geological and hydrogeological knowledge is lacking for many areas in Ireland while at the same time the geology and hydrogeology of the country are complex. The bedrock has a fissure permeability only and, in the case of limestones, karstification may have occurred to varying degrees. The subsoils or Quaternary sediments are very variable in thickness, extent and lithology, reflecting their chaotic mode of deposition during the Ice Age. Also, there is seldom quantitative information on permeabilities, travel times or attenuation capacities, thus the vulnerability ratings are largely qualitative.

iii) For a groundwater protection scheme to be effective and used in the planning process, the number of zones should be small. As the vulnerability ratings influence the number of protection zones, it is necessary to keep the vulnerability ratings relatively simple and generalised.

iv) The ratings take account of the existing regulations and recommendations both in Ireland and abroad (e.g. SR6: 1991).

Guidelines for Vulnerability Mapping Based on Optimum Data Availability

The following table gives the basis for the vulnerability guidelines being proposed and used by the GSI.

Vulnerability Rating	Hydrogeological Setting	
Extreme	1	Outcropping bedrock or where bedrock is overlain by shallow (≤ 3m) subsoil.
	2	Sand and gravel aquifers with a shallow (≤ 3m) unsaturated zone.
	3	Within 30m of karstic features (including areas of loss, of losing or sinking streams) and within 10m on either side of losing or sinking streams upflow of the area of loss. (In certain circumstances, for instance, where overland runoff is likely, greater distances may be needed).
High	1	Bedrock overlain by > 3m of high permeability sand and gravel, or 3-10m of intermediate permeability subsoil such as sandy till or 3-5m of low permeability subsoil such as clayey till, clay or peat.

	2	Unconfined sand and gravel aquifers with an unsaturated zone > 3m.
Moderate	1	Bedrock overlain by > 10m of intermediate permeability subsoil such as sandy till or 5-10m of low permeability subsoils such as clayey till, clay or peat.
	2	Sand and gravel aquifers overlain by > 10m of moderate permeability subsoil such as sandy till or 5-10m of low permeability subsoil such as clayey till, clay or peat.
Low	1	Bedrock overlain by > 10m of low permeability subsoil such as clayey till, clay or peat.
	2	Confined gravel aquifers where overlain by > 10m of low permeability clayey till or clay.

These ratings assume the following :

- 1-2m of subsoil and, in the case of sand and gravel aquifers, a 1-2m thick unsaturated zone below the point of release of contaminants to allow a change of rating from extreme to high.
- Sand and gravel do not have a sufficient protecting capacity, no matter how thick, to merit a moderate rating.
- A minimum of 8m of sandy till and 3m of clayey till or clay, below the point of release of contaminants, enables a rating of moderate.
- Sandy till does not give sufficient protection to allow a low vulnerability rating no matter how thick it is.
- At least 8m of clayey till or clay, below the point of release of contaminants are needed to merit a low vulnerability rating.

In order to draw a vulnerability map based on these ratings, the following geological and hydrogeological information must be available on maps.

1. Areas where the Quaternary sediment is generally less than 1m thick (bedrock outcrop or subcrop).
2. Sand / gravel deposits.
3. Till (boulder clay) deposits with details of basic matrix (textural) characteristics.
4. Peat: both cutover and intact bog.
5. Alluvium.
6. Lake clays.
7. Depth to bedrock map showing contours at 3m, 5m (in the case of clayey till and clay), and 10m.
8. Sand and gravel aquifers; with a differentiation between areas with ($\leq$3m) and thicker (>3m) unsaturated zones.
9. Karstic features such as sinking streams, collapse features etc.

Information with this level of detail is available for only a few small areas in Ireland and is never likely to be more widely available except perhaps around a limited number of major public supply sources. Routine Geological Survey mapping programmes provide adequate data with regard to the sediments but the paucity of depth to bedrock data is a problem. Consequently these guidelines are aspirational. However they do provide a basis for adoption.

In extensive karst areas, detailed studies by a karst specialist are advisable. Further research on karstification may allow future refinement of the vulnerability ratings in karst areas.

Diffuse pollution sources, such as land spreading of organic wastes, are likely to become more important in the future. With a slight adaptation, the ratings can be used to take account of this by producing a map which applies the "extreme" rating to areas of outcrop, subcrop (subsoil normally 1m) and around karst features, whereas the remainder of the area with shallow subsoil ($\leq$3m) could be ranked as "high".

Minimum Standard Vulnerability Mapping

The production of vulnerability maps for areas where the level of Quaternary geology information is poor is not recommended, as the level of uncertainty with the maps will make them indefensible and is likely to devalue the technique. Thus the minimum level of Quaternary geology information required in the short term (i.e. for present projects - Offaly, Limerick, Meath. Waterford and Tipperary S.R.) to enable defensible vulnerability maps to be drawn demands identification of the following:

1. Areas of outcrop and subcrop.
2. Sand and gravel areas.
3. Areas of till or boulder clay (permeability uncertain).
4. Lacustrine clay and peat areas.
5. Peatland areas.
6. Areas where subsoil is probably less than 3m.
7. Points where the subsoil is greater than 10m thick.
8. Sand and gravel aquifers in river flood plains.
9. Karst features.

From this information the following ratings are possible :

Extreme	1	Bedrock outcrop.
	2	In vicinity of karst features.
Probably Extreme	1	Areas of subcrop.
	2	Shallow ($\leq$ 3m) subsoil.
	3	Sand and gravel aquifers in river flood plains (where deptH to water table is likely to be shallow).
	4	Alluvium.
	5	Blanket Bog.
High		Sand and gravel areas.
Probably High	1	Bedrock overlain by >3m subsoil (excluding sand and gravel).
	2	Unconfined sand and gravel aquifers outside flood

plains.

Moderate	Area in the immediate vicinity of a borehole with a subsoil thickness greater than 10m.
Probably Moderate	Areas with lacustrine clay and cutover raised bog.
Probably Low	Areas of intact raised bog.

On maps based on these ratings, the areas of extreme and high vulnerability will be over estimated. It is suggested that a vulnerability map, which is based on these ratings, is at the absolute minimum level and that even it may be difficult to defend. Consequently it is essential that in the future a higher quality of Quaternary geology information should be required to enable more confident pollution risk assessments and more defensible groundwater protection schemes.

Improved and Achievable Vulnerability Mapping

The key to improving vulnerability mapping in the medium term is the availability of good quality Quaternary geology maps. (In the longer term, greater hydrogeological understanding of the bedrock in Ireland and its varying ability to attenuate contaminants may impact on vulnerability mapping). Consequently it is recommended that, prior to preparing vulnerability maps, the Quaternary geology information should be improved by reconnaissance mapping, trial pitting, augering and grain size analyses. The following information should be obtained:

1. Areas where Quaternary sediment is generally less than or equal to 1m thick (outcrop and subcrop).
2. Sand and gravel deposits (>1m thick).
3. Till deposits with details on texture (> 1m thick).
4. Peat.
5. Alluvium.
6. Lake clays.
7. Depth to rock map showing shallow subsoils (≤3m) and moderately thick subsoils (3-10m) and areas of thick subsoils (probably > 10m). However the 10m contour can only be attempted where the existing borehole information is adequate.
8. Sand and gravel aquifers with a thin (≤3m) unsaturated zone.
9. Karst features.

This information allows the following vulnerability ratings :

Extreme	1 Outcropping bedrock and subcrop. 2 Within 30m of karstic features (including the area of loss of losing or sinking streams) and within 10m either side of losing streams upflow of the area of loss of the source. (In certain circumstances, for instance where overland surface runoff is likely, greater distances may be needed).
Probably	1 Areas with thin (≤3m) subsoil over bedrock.

Extreme	2	Sand and gravel aquifers with a thin (≤3m) unsaturated zone.
	3	Alluvium.
	4	Blanket bog.
High	1	Areas where high permeability sand and gravel are >3m thick.
	2	Areas where intermediate permeability subsoil such as sandy till is known, from borehole records, to be 3-10m thick.
	3	Areas where low permeability subsoil such as clayey till, clay and/or peat is known, from borehole records, to be 3-5m thick.
Probably High	1	Areas where intermediate permeability soil such as sandy till is interpreted to be >3m and ≤10m thick, from sparse borehole records.
	2	Areas where low permeability subsoil such as clayey till, clay and/or peat is interpreted to be >3m and ≤5m thick from sparse borehole records.
	3	Unconfined sand and gravel aquifers where the unsaturated zone is >3m thick.
Moderate	1	Areas where intermediate permeability subsoil such as sandy till is known, from borehole records, to be >10m thick.
	2	Areas where low permeability subsoil such as clayey till, clay and/or peat is known, from borehole records, to be 5-10m thick.
Probably Moderate	1	Areas where intermediate permeability subsoils such as sandy till are interpreted to be >10m thick from sparse borehole records.
	2	Areas where low permeability subsoil such as clayey till, clay and/or peat is interpreted to be 5-10m thick from sparse borehole records.
Low		Areas where low permeability subsoil such as clayey till and/or clay and/or peat is known to be >10m thick, from borehole records.
Probably Low		Areas where low permeability subsoil such as clay till, clay and/or peat is interpreted to be >10m thick, from sparse borehole records.

Concluding Comments

These guidelines are based on pragmatic judgements, experience and limited technical and scientific information. Further research is needed into the factors that govern some of the ratings to enhance the defensibility of the guidelines. The guidelines will be reviewed on a regular basis as they are tested by ongoing protection schemes.

The guidelines have been influenced by discussions with and contributions from Paul Johnston (TCD), Catherine Coxon (TCD), Malcolm Doak (Sligo RTC), Richard Thorn (Sligo RTC), Margaret Keegan (GSI), Eugene Daly (GSI), Geoff Wright (GSI), Natalie Doerfliger (University of Neuchatel), Jean-Pierre Tripet (Swiss Hydrological and Geological Survey) and Brian Adams (British Geological Survey).

The above has been reproduced in full from The GSI Groundwater Newsletter, No. 25, July 1994 *and with the permission of the GSI.*

APPENDICES A - K

11 SOURCE REPORTS

APPENDIX A

KILKELLY PUBLIC SUPPLY

1 SPRING DETAILS

GSI No.	: 1429SW W--		
Grid Ref.	: M 445 915		
Elevation	: 96m OD		
6" Sheet	: Mayo 72		
Townland	: Knockbrack		
Depth to Rock at Spring	: >3m		
Average Spring Discharge	: (i) Abstraction Rate		
		(a) Co. Co. Pumps	320m³/d
		(b) Group Scheme pumps	991m³/d
		Total	1,311m³/d
	(ii) Spring Overflow Average:		2,000m³/d
	(iii) TOTAL Spring Discharge(i+ii):		3,311m³/d

2 SPRING LOCATION AND SITE DESCRIPTION

This public supply and group scheme spring is located in the northwest part of Kilkelly town, off a T junction near the national school. It is sited in a relatively isolated field downslope of an esker, in front of Kilkelly church (Photo 1). The spring and adjoining pumphouses are surrounded on all sides by high fencing and are well maintained.

The spring is totally enclosed in a concrete chamber up to 3m deep (Photo 2). The spring water is gravity fed to a collector sump 25m away immediately beside the three pumphouses (Photo 3). Several pumps extract water from the sump. Spring overflow is via the main Co. Co. pumphouse to a small stream which flows south to Kilkelly town.

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

The spring, at an elevation of about 96m OD, lies in a small river valley, directly in the break of slope of a narrow esker which has a height of 106m OD beside the church. The esker and spring lie south of a broad tract of undulating and hummocky glaciofluvial/glaciolacustrine

PHOTO 1
View of spring enclosure in front of esker/church

PHOTO 2
The concrete chamber

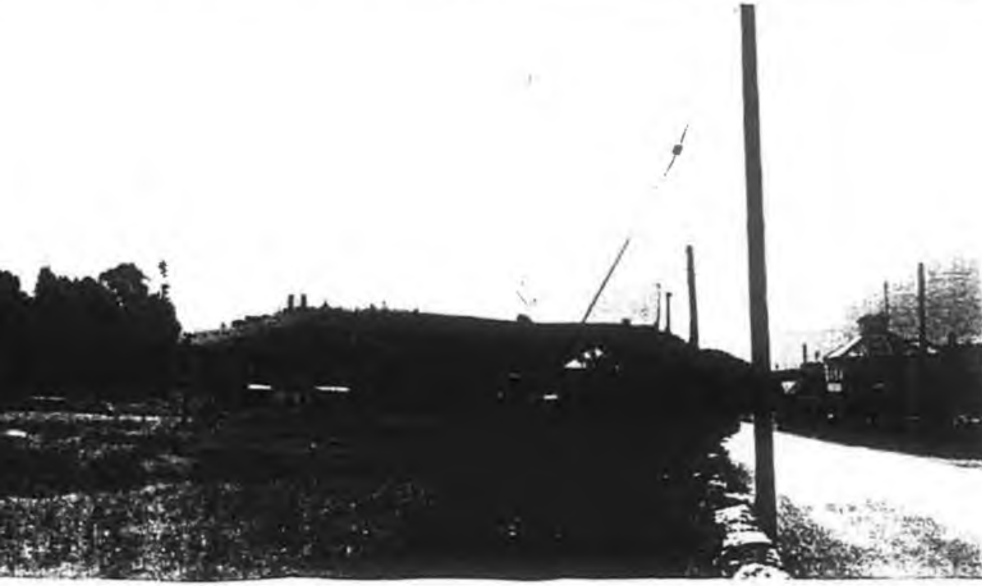


PHOTO 3
The 3 pumphouses and collector sump

sand and gravel deposits (Photo 4; aerial). Further northwest the topography is dominated by bedrock cored drumlins and higher ground which is overlain by blanket bog.

Several streams drain the area to the northwest flowing around the mass of gravels. There are no drains in the gravel area since it is free draining.

There is little agricultural activity in the area as the land is dominantly boggy apart from the gravel area where there are large scale gravel extraction pits in operation.

4 GEOLOGY

4.1 Bedrock Geology

The area is underlain by Lower Carboniferous sandstone (Boyle sandstone).

4.2 Subsoils Geology

Kilkelly is dominated by sands and gravels centred around the town/source. A small amount of fen peat lies immediately beside the spring, marking an area of former groundwater discharge. Sandstone till and Blanket bog lie in the peripheral areas to the spring, outside its proposed catchment. Copies of the 6" subsoil field sheets carried out by this author appear in Figure 1 and a digitised copy of the area (14/29 SW) at the 1:25,000 scale appears at the back of this appendix.

The sands and gravels are esker and glaciofluvial/glaciolacustrine related. Nearly 100% of the proposed catchment is overlain by sands and gravels.

The local esker shows a N-S orientation; sections show that it consists of a coarse boulder/cobble gravel in a sandy matrix with equal shares of limestone and sandstone clasts. This esker merges into the glaciofluvial related sands and gravels north of the spring. Pit face sections show that these sand and gravels are greater than 20m deep.

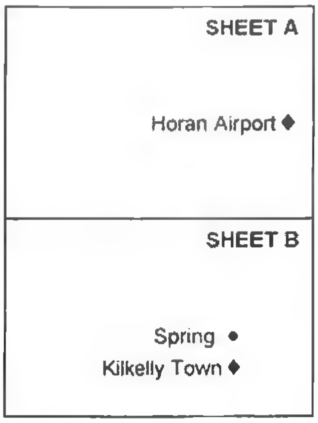
Overall the sediments around Kilkelly were formed in a similar situation to the sands and gravels at Ballyhaunis, 13km SE. The esker in Kilkelly may have acted as a tunnel input under a local glacier dumping sediment into a proglacial ice age lake about 2km north of the town.

PHOTO 4
Aerial Photograph of the Kilkelly area

4.4 Depth-to-rock

There are believed to be no outcrops although large angular sandstone boulders are found on the drumlins to the west of the spring. The gravel areas are > 15m to rockhead.

Figure 1
6" Subsoil Field Sheets for Kilkelly



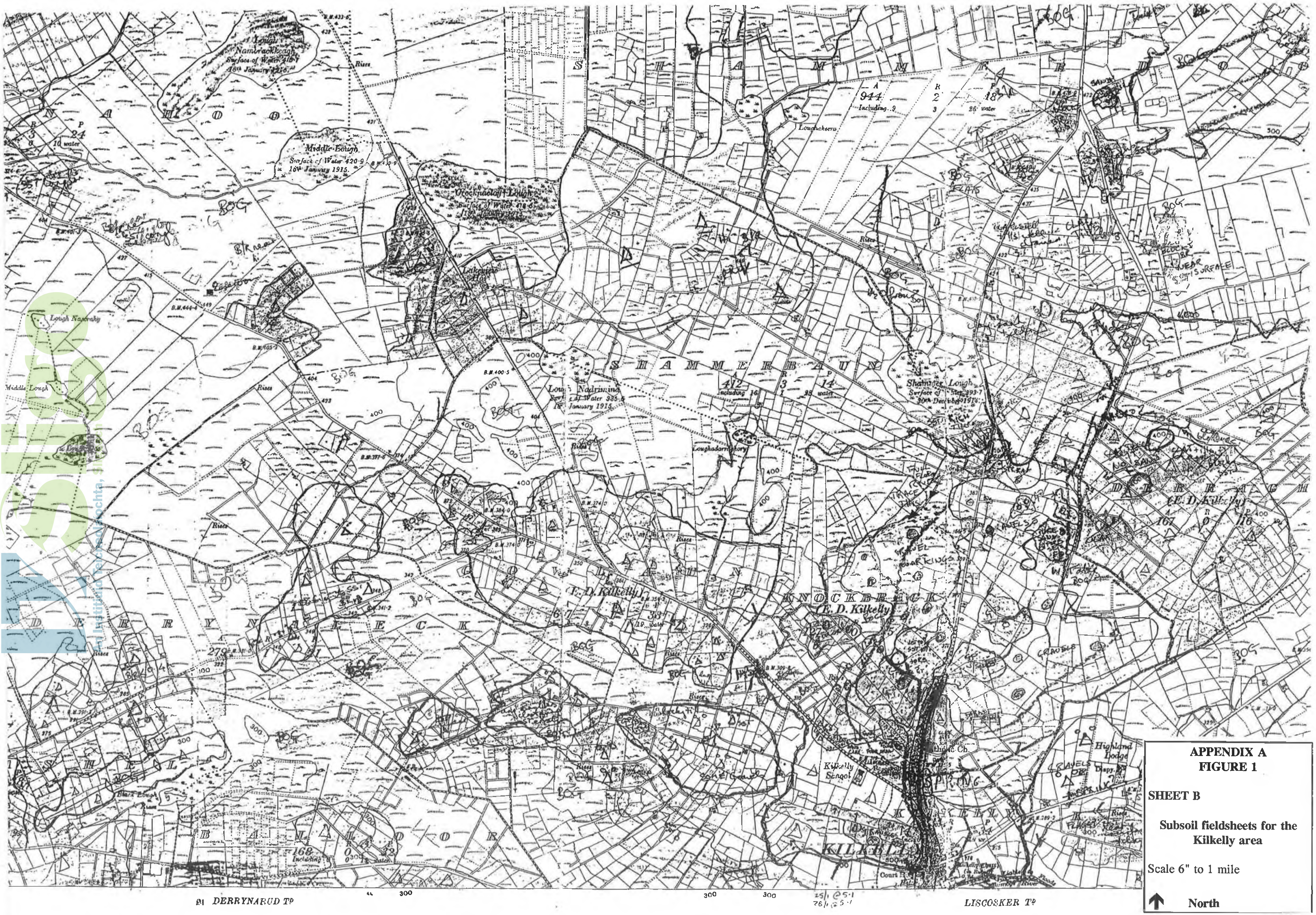
APPENDIX A
FIGURE 1

SHEET A

Subsoil fieldsheets for the Kilkelly area

Scale 6" to 1 mile

↑ **North**



APPENDIX A
FIGURE 1

SHEET B

Subsoil fieldsheets for the Kilkelly area

Scale 6" to 1 mile

↑ North

5 METEOROLOGY

Daily rainfall data for the October 1992 to September 1993 period at Kilkelly, were calculated from the Horan International Airport rainfall station (213m OD), since it is only 4km to the NE of the spring. The nearest other rainfall station is at Claremorris (71m OD) but it is 30km away. At Horan rainfall was 1423mm. Rainfall would have been about 1323mm when altitude is taken into account. AE for the area was estimated at 365.5mm, the same value as PE at Claremorris since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures potential recharge was taken to be approximately 957.5mm for the October 1992 to September 1993 field season (see Figure 2).

These calculations are summarised below:

Precipitation	1323mm
P.E.	365.5mm
Estimated A.E. (100% P.E.)	365.5mm
Potential recharge	957.5mm

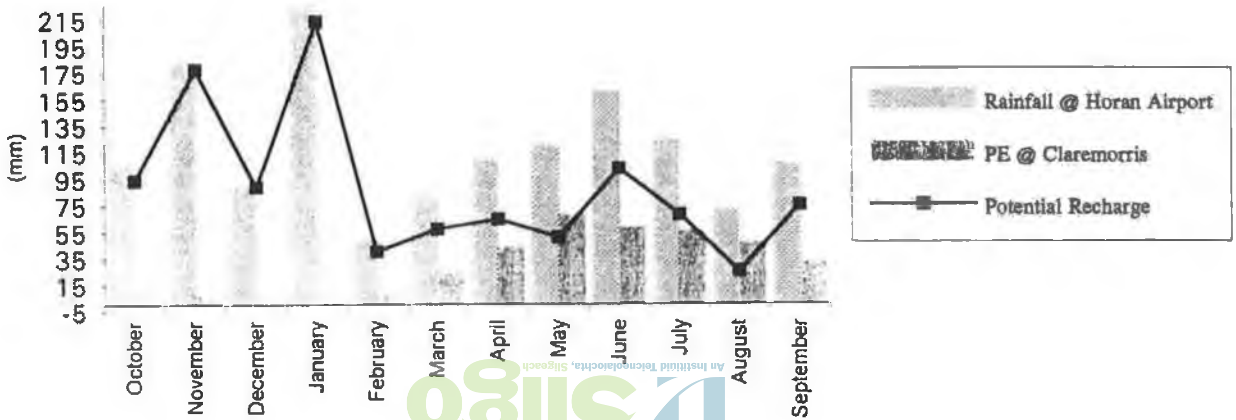
6 WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed in the spring area an understanding of the size of the spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies was to occur within the spring recharge zone. It was decided that, as an initial step, the spring catchment area would be *estimated* by a water balance, the principles which have been discussed in Chapter 3.

The recharge area required to supply the October 1992 to September 1993 discharge levels of this spring was calculated by:

$$\left(\begin{array}{c}\textbf{Outflows}\\ \text{Total Spring Output}\\ +\text{ Abstraction}\\ +\text{ Flow to other}\\ \text{aquifers}\end{array}\right) / \left(\begin{array}{c}\textbf{Inflows}\\ \text{Direct Recharge}\\ +\text{ Indirect Recharge}\\ +\text{ Flow from other aquifers}\\ +\text{ Urban Recharge}\end{array}\right) = \begin{array}{c}\textbf{Catchment}\\ \textbf{Area}\end{array}$$

FIGURE 2
1992-93 Meteorology for Kilkelly (Horan Airport) with calculated Potential Recharge



Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

Total Spring Output

Overflow from the spring and total pumping rates at the pumphouses were needed to find the total spring output. A staff gauge at the overflow stream beside the road was used to determine the spring overflow. Water levels were converted to discharge with a rating curve developed by this author, with a midget current meter and salt dilution gauging. It was found that overflow at the weir averaged 2,000 m^3/day. Total pumping rates at the spring were 1,311m^3/day.

Therefore, the total spring output for Kilkelly is 3,311m^3/day. $\Rightarrow$ 3,311m^3/d

Abstraction

Disregarded, see Chapter 3.

Flow to other aquifers

Disregarded, see Chapter 3.

Total outflows from the spring $\Rightarrow$ 3,311m^3/d

Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

Direct Recharge

As there are relatively high permeability subsoils in the area and there are few drainage features, a high proportion of potential recharge, infiltrates to the water table. Estimating runoff to be in the order of 10% of potential recharge, direct/actual recharge to the aquifer was taken to be 861 mm.

$\Rightarrow$ 2.36×10^{-3} m/d

Indirect recharge Nil

Flow from other aquifers

See Chapter 3. The flow from the sand and gravel aquifer near the source is accounted for in the runoff calculations above.

Total inflows to the aquifer at Kilkelly ⇒ 2.36×10^{-3} m/d

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

$$\frac{\text{Total outflows from the Kilkelly spring}}{\text{Total inflows to the aquifer at Kilkelly}} = \frac{3{,}311 m^3/d}{2.36 \times 10^{-3} \text{ m/d}} = 1.4 km^2$$

7 HYDROGEOLOGY

7.1 Groundwater levels

Groundwater data is sparse for the Kilkelly area.

7.2 Groundwater flow direction, gradient and time of travel

Regional groundwater is postulated to flow from N to S in sandstone bedrock and overlying sands and gravels.

7.3 Physical structure of the spring catchment area

There is a large sand and gravel area directly north of the spring. It is at the break in slope from these gravels to lower ground that the spring discharges. It is hypothesised that the spring is a joint sand and gravel / sandstone bedrock source since the year round hardness at the spring was relatively low with an average of 230mg/l $CaCO_3$ and an EC of 449μS/cm. If the spring was entirely draining the gravels these readings would probably have been higher.

Generally transmissivity is thought to occur in the underlying fractured? sandstones but the majority of storage occurs in the gravels.

7.4 Physical Demarcation of the Catchment Area

The catchment boundaries for this spring were principally determined by topography since there were no watertable maps, keeping in mind that the water balance method estimates the size of the catchment to be 1.4km². The area to the north of the spring was concentrated on since as it is more likely to recharge the spring as it is uphydraulic gradient to it.

The physically determined catchment area for the spring was judged to be 1.6km²; it appears in Figure 1. These figures may be used as a starting indicator that the physically determined catchment area recharges the spring.

8 VULNERABILITY ASSESSMENT

A vulnerability map was determined at the 6" scale for the confines of the proposed catchment area (Figure 3). The GSI Guidelines (Daly and Warren, 1994) were applied in the production of the vulnerability map, using the data from the subsoil maps (Figure 1), the soils map of Ireland, and aerial photography. The "improved and achievable vulnerability mapping" guidelines were the main rules used since much of the catchment was mapped at reconnaisance level with trial pitting. The "minimum standard vulnerability mapping" guidelines were used specifically for areas of undifferentiated till (TUD) where details on till texture were not known. Undifferentiated till is common within the catchment, where it has not been possible to extrapolate textures from trial pits to the more distant areas.

The spring catchment at Kilkelly is considered to have a high vulnerability to pollution since it is overlain by high permeability subsoils. The coefficient of variation in the year round electrical conductivity measurements was 5.6%, the smallest for any of the eleven springs. This signature reflects the diffuse recharge, the relatively slow intergranular flow and the relatively long residence time for groundwater in this sandstone/sand and gravel aquifer.

The mapped vulnerabilities for this source's catchment area are presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), that occur within the confines of the catchment.

The % value is: 1% Extreme
99% High.

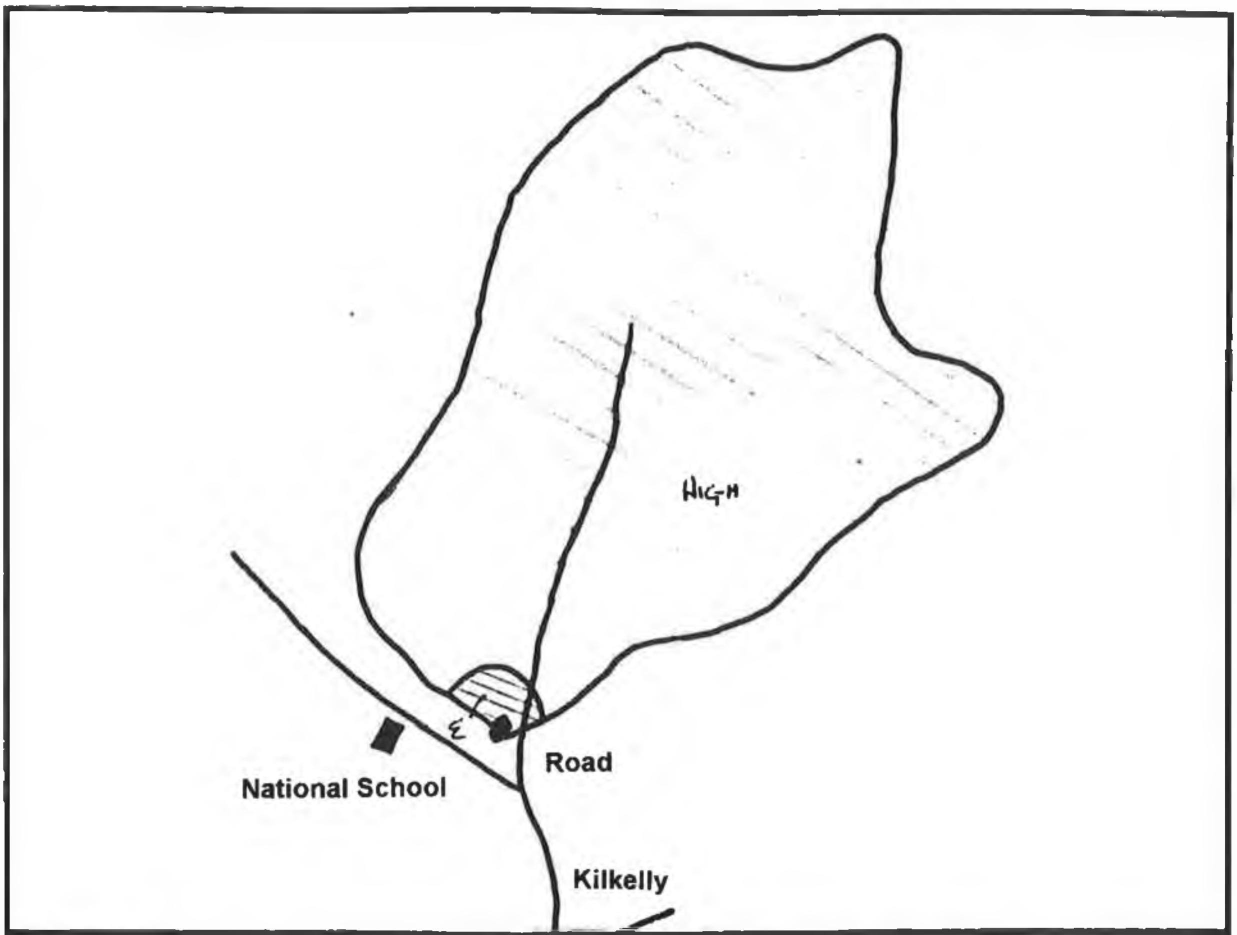


FIGURE 3
Kilkelly
Groundwater Vulnerability

Scale 6" to One Mile

☐	**Extreme Vulnerability**
☐	**High Vulnerability**
(outline)	**Catchment**
↑	**North**

9 POTENTIAL POLLUTION SOURCES

Septic tanks are considered to be the main threat to the spring catchment particularly at the nearby church and gravel works. There is little to no agricultural activity in the proposed catchment and so it would have a minimal effect on the water quality of the springs.

APPENDIX B

CROSSMOLINA PUBLIC SUPPLY

1 SPRING DETAILS

GSI No.	: 08/31SE W --	
Grid Ref.	: 109950 317100	
6" Sheet	: Mayo 37, 38	
Townland	: Moylaw	
Elevation	: ~51.5m OD	
Depth to Rock	: rockhead not known, in gravels	
Average Spring Discharge	: (i) Abstraction Rate	726m^3/d
	(ii) Spring Overflow Average:	838m^3/d
	(iii) TOTAL Spring Discharge(i+ii):	1564m^3/d

2 SPRING LOCATION AND SITE DESCRIPTION

The Crossmolina source, which is used for public and group supply is located 3.8km west of the town in a boggy field, on the main Crossmolina to Belmullet road, at the Moylaw T junction (Figure 1).

The source consists of a spring and pump enclosed in a wooden shed. The water level of the spring is kept at a stable height by a steel plate standard V notch weir (Photo 1). Overflow is to a small channel. Another group scheme takes its water from this overflow (Photo 2).

The source lies immediately beside a main road and is open to vandalism.

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

The spring, at an elevation of about 51m OD lies in the Deel River valley (Photo 3). The Deel River is 1.5km south of the source at an elevation of 46m OD; it flows to Lough Conn.

Several areas of high ground lie NW of the spring and reach a maximum height of 72m OD. This area consists of gravels which are relatively free draining. Blanket bog lies futher NW. Minor tributaries run southwest from the blanket bog.

Land use in the area is mainly livestock farming, both dairy and drystock.

PHOTO 1
Crossmolina Spring and V-notch weir

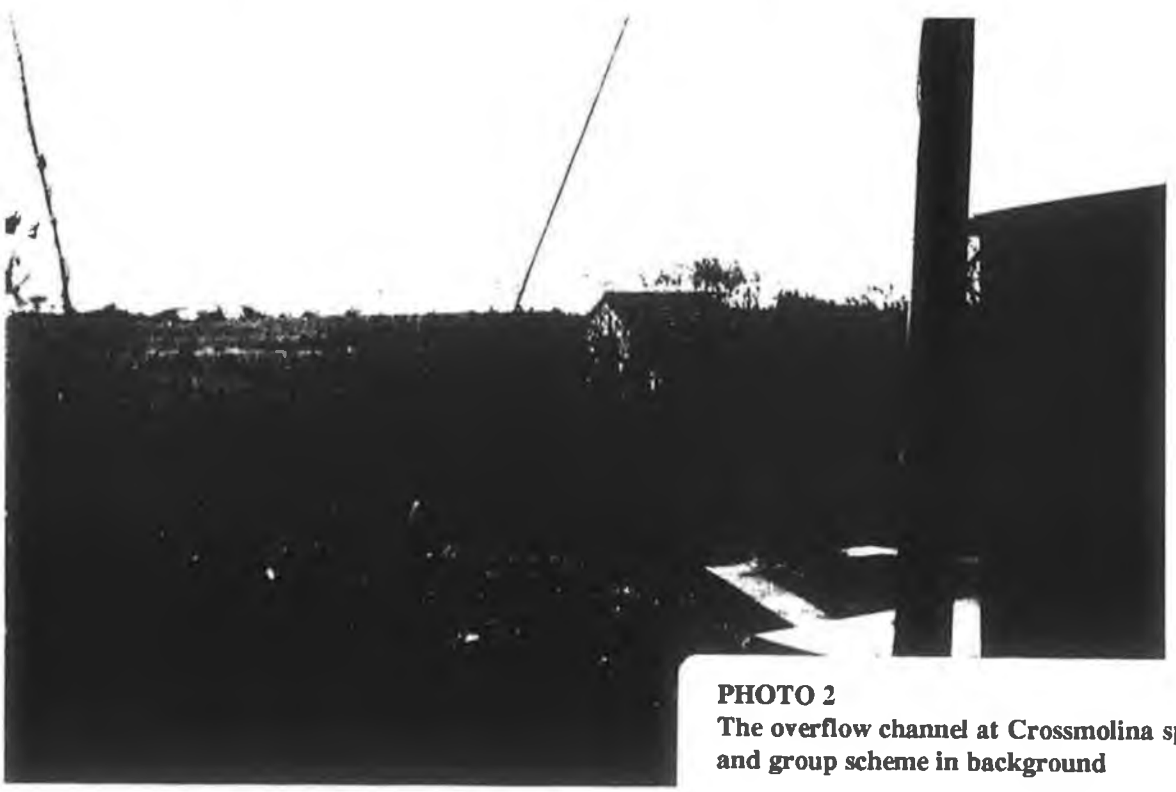


PHOTO 2
The overflow channel at Crossmolina spring and group scheme in background

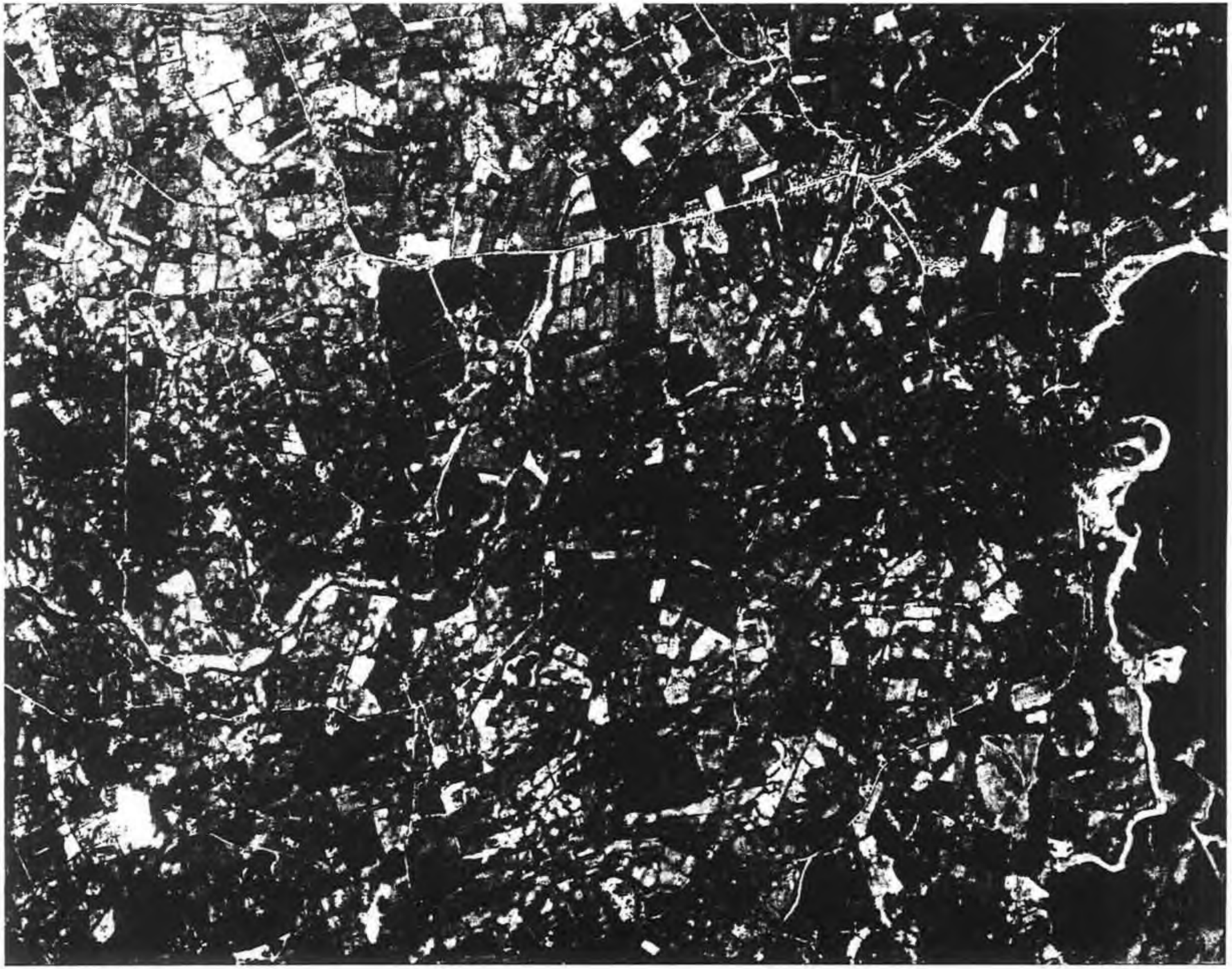
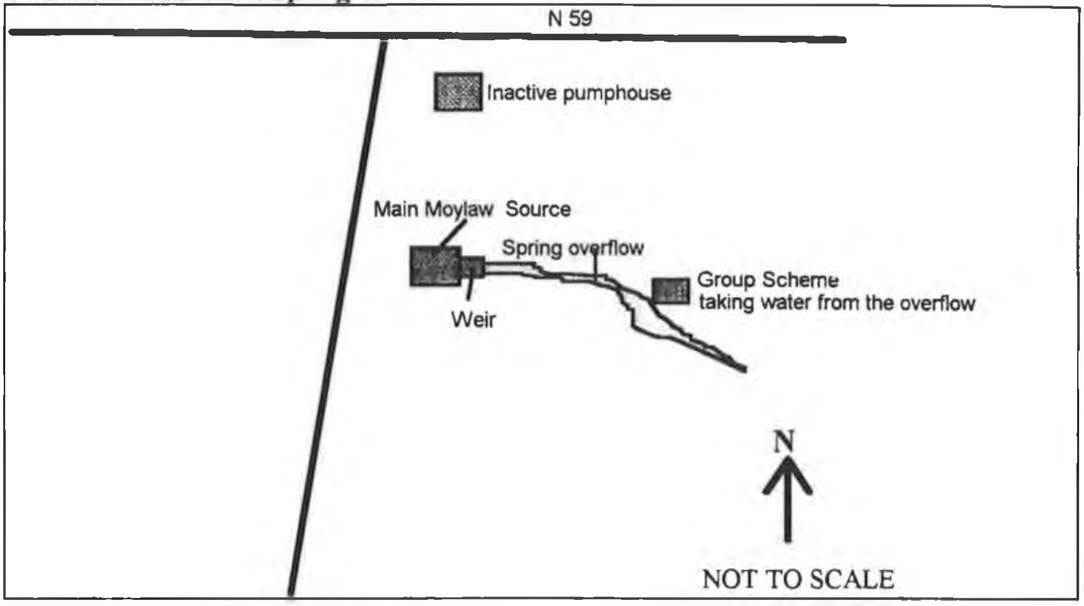


PHOTO 3
Aerial Photograph of the Moylaw area

FIGURE 1

Sketch of Crossmolina Spring Works



4 GEOLOGY

4.1 Bedrock Geology

The bedrock of the area is Carboniferous limestone, the Ballina group (Chevron 1992), and is Dinantian in age.

4.2 Subsoils Geology

Copies of the 6" subsoil field sheets near the spring mapped by this author appear in Figure 2a, and the digitised 1:25,000 scale version (8/31SE, 11/31SW) of the larger area outside the spring (Figure 3b) appears at the back of this appendix. Generally there are three dominant subsoils units: (a) Sand and gravel areas with undulating, hummocky terrain; (b) Blanket peat; and (c) Limestone till.

4.2.1 Sands and gravels

Over 80% of the proposed catchment, determined in Section 7, is overlain by sands and gravels with many local extraction pits. These deposits are glacio-lacustrine related. Pit face sections 500m NW of the spring show that the sands and gravels are greater than 10m deep. The deposits consist of pure sand lenses up to 1m thick interbedded with large units of cobble gravel > 4m thick. Certain pits show foresets in the sand units. Clast lithology is mixed, dominantly limestone and sandstone with some metamorphics. All clasts are sub-rounded and reach a maximum of 30cm.

APPENDIX B
FIGURE 2a

SHEET A

Subsoil fieldsheets for the Crossmolina (Moylaw) area

Scale 6" to 1 mile

North

4.2.2 Blanket peat

Blanket peat overlies the highest part of the proposed spring catchment specifically to the NW. It is often less than 1m deep and overlies clayey tills. This peat is at the very western edge of a large sweep of blanket peat that surrounds the Bellacorrick area.

4.2.3 Limestone till

Subsoils immediately south and east of the blanket peat consist of limestone till (diamictic sediments). These sediments are characterised by their bimodal particle size distribution. They are largely composed of sub-rounded assorted limestone clasts supported by a clayey matrix, with small amounts of sand.

4.3 Depth-to-rock

Depth-to-bedrock within 10km radius of the spring is believed to be greater than 4m, from scant well records. The only outcrop in the area is found along the banks of the Deel River 1.5km south of the source. The bedrock here is limestone and is partly karstified.

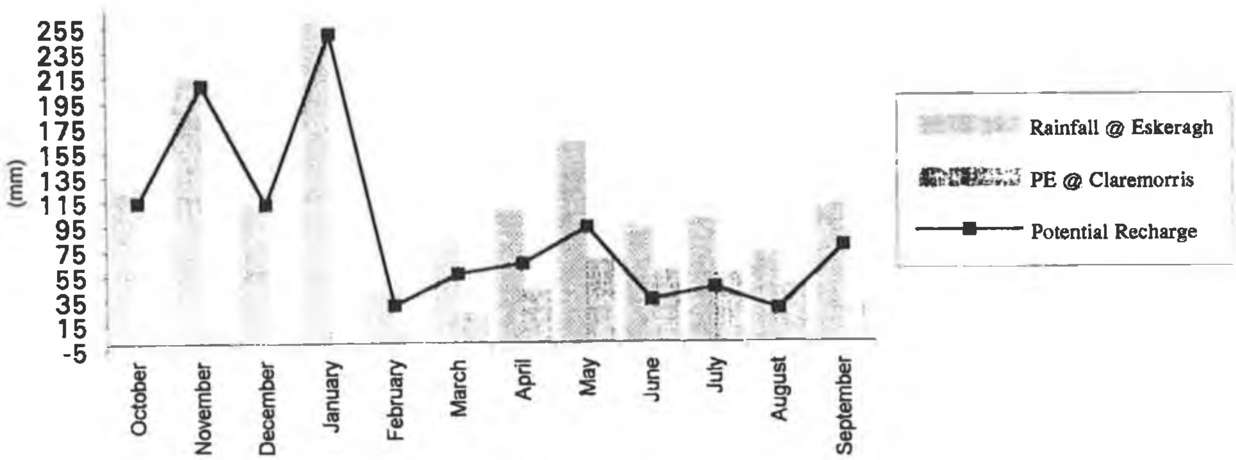
5 METEOROLOGY

Daily rainfall data for the October 1992 to September 1993 period was taken directly from the Eskeragh rainfall station (85m OD), which is 5km to the NW of the source. Rainfall was 1479mm. The Theissen polygon method could not be utilised in calculating rainfall because records at the nearby Crossmolina Garda station were incomplete. Potential Evapotranspiration (PE) was taken from Claremorris, the nearest synoptic station; it was 365.5mm for the same period. Actual Evapotranspiration (AE) was estimated at 365.5mm, the same value as PE, since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures potential recharge was taken to be approximately 1113mm for the October 1992 to September 1993 field season (see Figure 3).

These calculations are summarised below:

Precipitation	1479mm
P.E.	365.5mm
Estimated A.E. (100% P.E.)	365.5mm
Potential recharge	1113mm

FIGURE 3
1992-93 Meteorology for Crossmolina with calculated Potential Recharge



6 WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed in the spring area, an understanding of the size of the spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies was to occur within the spring recharge zone. It was decided that, as an initial step, the spring catchment area would be *estimated* by a water balance. Hydrogeological work was carried out later to confirm the estimated catchment area. This work is described in Section 7.

The recharge area required to supply the October 1992 to September 1993 discharge levels of this spring was calculated by:

(**Outflows**
Total Spring Output
+ Abstraction
+ Flow to other aquifers) / (**Inflows**
Direct Recharge
+ Indirect Recharge
+ Flow from other aquifers
+ Urban Recharge) = **Catchment Area**

Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

Total Spring Output

Overflow from the spring and total pumping rates at the pumphouse were needed to find the total spring output for the October 1992 to September 1993 period. A staff gauge at the V-notch thin plate weir was used to determine the spring overflow. Water levels were converted to discharge with the British standards equation for a 90° V-notch. It was found that overflow at the weir averaged 838m^3/day. Total pumping rates at the spring were 726m^3/day. Therefore, the total spring output for Crossmolina is 1564m^3/day.

⇒ 1564m^3/d

Abstraction

Disregarded, see Chapter 3.

Flow to other aquifers

Disregarded, see Chapter 3.

Total outflows from the Crossmolina Source ⇒ 1564m^3/d

Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

Direct Recharge

Run-off from the blanket peat in the NW recharges the sands and gravels which has few drainage features. A relatively high proportion of potential recharge, determined in Section 5 therefore infiltrates to the water table. Direct/actual recharge to the aquifer was taken to be 90% of potential recharge at 1002mm.

⇒ 2.74×10^{-3}m/d

Indirect recharge Nil

Flow from other aquifers

See Chapter 3 —

Urban Recharge Nil

Total inflows to the aquifer at Crossmolina ⇒ 2.74×10^{-3}m/d

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

$$\frac{\text{Total outflows from the Crossmolina Source}}{\text{Total inflows to the aquifer at Crossmolina}} \simeq \frac{1564\text{m}^3/\text{d}}{2.74 \times 10^{-3}\text{m/d}} = 0.57\text{ km}^2$$

7 HYDROGEOLOGY

7.1 Data Availability

Groundwater data is sparse for the Crossmolina area.

7.2 Groundwater flow direction, gradient and time of travel

Regional groundwater flows from the north west to south east in the sand and gravels. Recharge occurs within the vicinity of the blanket peat uplands and regional groundwater discharge occurs at the Deel River. There was no information on the gradient or TOT of the groundwater since no tracing could be carried out.

7.3 Physical Demarcation of the Catchment Area

The catchment area for this spring was principally determined by topography; it was judged to be 0.85km^2. The outline of the catchment appears in Figure 2a,b.

The estimated catchment area determined by the water balance technique in Section 6 of the thesis was calculated to be 0.57km^2. These figures may be used as a starting indicator that the physically determined catchment area recharges the Crossmolina source.

8 VULNERABILITY ASSESSMENT

A vulnerability map was determined at the 6" scale for the confines of the proposed catchment area (Figure 4). The GSI Guidelines (Daly and Warren, 1994) were applied in the production of the vulnerability map, using the data from the subsoil maps (Figure 2a,b), the soils map of Ireland, and aerial photography. The "improved and achievable vulnerability mapping" guidelines were the main rules used since much of the catchment was mapped at reconnaisance level with trial pitting. The "minimum standard vulnerability mapping" guidelines were used specifically for areas of undifferentiated till (TUD) where details on till texture were not known. Undifferentiated till is common within the catchment, where it has not been possible to extrapolate textures from trial pits to the more distant areas.

The spring catchment at Crossmolina is considered to have a high vulnerability to pollution. The wide sand and gravel extent, although dominantly > 3m deep, causes groundwater to be highly vulnerable to pollution since it has a high permeability. However the coefficient of variation in the year round electrical conductivity measurements was relatively low at 6.6%. This signature reflects the diffuse recharge, the relatively slow intergranular flow and the relatively long residence time for groundwater in the sand and gravel aquifer.

The mapped vulnerabilities for this source's catchment area are presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), that occur within the confines of the catchment.

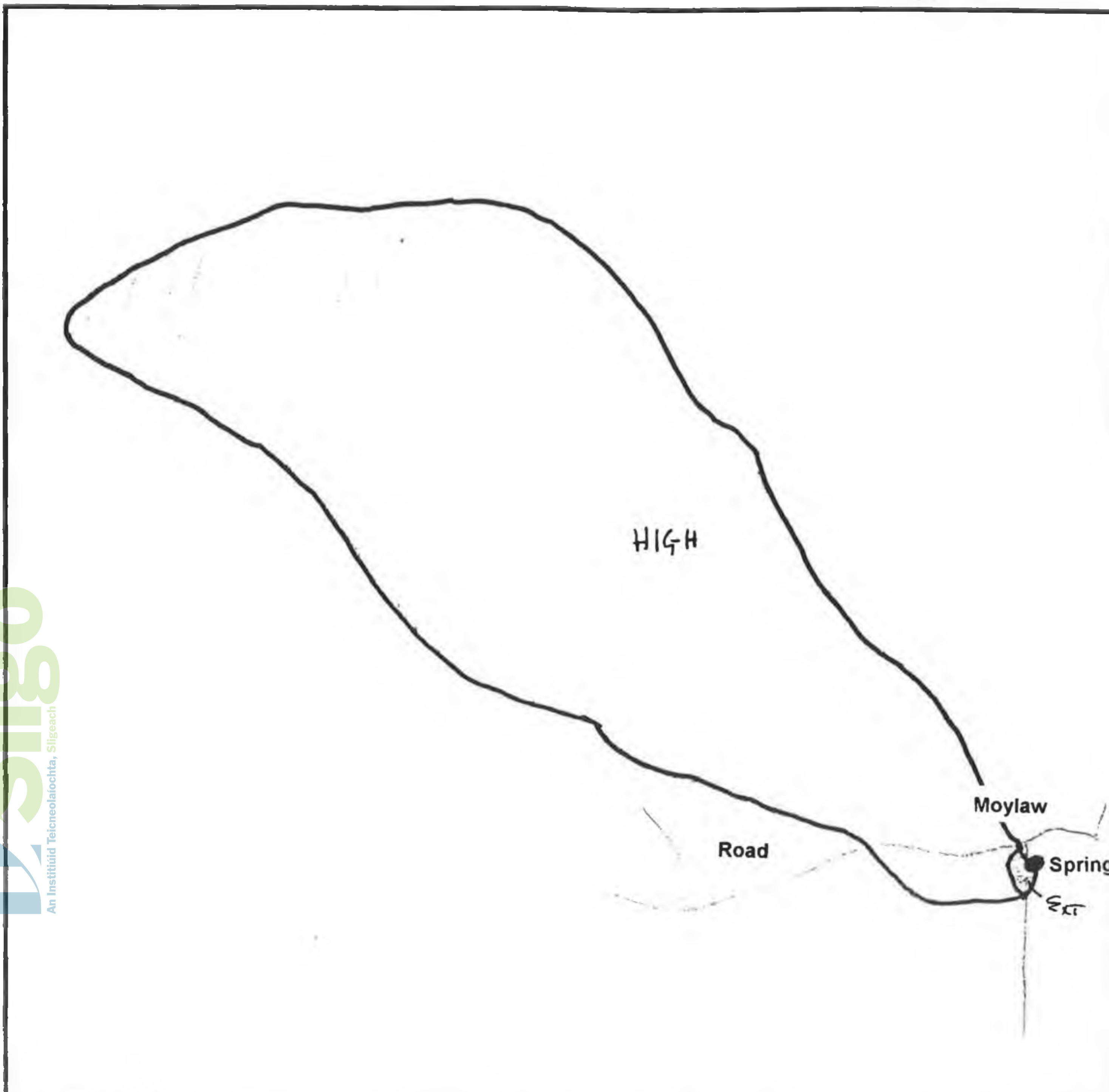


FIGURE 4

Crossmolina

Groundwater Vulnerability

Scale 6" to One Mile

☐ **Extreme Vulnerability**

☐ **High Vulnerability**

Catchment

North

The % values are: 0.1% Extreme
99.9% High.

9 POTENTIAL POLLUTION SOURCES

The area within the proposed spring catchment area consists entirely of farmland, where livestock farming is the dominant activity. Farm yards, silage clamps and landspreading of animal wastes are the main threat to the source since the subsoils although thick, have a high permeability

The source at Moylaw lies beside a main road which is open to vandalism since it is not fenced off. It is a definite risk to the water quality of the spring.

APPENDIX C

MID GALWAY/BARNADERG SCHEME

1 SPRING DETAILS

GSI No.	: 1423NW W --
Grid Ref.	: 15395 24475
6" Sheet	: Galway 44, 58
Townland	: Danganbeg
Elevation	: 56m OD
Depth to Rock at Spring	: >3m

2 SPRING LOCATION AND SITE DESCRIPTION

Twelve or more springs marked as zone A in Figure 1, provide water for the Mid-Galway groundwater scheme. Two of the larger springs appear in Photos 1 and 2. They range in size from small seepages along the 'Danganbeg stream', to large diameter springs (10m) with outflows in the region of 3,000m^3/d. Flow from the springs runs SW to the Mid-Galway pumphuse via the 'Danganbeg Stream'.

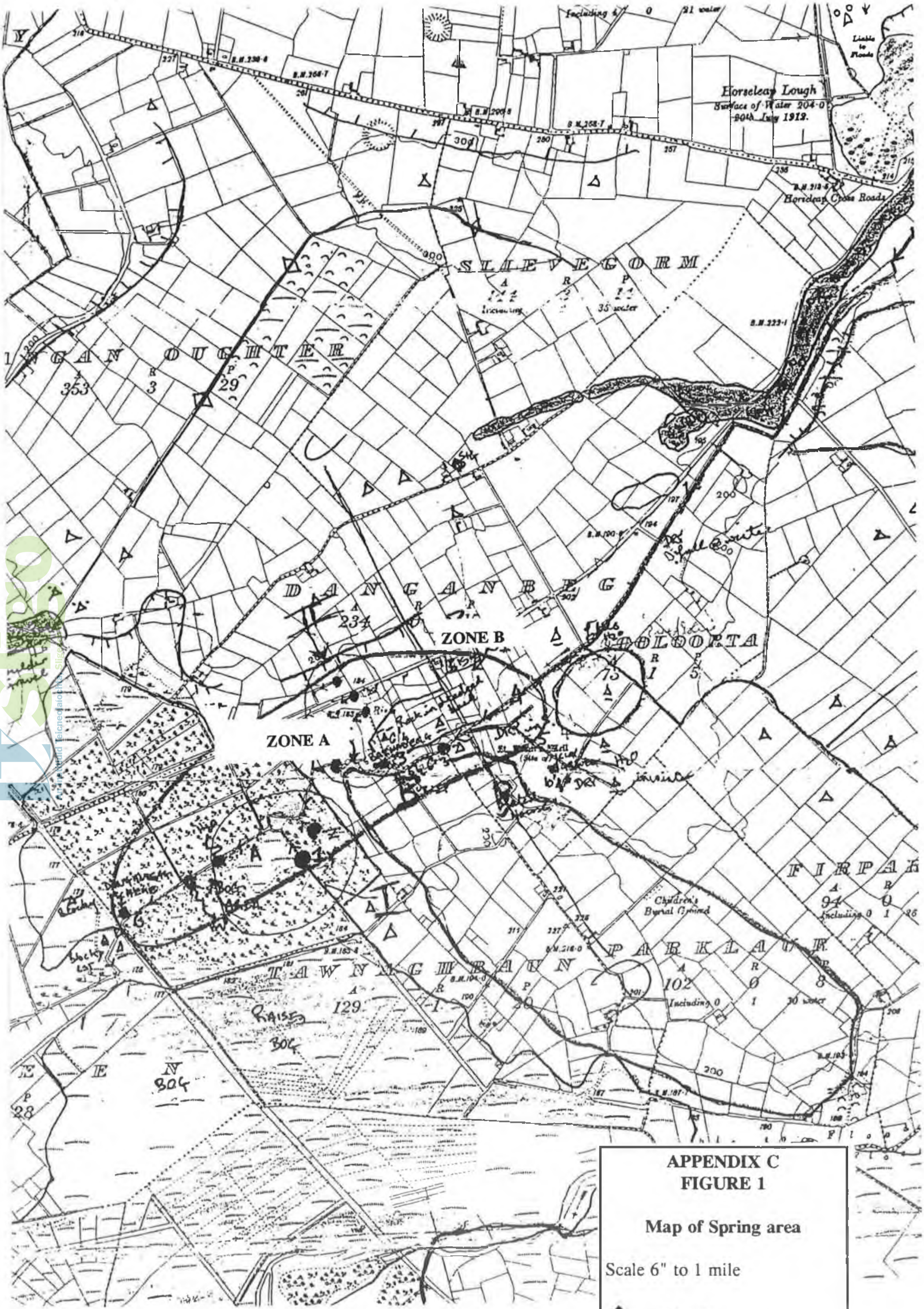
The Barnaderg group scheme supplies 400 persons. It takes its water directly from one of the smaller shallow springs which occur at the edge of a superficial bog that is underlain by silt/sand. This spring is enclosed by coarse limestone chippings.

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

The springs in Zone A lie at the headwaters of the Abbert River which drains a narrow karstic upland to the east where there are few surface drains. This ridge acts as the regional watershed; the River Suck lies to the east and Lough Corrib lies to the west (Photo 3). A turlough lies 2km NE of the springs at Horseleap cross-roads.

At a meso scale, low relief drumlins lie immediately beside the springs. Several drains lie in the depressions between the drumlins which host small raised bogs. The 'Danganbeg stream' is liable to flood immediately downstream of the Mid-Galway pumphouse.

Land use in the area is mainly livestock farming, both dairy and drystock.



APPENDIX C
FIGURE 1

Map of Spring area

Scale 6" to 1 mile

North

PHOTO 1
One of the springs feeding the source

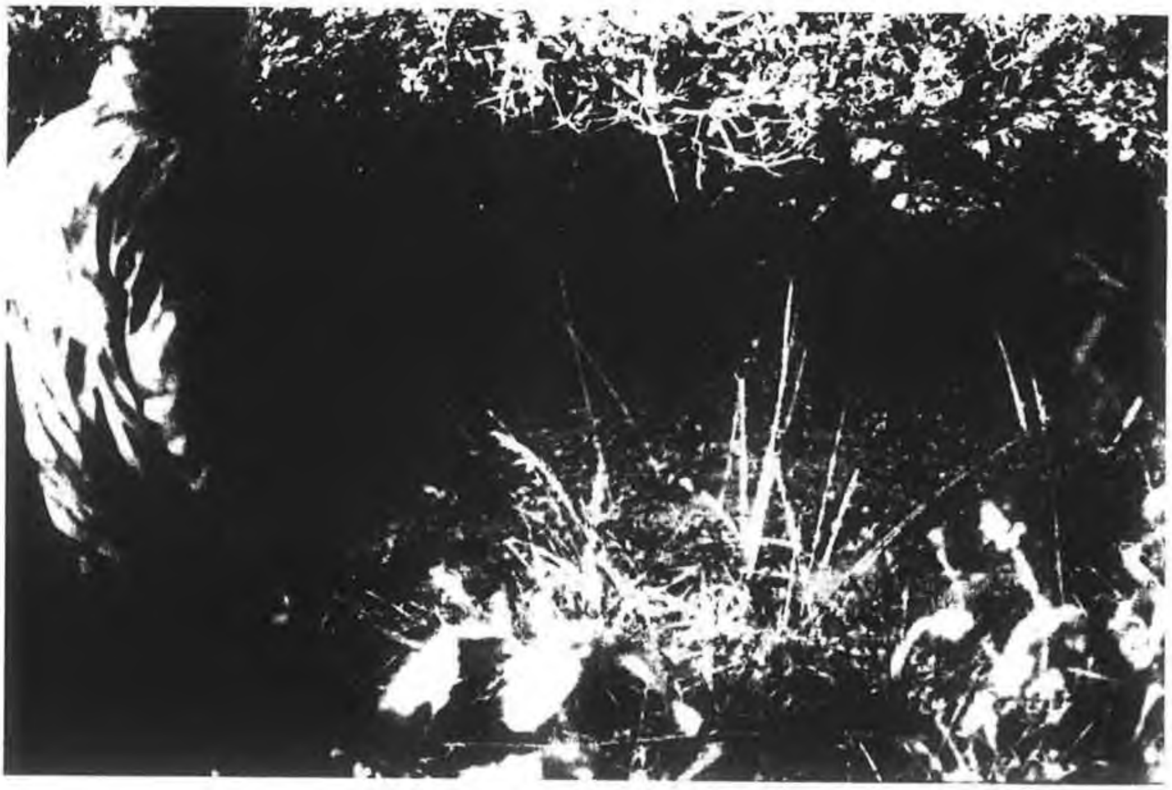


PHOTO 2
One of the springs feeding the source

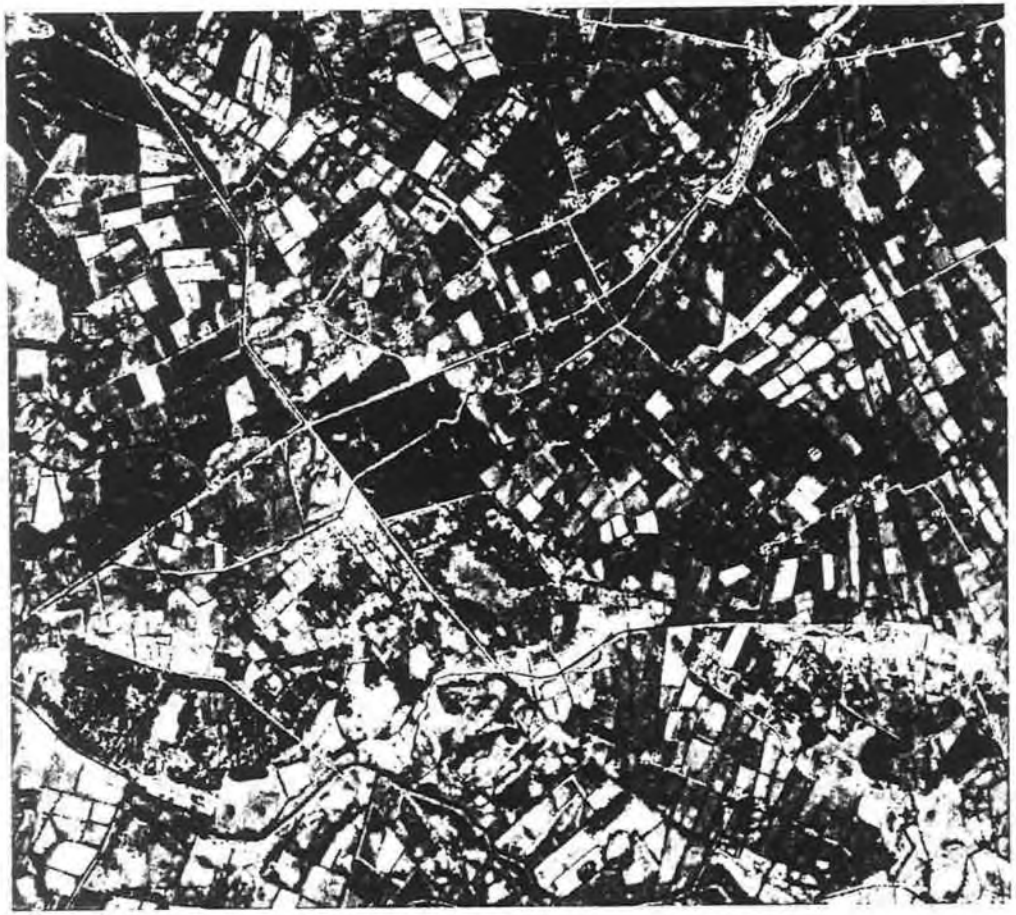


PHOTO 3
Aerial Photograph of the Barnaderg area

4 GEOLOGY

4.1 Bedrock Geology

The dominant rock type in the area is Pure Limestone (shallow water limestone; Burren). The Pure Limestone is Upper Dinantian which forms the upland topography to the east, around Mount Bellew.

4.2 Subsoils Geology

Copies of 6" subsoil field sheets for the area, carried out by this author appear in Figure 2a, and a digitised copy of the area (14/23 NW) at the 1:25,000 scale appears at the back of this report (Figure 2b). Generally subsoil sections show that there are three types of sediment; clayey till, gravels and pure sand, and bog. There is a SW/NE trending Esker system NE of the springs which outcrops extensively at Horseleap Crossroads.

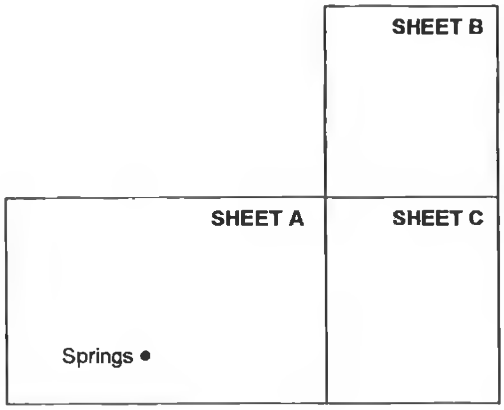
Peat is concentrated in the low lying areas, particularly around Zone A in Figure 1. Trial pits in Zone A show that peat of 0.7m thickness overlies 0.5m shell marl, which overlies pure clay. The maximum depths of the two trial pits were 3m, and no bedrock was encountered.

The area immediately around the springs is dominated by clayey till/clays which lie at depth. More permeable sediments overlie the clayey tills. Several new drains up to 2m deep carried out as part of a local field drainage scheme were inspected immediately beside the spring at Danganbeg. At the surface, thin poorly humified peat lies on stonefree silt and fine sand. These sediments overlie a unit of pure clay 20cm deep. The clay unit in turn, lies on pure sand, and the sand lies on clays. The peat probably formed when the stream at Danganbeg periodically overflowed.

4.3 Depth-to-rock

There is no information on depth to rock but it is believed to be >3m deep in the vicinity of the springs.

Figure 2a
6" Subsoil Field Sheets for Barnaderg



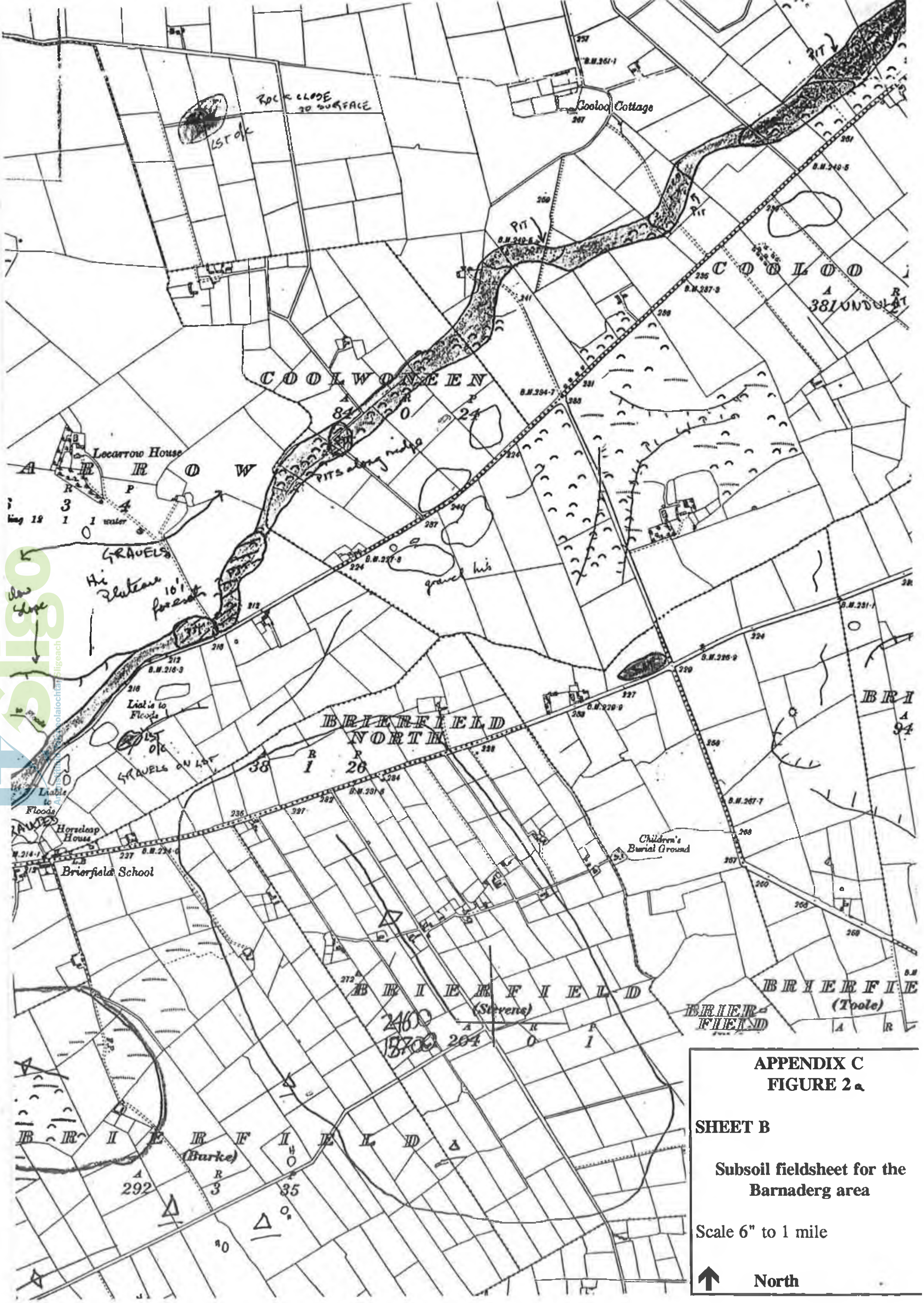
APPENDIX C
FIGURE 2a

SHEET A

Subsoil fieldsheet for the Barnaderg area

Scale 6" to 1 mile

North



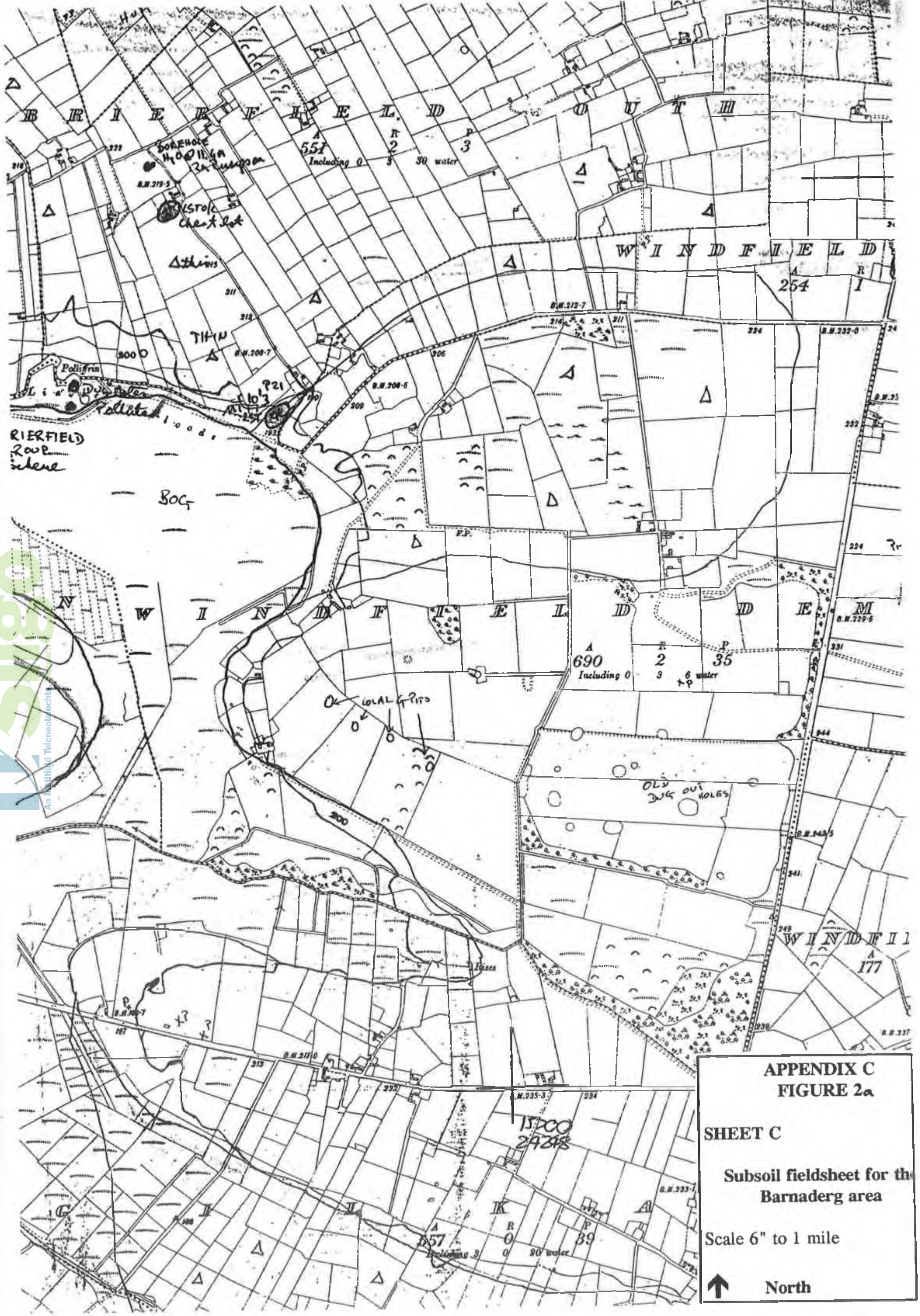
APPENDIX C
FIGURE 2a

SHEET B

Subsoil fieldsheet for the Barnaderg area

Scale 6" to 1 mile

↑ **North**



APPENDIX C
FIGURE 2a

SHEET C

Subsoil fieldsheet for the Barnaderg area

Scale 6" to 1 mile

↑ **North**

5 METEOROLOGY

Daily rainfall data for the October 1992 to September 1993 period, were taken directly from the Ballygar rainfall station (61 m OD), which is 35km NE of the springs. It is the only station in the area for which information was available for this period. Rainfall was 1038.5mm. Potential Evapotranspiration (PE) at Claremorris was 365.5mm for the same period. Actual evapotranspiration (AE) for the Barnaderg area was estimated at 365.5mm, the same value as PE at Claremorris, since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures, potential recharge was taken to be approximately 673mm for the October 1992 to September 1993 field season (see Figure 3).

These calculations are summarised below:

Precipitation	1038.5mm
P.E.	365.5mm
Estimated A.E. (100% P.E.)	365.5mm
Potential recharge	673mm

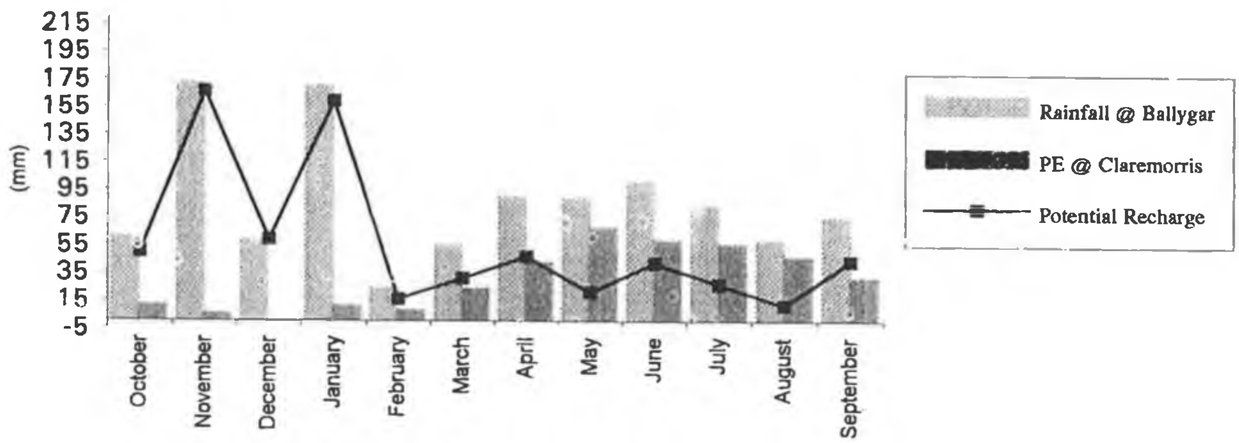
6 WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed around the source area an understanding of the size of the spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies was to occur within the source recharge zone. It was decided that only the spring catchment area for the Barnaderg group scheme at Danganbeg would be *estimated* by a water balance. The time constraints for this study did not allow the investigation of the other springs.

The recharge area required to supply the October 1992 to September 1993 discharge levels of the Danganbeg spring was calculated by:

$$\left(\begin{array}{c} \textbf{Outflows} \\ \text{Total Spring Output} \\ + \text{Abstraction} \\ + \text{Flow to other} \\ \text{aquifers} \end{array} \right) \Big/ \left(\begin{array}{c} \textbf{Inflows} \\ \text{Direct Recharge} \\ + \text{Indirect Recharge} \\ + \text{Flow from other aquifers} \\ + \text{Urban Recharge} \end{array} \right) = \begin{array}{c} \textbf{Catchment} \\ \textbf{Area} \end{array}$$

FIGURE 3
1992-93 Meteorology for Mid-Galway/Barnaderg with calculated Potential Recharge



Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

Total Spring Output

Overflow from the spring and total pumping rates at the pumphouse were needed to find the total spring output for the October 1992 to September 1993 period. It was found that the total spring output for the Barnaderg group scheme was 1000m³/d.

⇒ $1000 m^3/d$

Abstraction

Disregarded, see Chapter 3.

Flow to other aquifers

Disregarded, see Chapter 3.

Total outflows from the source ⇒ $1000 m^3/d$

Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

Direct Recharge

As there are relatively high permeability subsoils overlying units of low permeability clayey tills in the area and there are several bogs, only a moderate proportion of potential recharge, determined in Section 5, is believed to infiltrate to the water table. Estimating runoff to be in the order of 40% of potential recharge, direct/actual recharge to the aquifer was taken to be 404mm.

⇒ $1.1 \times 10^{-3} m/d$

Indirect recharge

Nil

Flow from other aquifers

See Chapter 3.

—

Total inflows to the aquifer ⇒ $1.1 \times 10^{-3} m/d$

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

$$\frac{\text{Total outflows from the spring at Danganbeg}}{\text{Total inflows to the aquifer}} = \frac{1000m^3/d}{1.1 \times 10^{-3}m/d} = 0.9km^2$$

7 HYDROGEOLOGY

7.1 Data Availability

Groundwater data is sparse for the Barnaderg area.

7.2 Groundwater flow direction, gradient and time of travel

Regional groundwater flows from E to W in the Pure Limestone.

7.3 Physical Demarcation of the Catchment Area

The catchment area for this spring was principally determined by topography; it was judged to be 1km^2. The outline of the catchment appears in Figure 4.

The estimated catchment area determined by the water balance technique in Section 6, was calculated to be 0.9km^2. These figures may be used as a starting indicator that the physically determined catchment area recharges the Barnaderg group scheme spring at Danganbeg.

8 VULNERABILITY ASSESSMENT

A vulnerability map was determined at the 6" scale for the confines of the proposed catchment area (Figure 4). The GSI Guidelines (Daly and Warren, 1994) were applied in the production of the vulnerability map, using the data from the subsoil maps (Figure 2a, 2b), the soils map of Ireland, and aerial photography. The "improved and achievable vulnerability mapping" guidelines were the main rules used since much of the catchment was mapped at reconnaisance level with trial pitting.

The spring catchment at Danganbeg is considered to have a moderate to high vulnerability to pollution since the subsoils at depth have a low permeability. The coefficient of variation in the year round electrical conductivity measurements was 6.95%, which was rather low.

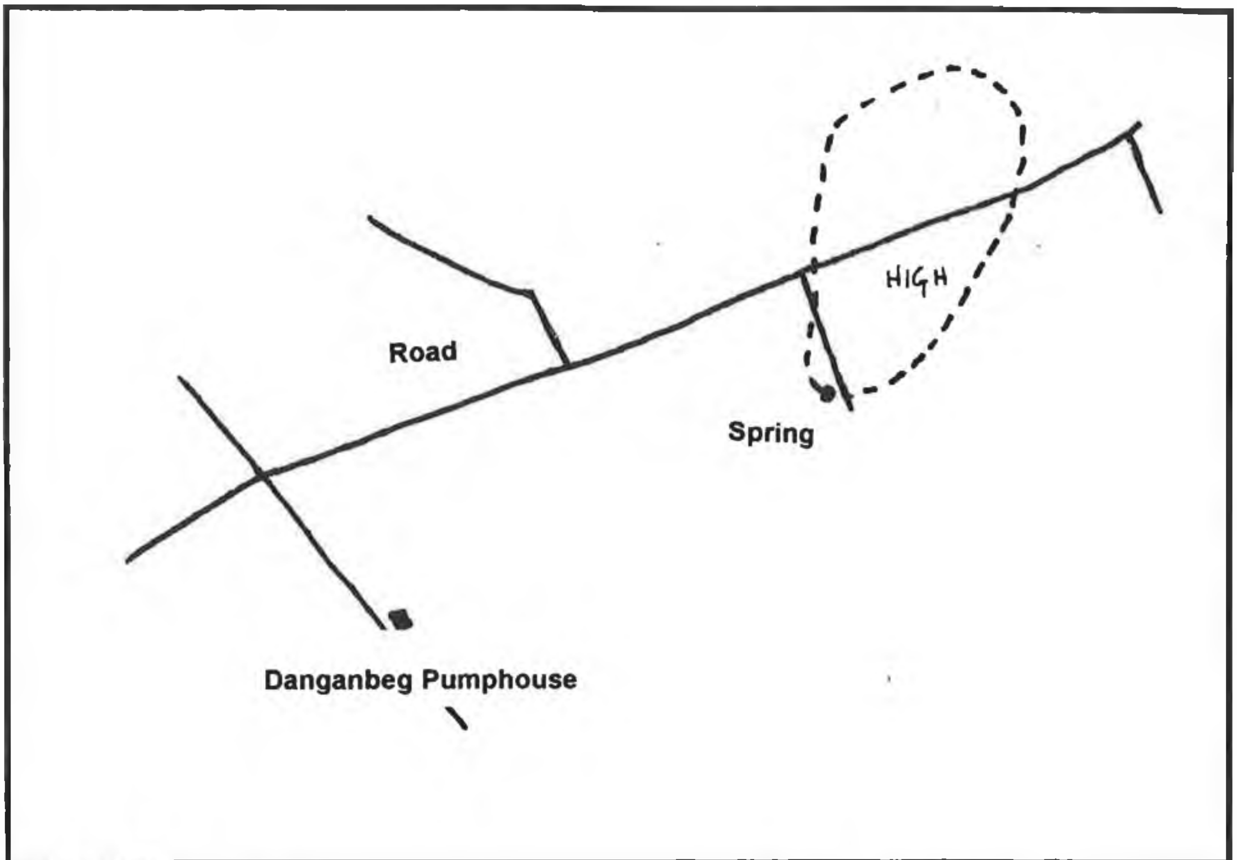


FIGURE 4
Mid-Galway/Barnaderg Groundwater Vulnerability

Scale 6" to One Mile

□ **High Vulnerability**

Catchment

↑ **North**

The mapped vulnerabilities for this source's catchment area are presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), that occur within the confines of the catchment.

The % value is: 100% High.

9 POTENTIAL POLLUTION SOURCES

Three sites marked B in Figure 1 are farms that should be visited regularly to protect the Barnaderg group scheme at Danganbeg, particularly the one at B1, which on last visit 10/8/93 had a farmyard that was in an unsatisfactory condition.

APPENDIX D

BALLINLOUGH PUBLIC SUPPLY

1 SPRING DETAILS

GSI No.	: 14/27 SE W --
Grid Ref.	: M 575 748
6" Sheet	: Roscommon 32
Townland	: Ballybane
Elevation	: ~88m OD
Depth to Rock	: 6.1m

TOTAL Average Spring Discharge: 3000m³/d

2 SPRING LOCATION AND SITE DESCRIPTION

The Ballybane spring(s) 2.5km SSE of Ballinlough town are used for the town's public supply and are managed by Roscommon Co. Co.. They are located at the foot of a low relief esker and are adjacent to a moderate expanse of cutover raised bog (Photo 1 and Figure 1).

A concrete sump about 3m deep encloses the site of the spring(s). Two large suction pumps extract water 24 hours/day from the bottom of the sump and pump it to the local reservoir. Over much of the summer field period all water that entered the sump was pumped to the reservoir. However in winter there was reported to be a small overflow at the sump.

Recently (November 1993) a full hydrogeological study was carried out by K.T. Cullen and Co. Ltd. at Ballybane which included the drilling of two boreholes (Photo 2) and extensive pumping tests.

The source is well fenced off and access can only be gained from a side road via a locked gate 150m NE.

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

The spring(s) lie in the Island River valley, a tributary of the River Suck which lies at an elevation of about 88m OD. A limestone upland (135m OD) lies 1.8km SW of the source where there are few surface drains since limestone bedrock is close to surface and the soils are

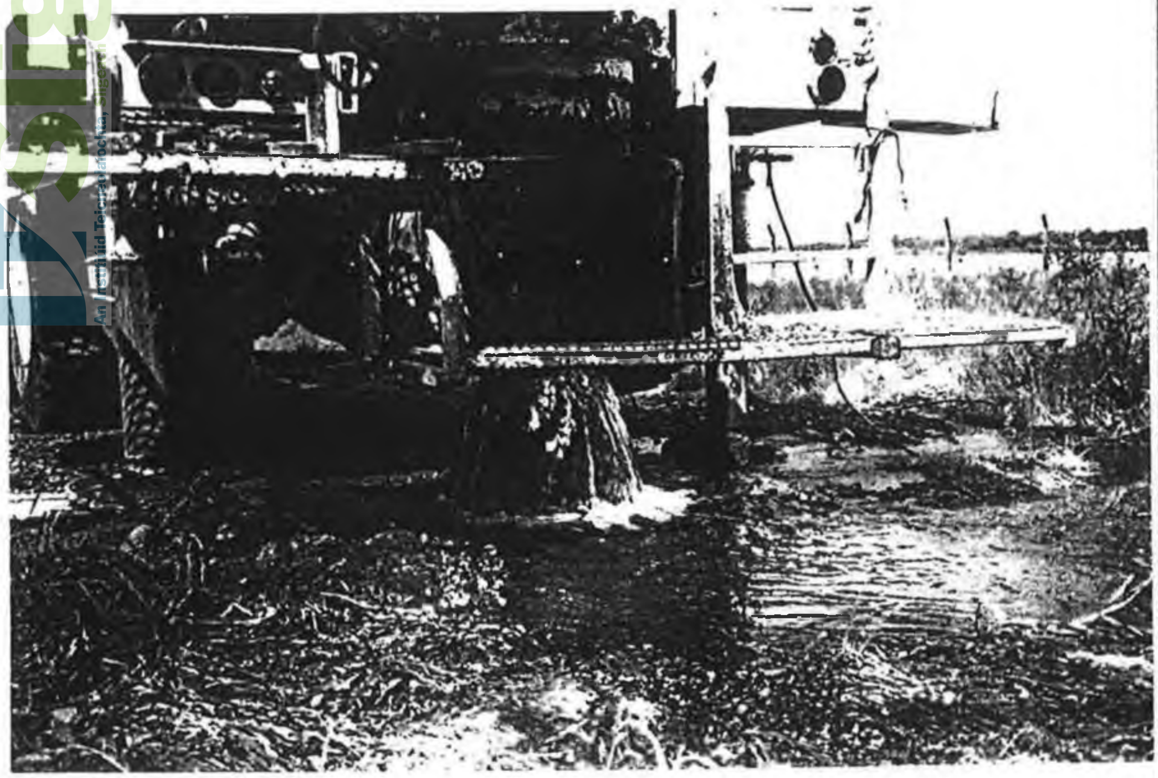
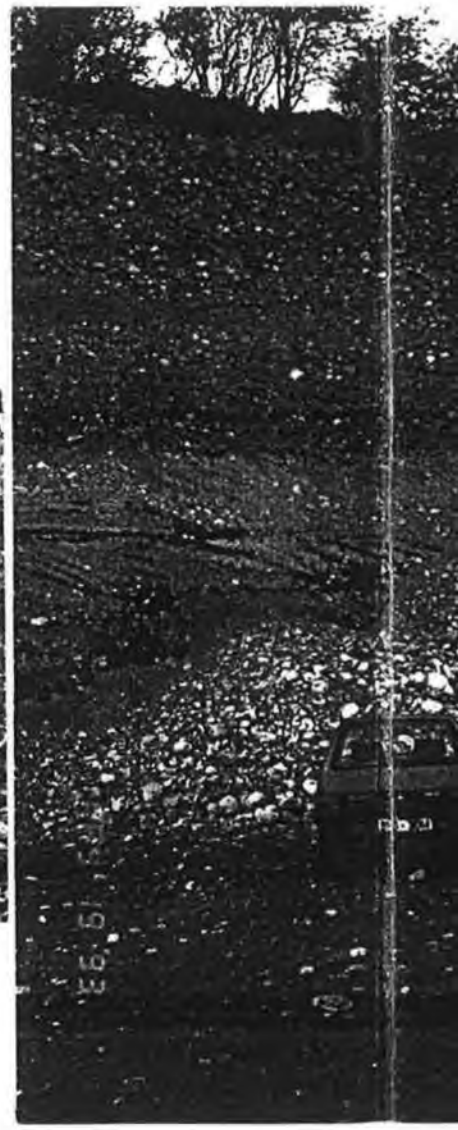


PHOTO 2
Drilling at Ballinlough



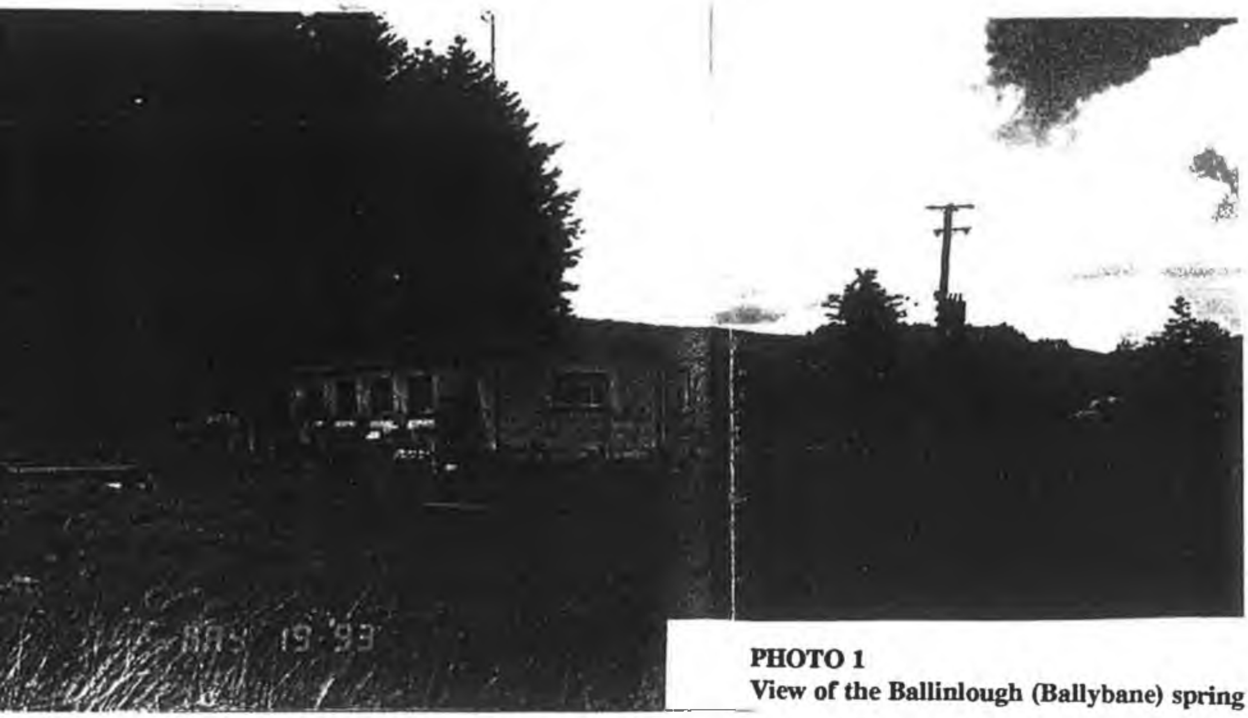
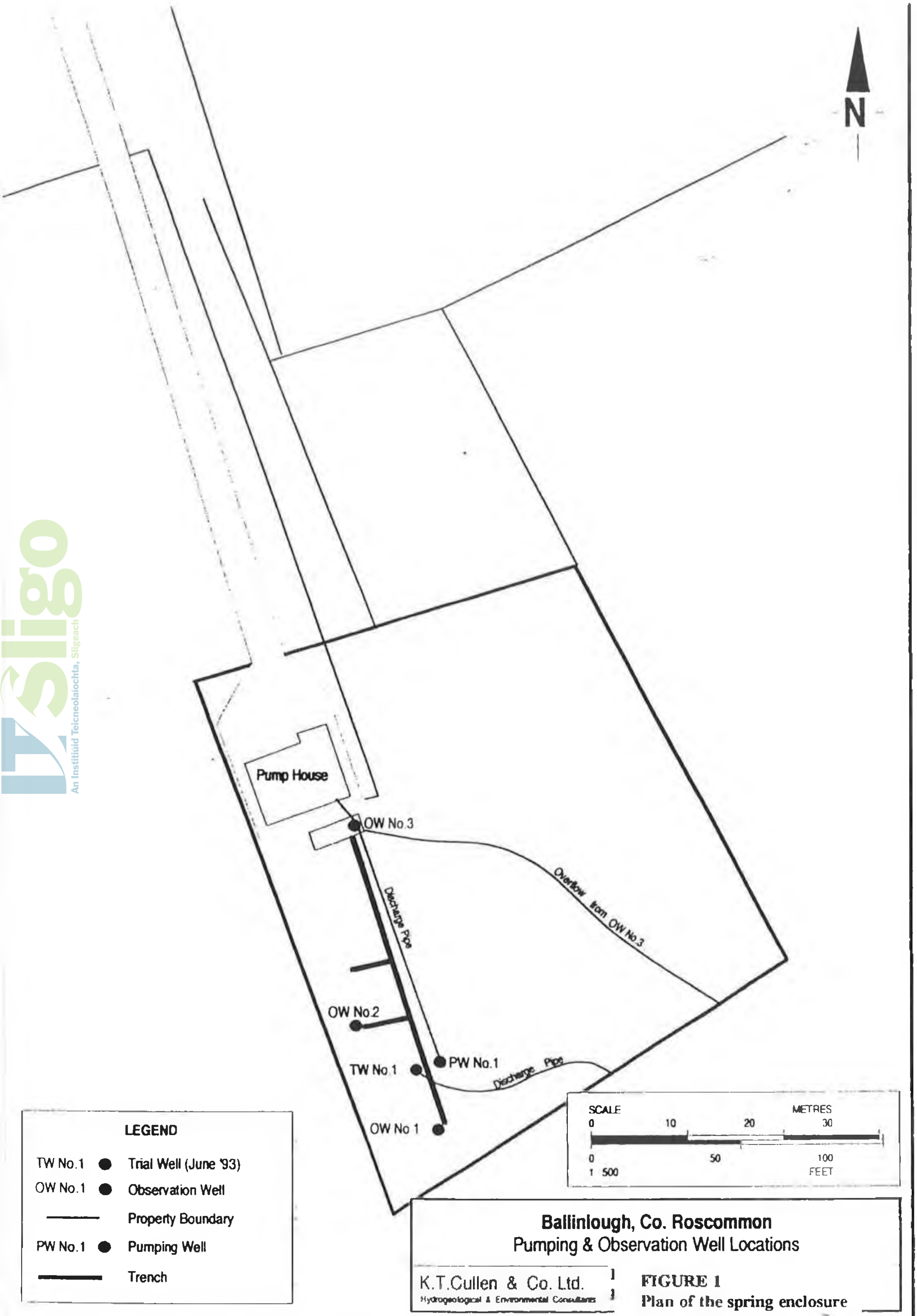


PHOTO 1
View of the Ballinlough (Ballybane) spring enclosure



Ballinlough, Co. Roscommon
Pumping & Observation Well Locations

K.T.Cullen & Co. Ltd.
Hydrogeological & Environmental Consultants

FIGURE 1
Plan of the spring enclosure

free draining (Photo 3). The ridge acts as the regional watershed; the River Clare lies to the west and the River Suck lies to the east.

At the meso scale, a relatively wide ridge of glaciofluvial sands and gravels lie between the limestone ridge and the spring(s). Again there are few drains or streams within this area since the subsoils have a high permeability and are free draining.

Land use in the area is mainly livestock farming, both dairy and drystock.

4 GEOLOGY

4.1 Bedrock Geology

The dominant rock type in this area is a black cherty limestone (Oakport Limestone).

4.2 Subsoils Geology

Ballinlough has a varied subsoils geology (Quaternary) dominated by sands and gravels around the source. Copies of the 6" subsoil field sheets for the area, carried out by this author appear in Figure 2a and a digitised copy of the area (Figure 2b [14/27 SE]) at the 1:25,000 scale appears at the back of this report. Generally within the zone of proposed catchment and 1km outside it, there are three subsoil types: Sands and gravels, Limestone till and Raised bog.

4.2.1 Sands and gravels

Sands and gravels were recorded in most localities around the source. They are esker and glaciofluvial/glaciolacustrine related. Over 85% of the proposed catchment is overlain by this subsoil type.

Two eskers run NW-SE through a mass of varying sands and gravels; they are morphologically sinuous but appear to have a low topographic relief since they are partly overlain by outwash or subglacial deposits. The eskers are found to merge into the glaciofluvial related sands and gravels within the proposed catchment. Limestone is the dominant clast in the eskers (usually 99%) but often there are some ORS clasts.

The glaciofluvial/glaciolacustrine sand and gravels are also relatively widespread outside the proposed catchment as is apparent in Figure 2b, which appears at the back of this report.

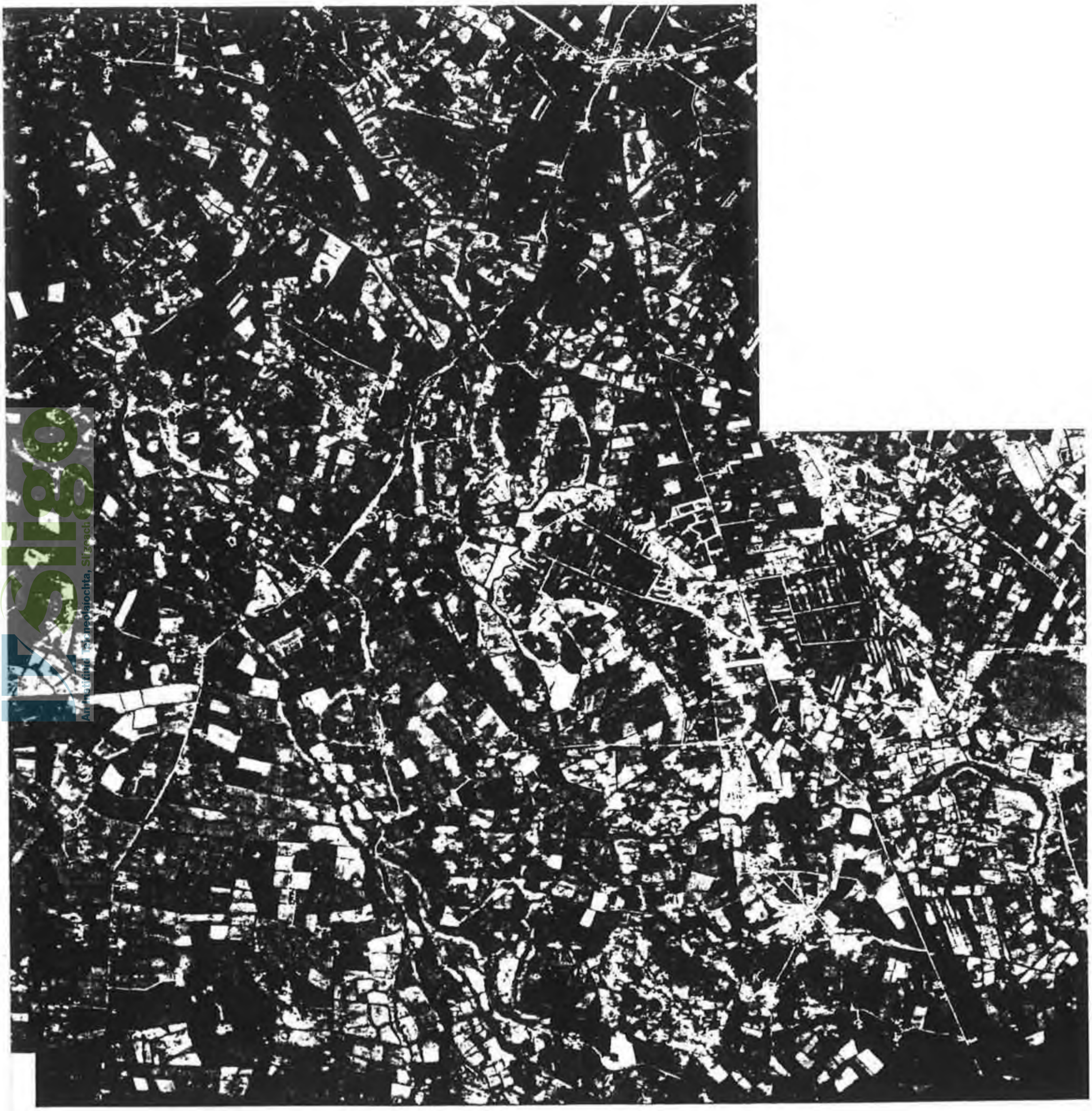
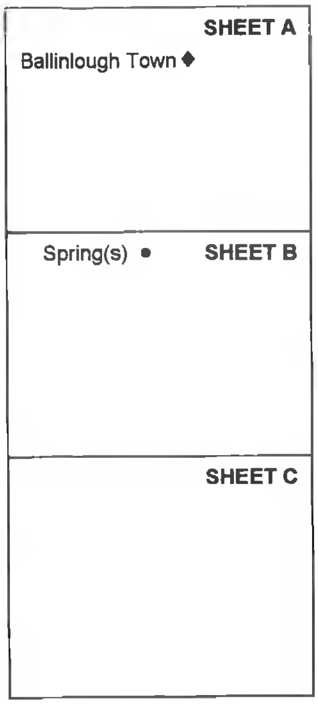


PHOTO 3
Aerial Photograph of the Ballybane area

Figure 2a
6" Subsoil Field Sheets for Ballinlough



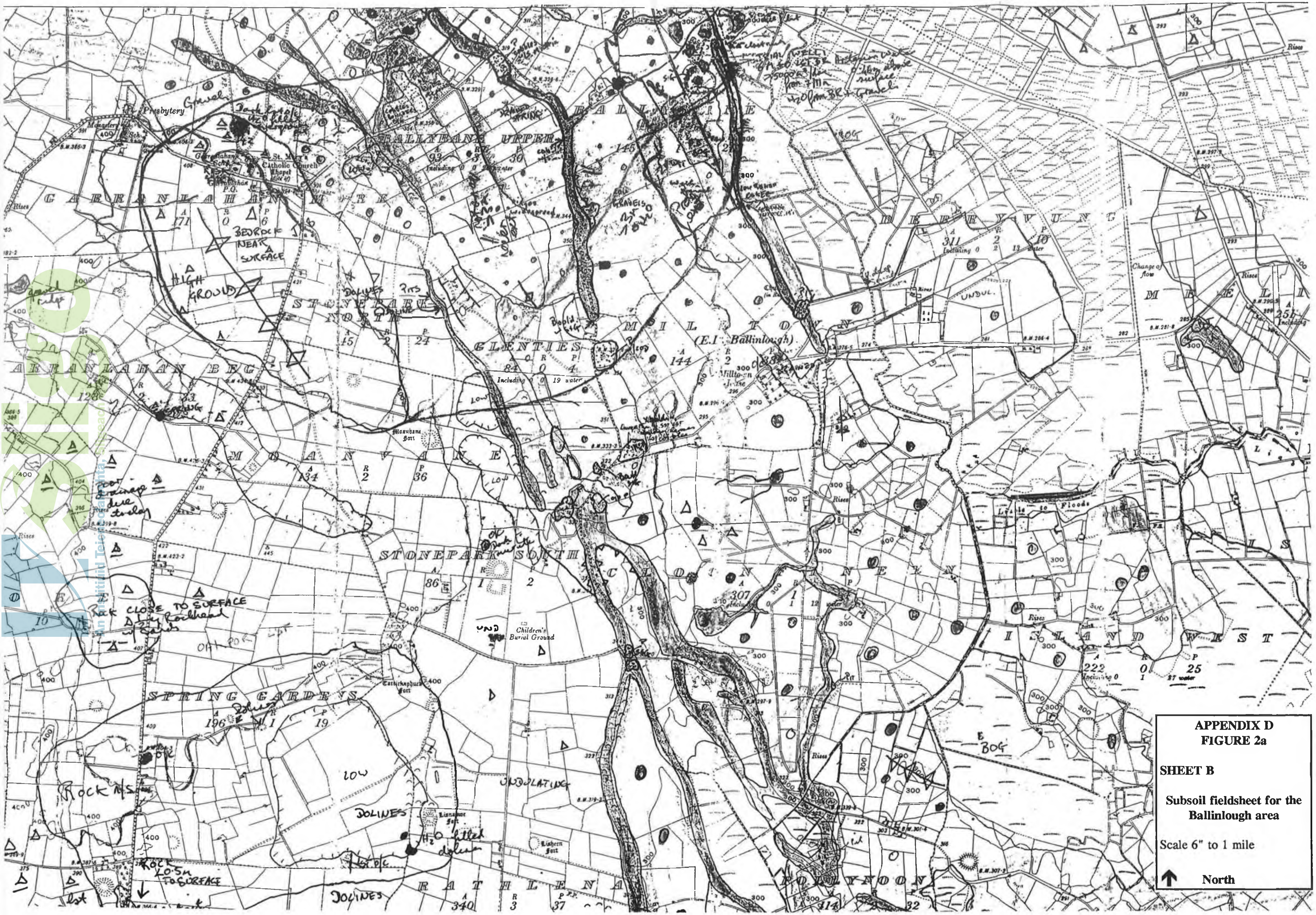
APPEN
FIGU

SHEET A

Subsoil field
Ballinlou

Scale 6" to 1

North



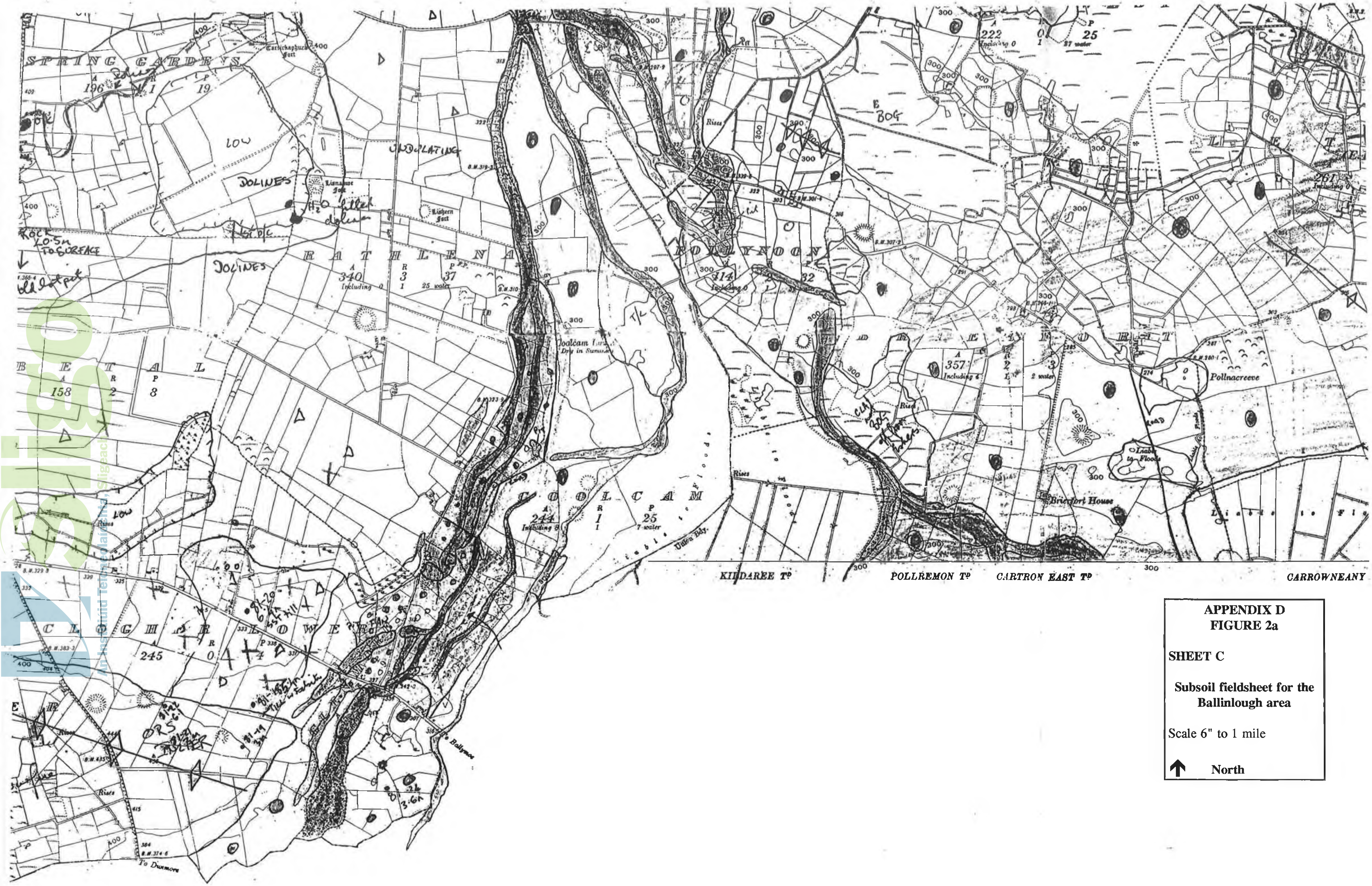
APPENDIX D
FIGURE 2a

SHEET B

Subsoil fieldsheet for the Ballinlough area

Scale 6" to 1 mile

North



APPENDIX D
FIGURE 2a

SHEET C

Subsoil fieldsheet for the Ballinlough area

Scale 6" to 1 mile

↑ **North**

4.2.2 Limestone Till

Limestone till is found in only a small area of the proposed catchment on the limestone ridge which lies SW of the springs. The till is a clayey diamicton which contains striated subangular limestone clasts. It also contains some angular sandstone erratics and occasional very rounded quartz clasts.

4.2.2 Raised Bog

Peat occurs in a low lying area to the immediate west of the small esker nearest to the spring at Ballybane. The peat is believed to have formed at a local groundwater discharge point.

4.3 Depth-to-rock

Cobra drilling by Roscommon Co. Co. (1993) in a 200m^2 grid around the source indicates that depth-to-bedrock ranges from 1.35m-10.2m. Details of the drilling appear in Figure 3. Rockhead at the two boreholes carried out for K.T. Cullen and Co., is 6.1m below ground level (Figures 4 and 5). Trial pits carried out by this author within the same grid, encountered peat to 1.9m below surface, underlain by shell marl and clays.

Outcrop occurs in the limestone upland to the SW at Garranlahan townland.

5 METEOROLOGY

Daily rainfall and evaporation data for the October 1992 to September 1993 period, were taken directly from the Claremorris synoptical weather station (71m OD) which is 23km west of the spring. It is the nearest station with information available for this period. Rainfall was 1245mm and PE was 365.5mm. AE for the area was estimated at 365.5mm, the same value as PE, since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures potential recharge was taken to be approximately 879.5mm for the October 1992 to September 1993 field season (see Figure 6).

These calculations are summarised below:

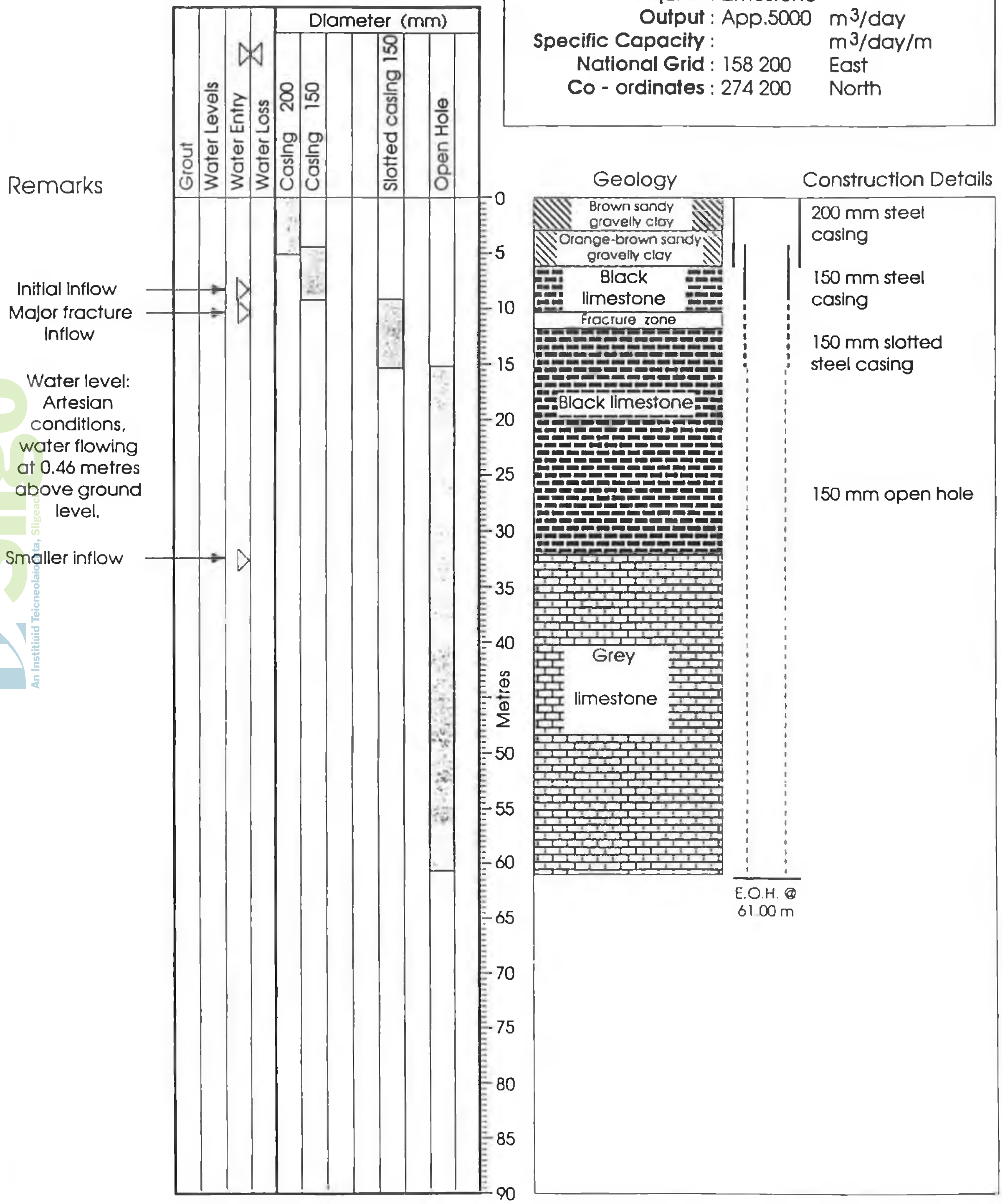
Precipitation	1245mm
P.E.	365.5mm
Estimated A.E. (100% P.E.)	365.5mm
Potential recharge	879.5mm

FIGURE 3
Plan of Cobra drilling around the source

Completed Well Design

Trial Well No. 1

Client : Roscommon County Co.
Project : Groundwater Development
Location : Ballybane, Ballinlough
County : Roscommon
Date : June 16-17, 1993.
Driller : Briody's Aquadril Services
Aquifer : Limestone
Output : App.5000 m³/day
Specific Capacity : m³/day/m
National Grid : 158 200 East
Co - ordinates : 274 200 North



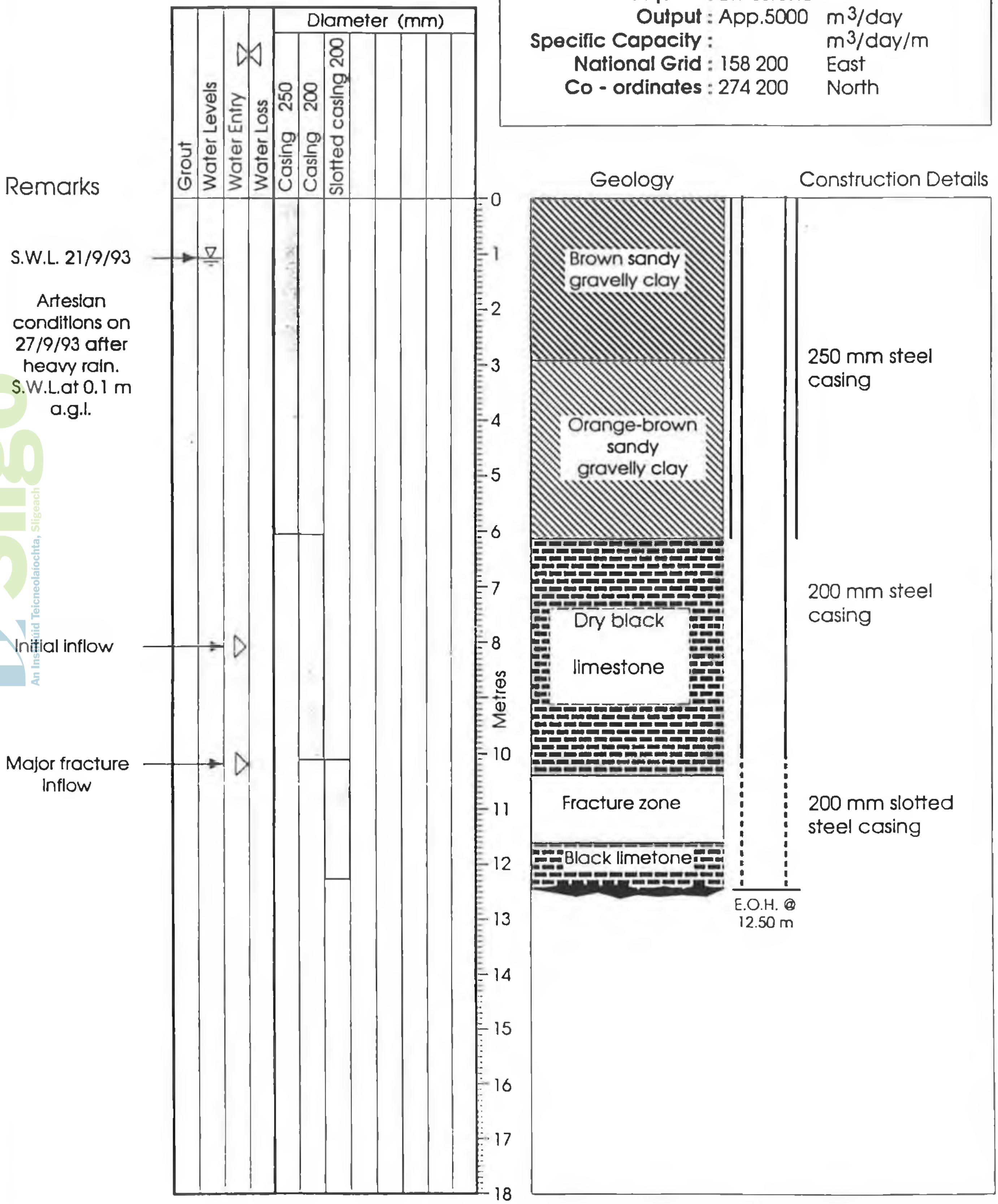
K.T.Cullen & Co. Ltd.
Hydrogeological & Environmental Consultants

FIGURE 4
Log of borehole at source

Completed Well Design

Pumping Well No. 1

Client : Roscommon County Co.
Project : Groundwater Development
Location : Ballybane, Ballinlough
County : Roscommon
Date : August 4, 1993.
Driller : Briody's Aquadril Services
Aquifer : Limestone
Output : App.5000 m^3/day
Specific Capacity : m^3/day/m
National Grid Co - ordinates : 158 200 East, 274 200 North



K.T.Cullen & Co. Ltd.
Hydrogeological & Environmental Consultants

FIGURE 5
Log of borehole at source

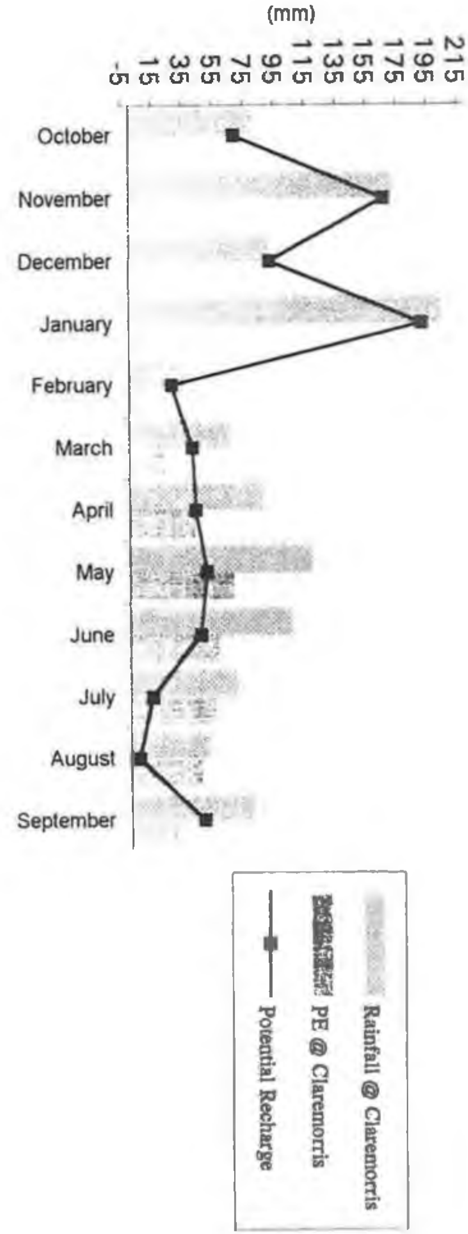

(mm)
-5
15
35
55
75
95
115
135
155
175
195
215
October
November
December
January
February
March
April
May
June
July
August
September
Rainfall @ Claremorris
PE @ Claremorris
Potential Recharge

FIGURE 6
1992-93 Meteorology for Ballinlough with calculated Potential Recharge

6 WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed in the spring area an understanding of the size of the spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies was to occur within the spring recharge zone. It was decided that, as an initial step, the spring catchment area would be *estimated* by a water balance. Examination of the recent hydrogeological report for the source was carried out later to confirm the estimated catchment area. This work is described in Section 7.

The recharge area required to supply the October 1992 to September 1993 discharge levels of this spring was calculated by:

$$\left(\begin{array}{c} \textbf{Outflows} \\ \text{Total Spring Output} \\ + \text{ Abstraction} \\ + \text{ Flow to other} \\ \text{aquifers} \end{array} \right) / \left(\begin{array}{c} \textbf{Inflows} \\ \text{Direct Recharge} \\ + \text{ Indirect Recharge} \\ + \text{ Flow from other aquifers} \\ + \text{ Urban Recharge} \end{array} \right) = \begin{array}{c} \textbf{Catchment} \\ \textbf{Area} \end{array}$$

Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

Total Spring Output

Overflow from the spring and total pumping rates at the pumphouse were needed to find the total spring output for the October 1992 to September 1993 period. Total pumping rates at the spring were 2,945m^3/d and limited outflow occurred in the winter months. The total spring output for this spring is believed to be in the region of 3,000m^3/d.

⇒ 3,000m^3/d

Abstraction

Disregarded, see Chapter 3.

Flow to other aquifers

Disregarded, see Chapter 3.

Total outflows from the Ballybane Source ⇒ 3,000m^3/d

Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

Direct Recharge

As there are relatively high permeability subsoils in the area and there are few drainage features, a relatively large proportion of potential recharge, determined in Section 5, is believed to infiltrate to the water table. Estimating runoff to be in the order of 5% of potential recharge, direct/actual recharge to the aquifer was taken to be 835mm.

$\Rightarrow 2.29 \times 10^{-3}$m/d

Indirect recharge

Nil

Flow from other aquifers

See Chapter 3. —

Total inflows to the aquifer at Ballinlough $\Rightarrow 2.29 \times 10^{-3}$m/d

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

$$\frac{\text{Total outflows from the Ballybane Source}}{\text{Total inflows to the aquifer}} = \frac{3{,}000\text{m}^3/\text{d}}{2.29 \times 10^{-3}\text{m/d}} = 1.3\text{km}^2$$

7 HYDROGEOLOGY

7.1 Data Availability

Cobra drilling, borehole drilling and pumping tests carried out by K.T. Cullen and Co. (11/1993) give a comprehensive overview of the hydrogeology of the Ballybane source. The reader is asked to consult this company if detailed information about the site is needed.

7.2 Groundwater flow direction

Regional groundwater flows from the SW to the NW in the dark limestone. Recharge occurs in the uplands to the SW at Garranlahan, and regional groundwater discharge occurs along the Island River immediately east of the Ballybane pumphouse enclosure. The widespread sands and gravels are considered to supply the main storage for the underlying limestones.

For the recent boreholes, inflows occur at fissures in limestone which are 8-10m below ground level. Static water level is 1m below ground level.

7.3 Physical Demarcation of the Catchment Area

The catchment boundaries for this source were principally determined by topography. The resultant catchment map appears in Figure 2b.

The physically determined catchment area for the spring was judged to be 1.6km^2. The estimated catchment area, determined by the water balance technique in Section 6, was calculated to be 1.3km^2. These figures may be used as a starting indicator that the physically determined catchment area recharges the Ballybane source.

8 VULNERABILITY ASSESSMENT

A vulnerability map (Figure 7) was prepared for the catchment and peripheral areas at the 1:25,000 scale by the GIS group at TCD, from this author's field maps, using the GSI vulnerability mapping guidelines (Daly and Warren, 1994). The vulnerability map appears at the back of this appendix.

The spring catchment at Ballybane is considered to be both highly and extremely vulnerable to pollution. The coefficient of variation in the year round electrical conductivity measurements was 7.9%.

The mapped vulnerabilities for this source's catchment area are presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), that occur within the confines of the catchment.

The % values are: 10% Extreme
90% High.

9 POTENTIAL POLLUTION SOURCES

The area within the proposed catchment area consists entirely of farmland, where livestock farming is the dominant activity. Farm yards, silage clamps and landspreading of animal wastes are the main threat to the source since the subsoils are free draining and limestone is close to the surface in the upland to the SW.

Discharge of silage effluent is ongoing at the outcrop/swallow hole in Garranlahan townland behind the graveyard. It is very likely that this area recharges the local groundwater.

The Co. Co. pumphouse and spring is clean, secure and well fenced off. However the production borehole (artesian) at the source is still overflowing and uncapped.

APPENDIX E

BALLYHAUNIS PUBLIC SUPPLY

1 SPRING DETAILS

GSI No. : 1427SW W013
Grid Ref. : 14925 27935
Elevation : ~75.3 m OD
Diameter : 5 m
Depth to Rock at spring : 4.3 m
Average Spring Discharge : (i) Abstraction Rate

(a) Co. Co. Pumps	1,100m^3/d
(b) Avonmore/Irish Meats	840m^3/d
Total	1,940m^3/d
(ii) Spring Overflow Average:	10,370m^3/d
(iii) TOTAL Spring Discharge(i+ii):	12,310m^3/d

Lowest recorded Total Spring Discharge over field period: 3930 m^3/day

2 SPRING LOCATION AND SITE DESCRIPTION

This public supply spring is located 450m southwest of Ballyhaunis town off the main Ballyhaunis to Dunmore road, in a relatively isolated field behind a group of buildings belonging to Avonmore Irish Meats (Figure 2). The spring and adjoining Co. Co. pumphouse works are surrounded on all sides by high fencing and is well maintained.

Two pipes, at about 0.5-1m depth below the spring water level extract water via two pumps, pumping up to 1,200 m^3/d. Irish Meats also extract water from the spring. They have a pumphouse outside the confines of the Co. Co. enclosure and abstract 840 m^3/d from two pipes. Spring overflow is via a rectangular weir for which there is a rating curve since 1991, initiated by the EPA (ERU) in Castlebar.

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

The spring, at an elevation of about 75m OD, lies in a small river valley, directly in the break of slope of a broad tract of esker sands and gravels (Figure A1). The broad esker deposits to the west form an undulating hummocky terrain, and have heights of up to 91.5m OD. Further

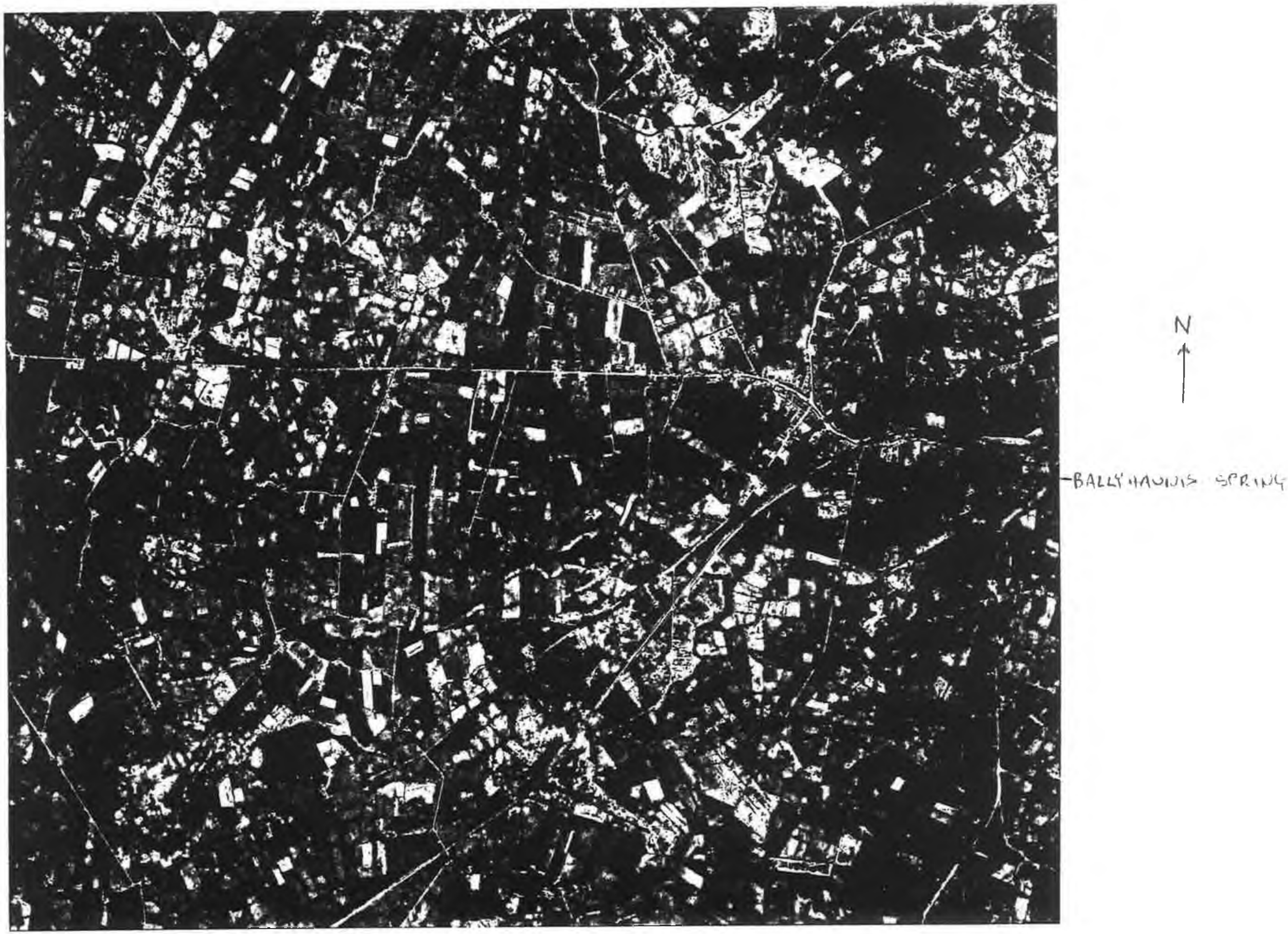


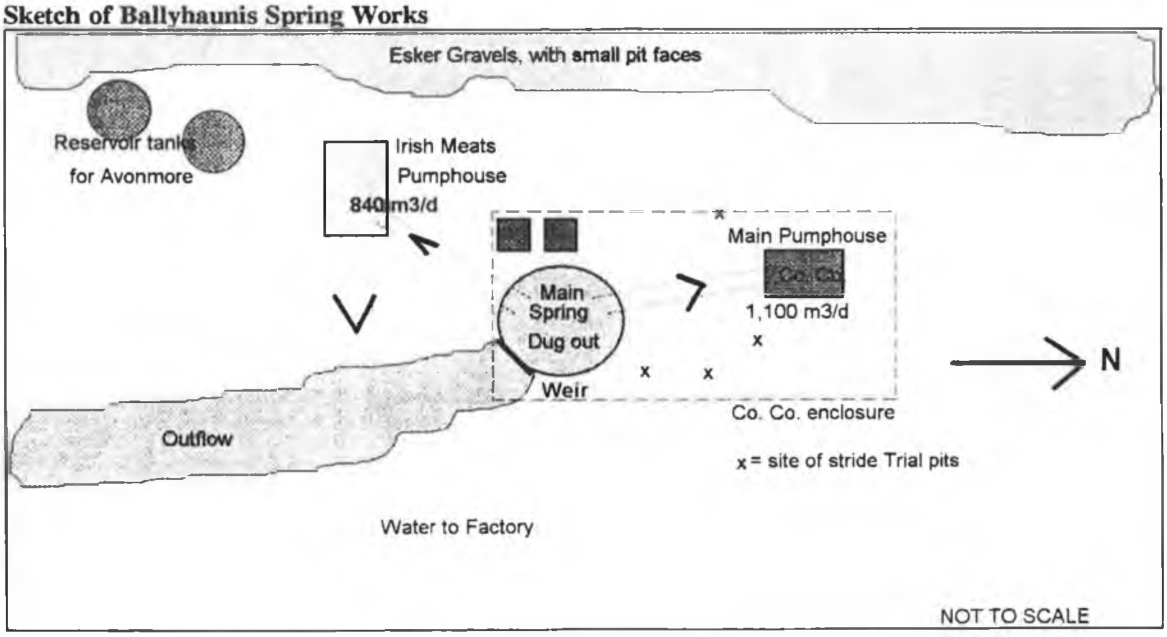
FIGURE A1
Aerial Photograph of the Ballyhaunis Spring Are

west the topography is dominated by limestone cored drumlins and irregular karstic depressions.

The Dalgan River 350m east of the spring flows south west to the River Clare. There are no surface streams to the west of the spring apart from the large drains and turlough that feed the Lassanny swallow hole, 3.5km away.

Land use in the area consists mainly of livestock farming. There are several meat/chicken factories and cattle fattening units concentrated on the Ballyhaunis/Dunmore road and the Ballyhaunis/Knock road, which are sited less than 3km from the spring.

FIGURE 2
Sketch of Ballyhaunis Spring Works



4 GEOLOGY

4.1 Bedrock Geology

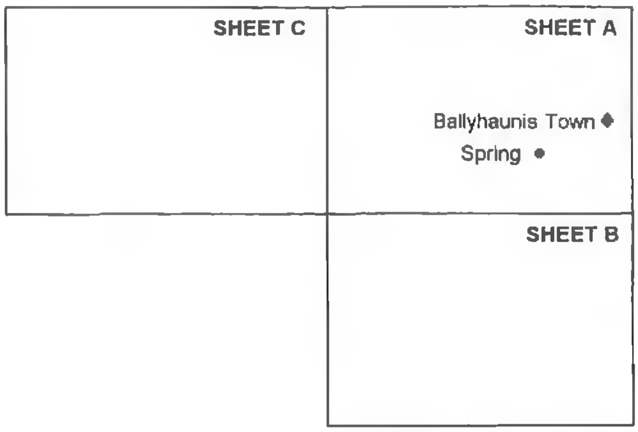
The area is underlain by argillaceous dark limestone (Muddy Limestone) which is well bedded. This limestone is often cherty, particularly in the outcrops seen west of Ballyhaunis town.

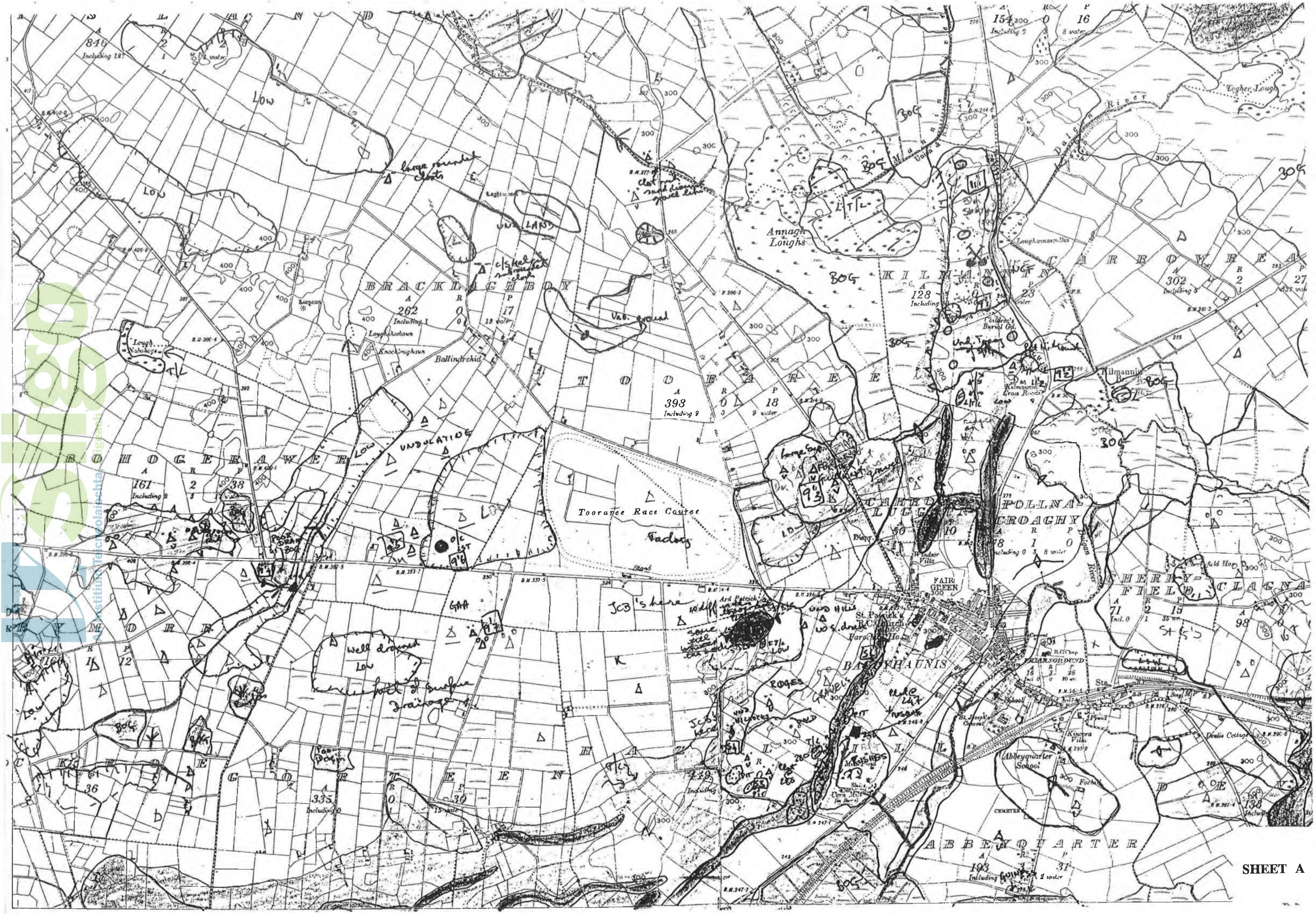
4.2 Subsoils Geology

Ballyhaunis has a varied subsoils geology (Quaternary) dominated by sands and gravels centred around the town/source, and limestone till in the peripheral areas to the west of the spring. Copies of the 6" subsoil field sheets near the spring mapped by this author appear in

Figure 3a, and a digitised copy of the area (Figure 3b [14/27 SW]) at the 1:25,000 scale appears at the back of this appendix.

Figure 3a
6" Subsoil Field Sheets for Ballyhaunis

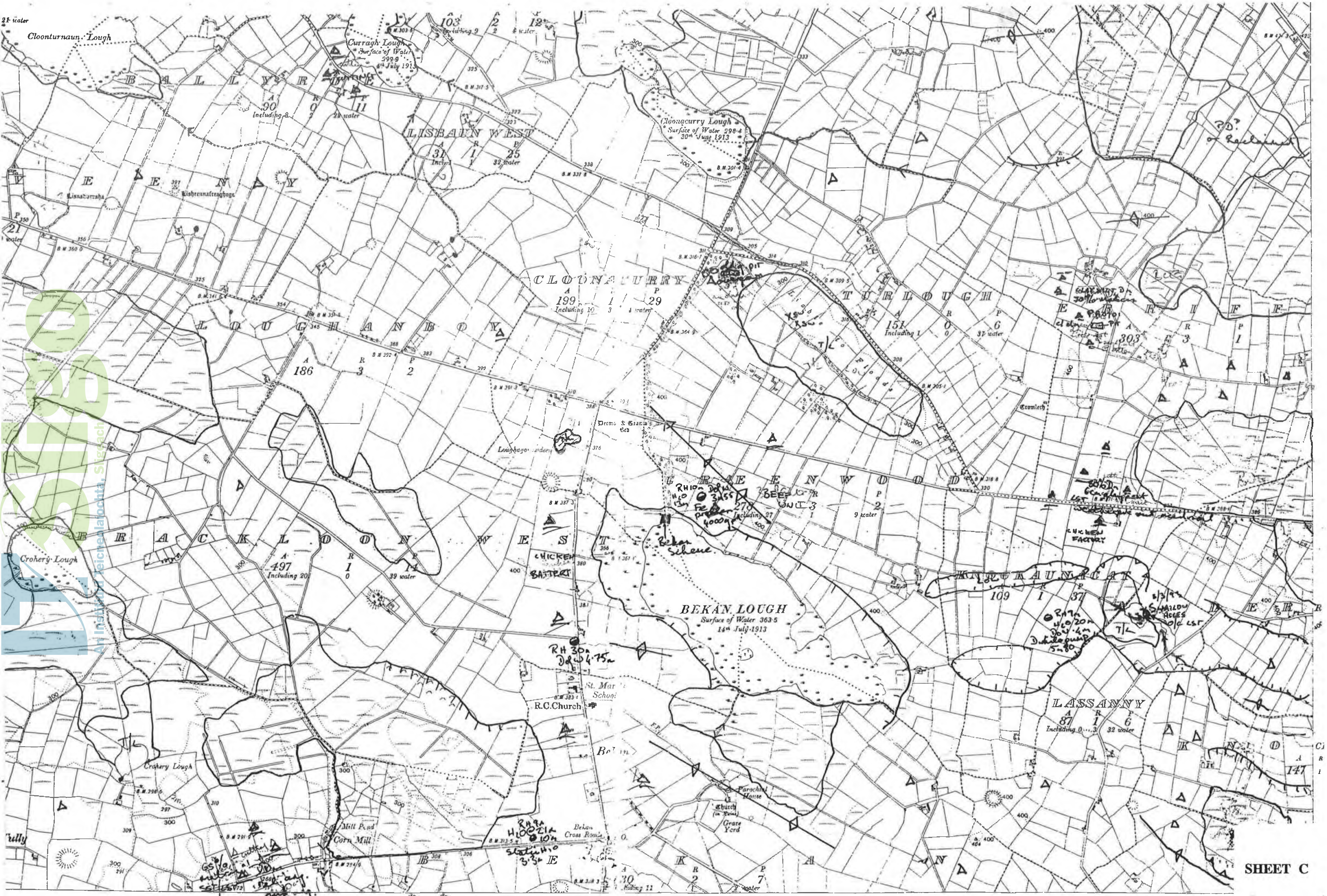



BRACKLAGHBOY
TOOREEN
CARROWREA
KILMANNIN
HOGEKRAWEER
POLLNACROAGHY
CARROWLUGGA
CHERRYFIELD
CLAGNA
ABBEYQUARTER
BALLYHAUNIS
Toorance Race Course
Annagh Loughs
Togher Lough
Dalgan River
Ballindrehid
Knockloughaun
Loughloohaun
Kilmannin Cross Roads
Fair Green
St. Patrick's R.C. Church
Windsor Villa
Abbeyquarter School
St. Joseph's Convent
Kincora Villa
Stand
BOG
LOW
UNDULATING
Well drained
JCB's here
GAA

SHEET A

COSTELLO BY
ABBEYQUARTER TD
DEVLIS TD
To Ballyhaunis
Level Crossing
Corn Mill
St. Patrick's Stone
St. Patrick's Font
Church (in Ruins)
Children's Burial Ground
Holywell Cross Roads
St. Patrick's Church
St. Patrick's Well
CHURCHPARK
Holywell House
M.G.W.R.
MAYO BRANCH
HOLYWELL LOWER
Children's Burial Ground
Smithy
BOG
LST
AL

SHEET B



LISSANISKA Tᴰ

94 95 96

CLOONTUMPER Tᴰ

CARROWKEEL EAST Tᴰ

4.2.1 Sands and Gravels

Sands and gravels were recorded at 11 localities around the source. They are esker and glaciofluvial/glaciolacustrine related. Over 30% of the proposed catchment contains sands and gravels.

The eskers show a SW-NE orientation; sections show that they consist of a coarse boulder/cobble gravel with a sandy matrix. Limestone is the dominant clast in the eskers (usually 99%) but often there are some ORS and metamorphic clasts. Several eskers show individual sand lenses where there is no clast support, and these lenses are often interbedded with a clay/silt matrix. The eskers are morphologically sinuous and may often overly limestone tills or boulder clay. They are found to merge into the glaciofluvial related sands and gravels at Ballyhaunis town.

Overall the glaciofluvial/glaciolacustrine sand and gravels are relatively widespread where they cover up to 3km^2 of the proposed catchment and account for over 20km^2 of the 14/27SW 1:25,000 scale sheet. Pit face sections 750m north of the spring, show that the sand and gravels are greater than 20m deep. These faces show units of sands up to 1m thick interbedded with large units of cobble gravel > 4m thick. Such consistent bedding shows that at one stage there was some sort of tunnel input under ice, dumping sediment into a proglacial lake about 3km north of the town. The eskers proximal to these sands and gravels support this theory in that they acted as tunnels. However, advance and retreat of the ice front has caused interference of the tunnels nearer the town, where they show as minor ridges within a mass of outwash gravels.

4.2.2 Limestone Till

Large areas 3km west of the spring are overlain by limestone till (diamictic sediments). These sediments are characterised by their bimodal particle size distribution. They are largely composed of angular to sub-angular striated limestone clasts supported by a clay/silt matrix, with small amounts of sand. There appears to be little reworking of the local glaciofluvial sediments as the clasts within the till are never rounded. To the west of the spring boreholes show till depth is a maximum of 15m to limestone bedrock. Drumlins at Derrymore are dominantly composed of clayey/silty limestone till with a bedrock core (from drill records), and their orientation is SE/NW. For much of the relevant 1:25,000 scale sheet till is undifferentiated with depths unknown or at a guesstimate, since much of the area was only reconnaissance mapped.

4.3 Soils

Degraded brown podzolics with low infiltration rates are common in the limestone till areas. Often gleys are found in the areas where there is poor draining clayey limestone till. Very thin rendzinas (10-20cm deep) are found in the well drained gravel areas. Raised bog (often cut-away in parts) is widespread in the 1:25,000 scale sheet for this area where it covers up to $35km^2$.

4.4 Depth-to-rock

There are only three outcrops to the west of the spring. Outcrop occurs in a swallow hole in the Bekan Lough area (Lassanny) which becomes a turlough in winter. Outcrop at Bracklaghboy on the main Knock road is within a large karstic depression. Outcrop of crinoidal argillaceous limestone is found in a former local quarry at Hazlehill 350m west of the spring. Borehole information (open file and well records, GSI) and trial pits carried out for this study suggest depth to rock is not greater than 15m in the limestone till. The gravel areas are suspected to be > 20m to rockhead.

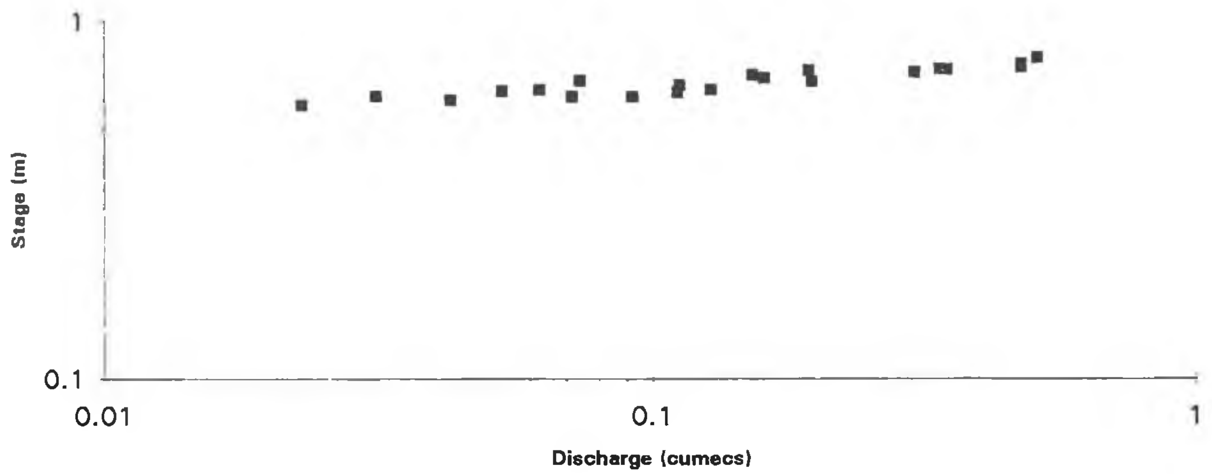
5 METEOROLOGY

Daily rainfall and evaporation data for the October 1992 to September 1993 period, were taken directly from the Claremorris synoptical weather station (71m OD), since it is only 17 km to the south-west of the spring, and at a similar ordnance datum. Rainfall was 1245mm and PE was 365.5mm for this period. This station suggests that the Ballyhaunis area had up to 242 rain days over the field season. AE for the area was estimated at 365.5mm, the same value as PE, since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures potential recharge was taken to be approximately 879.5mm for the October 1992 to September 1993 field season (see Figure 4).

These calculations are summarised below:

Raindays (> 1mm)	242 days
Precipitation	1245mm
P.E.	365.5mm
Estimated A.E. (100% P.E.)	365.5mm
Potential recharge	879.5mm

FIGURE 5
Rating Curve for the weir at Ballyhaunis



Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

Direct Recharge

As there are relatively high permeability subsoils in the area and there are few drainage features, a high proportion of potential recharge, infiltrates to the water table. Estimating runoff to be in the order of 10% of potential recharge, direct/actual recharge to the aquifer was taken to be 791.5 mm over the the October 1992 to September 1993 period.

$\Rightarrow$ 2.1686×10^{-3} m/d

Indirect recharge

Nil

Flow from other aquifers

See Chapter 3. The flow from the sand and gravel aquifer near the source is accounted for in the runoff calculations above. —

Urban Recharge

Up to 0.1 l/sec./km^2 of urban runoff and pipe leakage theoretically recharges the underlying aquifer. $\Rightarrow$ 8.64×10^{-6} m/d

Total inflows to the aquifer at Ballyhaunis $\Rightarrow$ 2.1772×10^{-3} m/d

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

$$\frac{\text{Total outflows from the Ballyhaunis Spring}}{\text{Total inflows to the aquifer at Ballyhaunis}} = \frac{12{,}310 \text{ m}^3\text{/day}}{2.1772 \times 10^{-3} \text{ m/d}} = 5.65 \text{ km}^2$$

7 HYDROGEOLOGY

7.1 Groundwater levels

Within a 5.65km^2 radius of the spring there are only ten wells of which four have useful data. None of the wells have been levelled to OD and so no water-table map could be defined. The four wells with data, are sited 4km west of the spring in the Bekan Lough area (muddy limestone) and yield up to 5 litres/sec. Water enters these wells at two intervals, at about 20m below ground level (b.gl.) [which is 10m into bedrock] and at 10m b.gl., an interval that marks the sand and gravel/limestone bedrock boundary. Static water level is at about 4.5m b.gl..

7.2 Groundwater flow direction, gradient and time of travel

A tracer Leucophor STA was introduced into the Lassanny swallow hole (20th May 1993) 3.5km west of the spring, where it disappeared below ground with the flow of its sinking stream. All possible outflow points were monitored for the tracer using a fabric detector constructed of sterile unbleached cotton gauze. Evaluation of the presence of the dye on the detector was visual, with a hand-held ultraviolet source. A positive trace at the spring occurred 8 hours later. This shows that groundwater is flowing from west to east in limestone bedrock at a rate of 440 m/hour (12.2cm/sec.).

Gradient of flow: Approx Input height 110m OD
Approx Spring height 75m OD => 36m in 3.5km
=> 1: 100

7.3 Physical structure of the spring catchment area

The relative fast flowing positive trace above, proves that the bedrock is providing water in a easterly direction to the spring at Ballyhaunis. It is thought that the easterly gradient of this trace, is the gradient of solutional conduits or well developed fractures in the bedrock.

There is a large sand and gravel area (1km^2) directly west of the spring. It is at the break in slope from these gravels to lower ground that the spring overflows. Trial pitting carried out under the supervision of this author, within and around the Co. Co. pumphouse works shows that there were relatively good inflows of water in the overlying gravels (1.35m b.gl.). This suggests that some of the spring water may originate in the gravels. It is hypothesised, that the spring is a joint sand and gravel / limestone bedrock source.

Generally transmissivity is thought to occur in the muddy fractured limestones but the majority of storage occurs in the gravels.

7.4 Physical Demarcation of the Catchment Area

The catchment boundaries for this spring were principally determined by topography and tracing since there were no watertable maps, keeping in mind that the water balance method estimates the size of the catchment to be 5.65 km^2. The area to the west of the spring and up hydraulic gradient was concentrated on since it is more likely to recharge the spring than the area to the east, which is downgradient to the Dalgan River.

Two areas for catchment were worked on, A and B which appear in Figure 3b and Figure 6.

A) Point recharge can enter the limestone aquifer via the swallow hole at Lassany, which is fed by two small streams with a catchment area of 2.2 km^2. Tracing has shown that an underground link exists between this swallow hole and the spring, 3.5km east. The tracing results show that groundwater flow is in a west to east direction, with a velocity of 440m/hr. It is assumed that all flow from the swallow hole flows to the spring. The catchments of the two streams act as a 'mini catchment' for the spring at Ballyhaunis.

B) Since recharge to the spring occurs in area A, and groundwater flow is west to east, it is assumed that the area between A and the spring, must also recharge the aquifer. This zone, Area B, was principally determined by topography. It was found to have an area of 3.8 km^2.

From the above, the physically determined catchment area for the spring was judged to be 6km^2. The estimated catchment area, determined in Section 6 by the water balance technique was calculated to be 5.65 km^2. These figures may be used as a starting indicator that the physically determined catchment areas, A and B, recharge Ballyhaunis spring.

8 VULNERABILITY ASSESSMENT

A vulnerability map at the 1:25,000 scale was determined for the confines of the proposed catchment areas, A and B, of 6km^2 (Figure 6B). The GSI Guidelines (Daly and Warren, 1994) were applied in the production of the vulnerability map, using the data from the subsoil maps (Figure 3, 6A). The "improved and achievable vulnerability mapping" guidelines were the main rules used since much of the catchment was mapped at reconnaisance level with trial

Subsoils Geology
and
Recharge areas, A & B

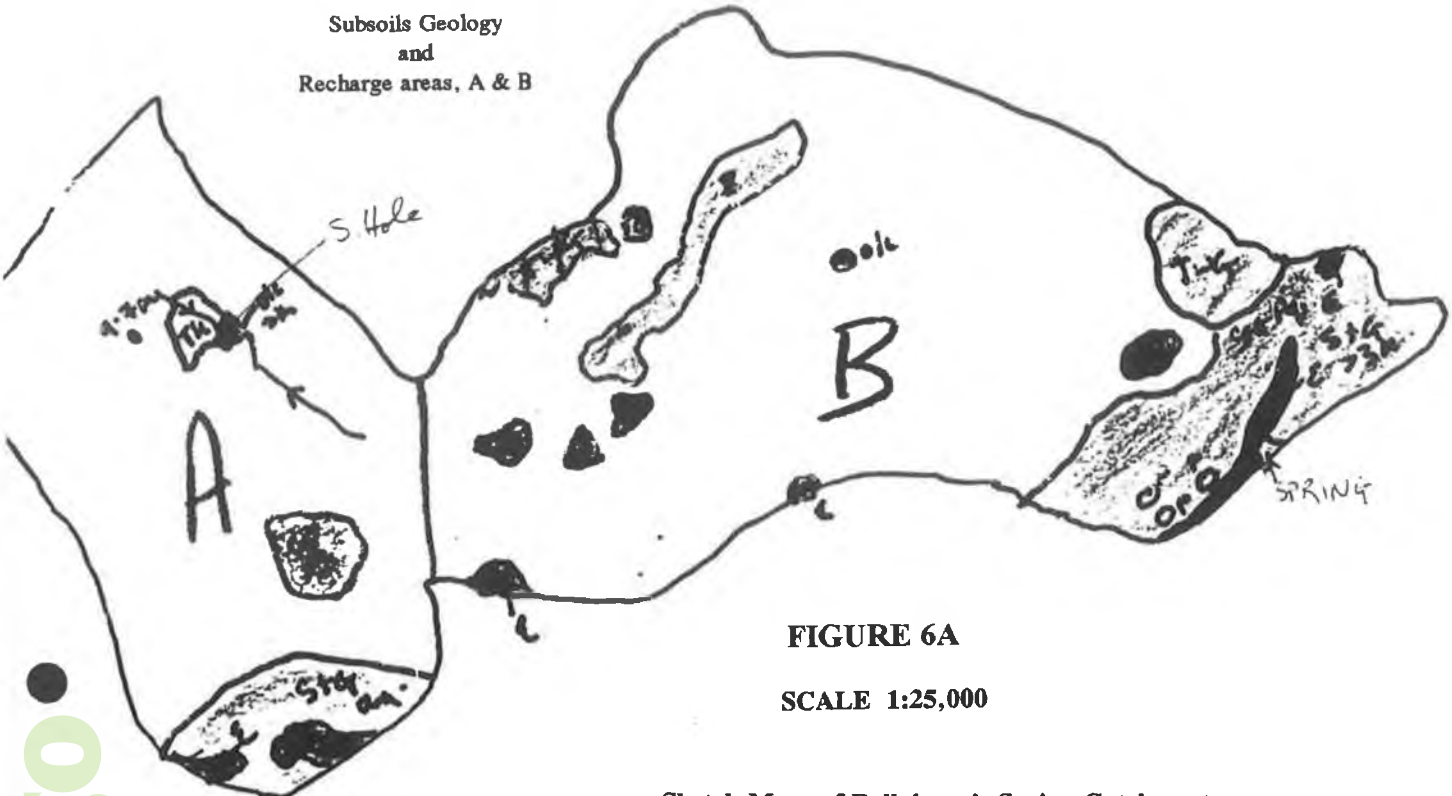


FIGURE 6A

SCALE 1:25,000

Sketch Maps of Ballyhaunis Spring Catchment

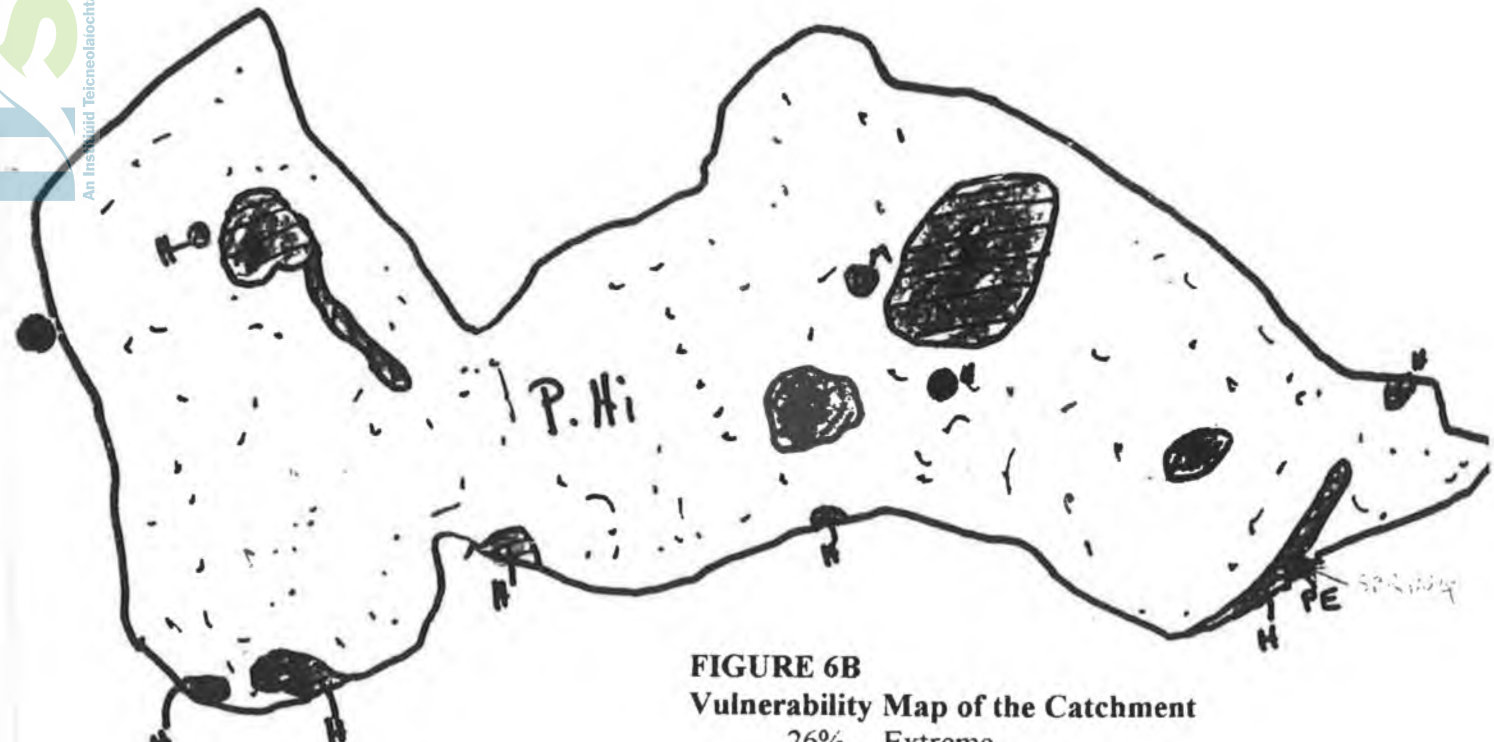


FIGURE 6B
Vulnerability Map of the Catchment

26% Extreme
69% High
5% Moderate

pitting. The "minimum standard vulnerability mapping" guidelines were used specifically for areas of undifferentiated till (TUD) where details on till texture were not known. Undifferentiated till is common within the catchment, where it has not been possible to extrapolate textures from trial pits to the more distant areas.

The mapped vulnerabilities for this spring in Figure 6b are presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), that occur within the confines of the spring catchment.

The % values are: 26% Extreme
69% High
5% Moderate.

8.1 Details of the Vulnerability of the Ballyhaunis Spring Catchment (Figure 6b)

Extreme: (i) There are three bedrock outcrops, which satisfy rule 1*.
(ii) 2 large karstic depressions, where overlying TUD is shallow. Outcrop appears within the larger depression, at Grid Reference (NGR)147809 279873. Satisfies rule 2.
(iii) The area within 30m of the Lassanny swallow hole, its adjacent turlough and feeding streams. The soils/subsoils around this area are relatively free draining. Infiltration rates are thought to be good on the slopes facing the swallow hole, and so surface runoff is not considered to be likely here. In this case, the 30m zones are thought to be satisfactory in applying an intrinsic vulnerability to the area.

Probably Extreme: (i) The area around the main spring satisfies rules 1 and 2.

High: (i) The eskers > 3m thick, non-aquifer sands and gravels, satisfy rule 1.
(ii) Borehole at Lassanny, silty till, 9.7m to rockhead satisfies rule 2.
(iii) Section at no. 37, satisfies rule 2.

Probably High: the rest of the catchment.
(i) The till with gravel areas satisfy rule 1.
(ii) Bog areas, which are superficial, satisfy rule 2.
(iii) The sand and gravel aquifers, along the southern margins of the catchment, where water-table is >3 m thick, satisfy rule 3.
(iv) TUD, since details on till texture are not known, satisfy rule 1 of the "minimum standard vulnerability mapping" guidelines

(v) The topographic low at Lassanny does not change this area's rating from probably high to probably extreme, since most of the area is thought to be > than 3 m to bedrock.

* See Improved and achievable vulnerability mapping guidelines, Daly and Warren (1994)

9 POTENTIAL POLLUTION SOURCES

The Knock road is host to several intensive livestock fattening units where landspreading of their wastes and discharge of their effluent is a risk to the swallow hole at Lassanny. In a future code of practice, Mayo Co. Co. may wish to set down spreading guidelines for the fields that are adjacent to the swallow hole, as technically these fields do not fall into an extreme vulnerability category, but only into the probably high vulnerability category; surface runoff here is not thought to be a risk as there is relatively free drainage. A chicken factory at NGR 14555 28000 on the drumlin high immediately north of the Lassanny swallow hole is a risk to the main Ballyhaunis spring. The secondary effluent from its treatment works flows directly to the swallow hole. Conductivity values taken in November 1993, at the stream feeding the swallow hole were > 1000 μS/cm, suggesting that some sort of contaminant was entering the swallow hole and hence the spring.

The Avonmore/Irish Meats pumphouse is dirty and often surrounded by waste plastic sheeting from the salt stocks; it is a definite risk to the Co. Co. pumphouse works and the spring itself.

The spring catchment of 6km^2 should be treated as a Zone 1 source protection zone.

APPENDIX F

BALLINAGARD PUBLIC SUPPLY

1 SPRING DETAILS

GSI No.	: 1725NE W --	
Grid Ref.	: 18742 26187	
6" Sheet	: Roscommon 39	
Townland	: Ballinagard	
Elevation	: 44.135m OD	
Depth to Rock at Spring	: >3m	
Average Spring Discharge	: (i) Abstraction Rate (136m³ x 16hrs)	2,176m³/d
	(ii) Spring Overflow Average:	9,200m³/d
	(iii) TOTAL Spring Discharge(i+ii):	11,376m³/d

2 SPRING LOCATION AND SITE DESCRIPTION

The Ballinagard source which is used for public supply at Roscommon town, is located 2.5km south of the town in a boggy field. The spring is located immediately north of the Hind River which drains eastward into Lough Ree.

The source consists of a deepened spring that is surrounded by a bank of coarse limestone chippings. The spring outlet is via a rectangular thin plate weir which is secured onto concrete (Photo 1). The crest of the weir is 0.5m high and the upstream approach channel width is 3.8m.

The source is well fenced off and access can only be gained from a side road via a locked gate and beside the pumphouse 200m north.

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

The Ballinagard spring, at an elevation of 44.13m OD, lies in the Hind River valley (Lough Ree). The Hind River drains a wide valley which runs SW/ENE (Photo 2). Two limestone uplands (150m OD) lie NW and S of the river where there are few surface drains since bedrock is close to surface and the soils are free draining. The two ridges act as the regional watershed; the River Suck lies to the west and the River Shannon lies to the east. Recharge for the Ballinagard spring occurs in the uplands to the NW.

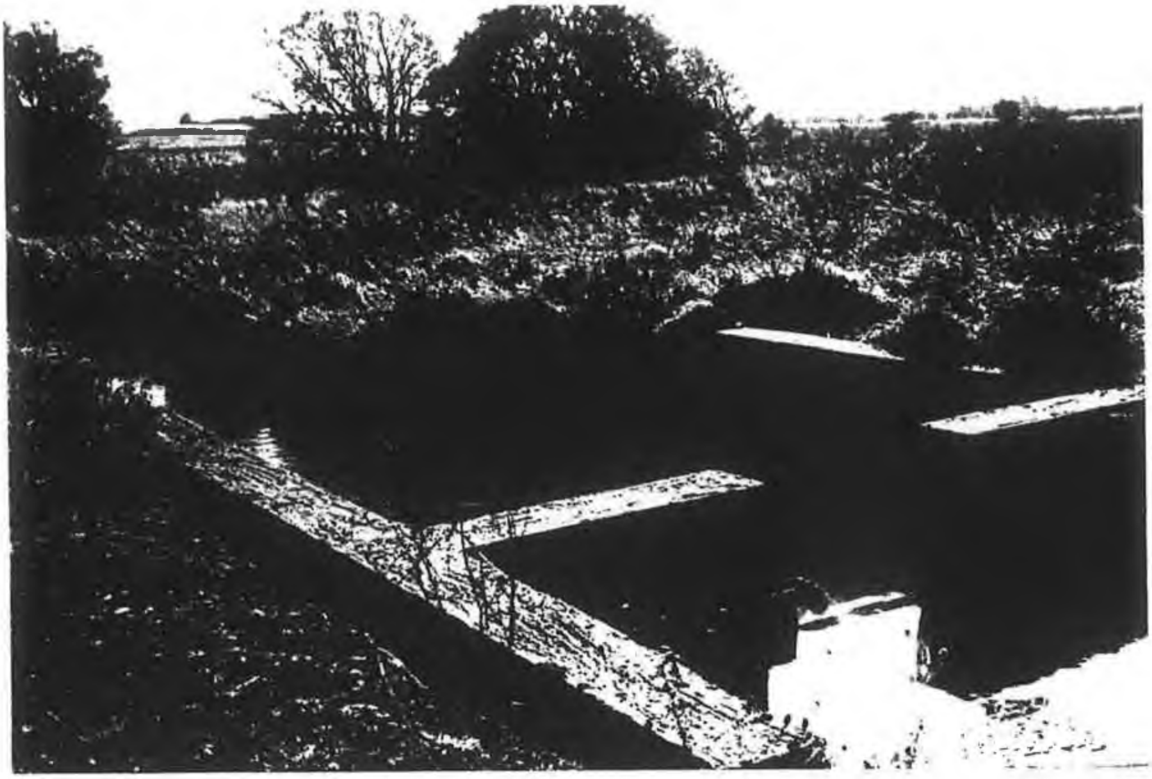


PHOTO 1
Ballinagard Spring and weir

PHOTO 3
The swallow hole at Fuerty

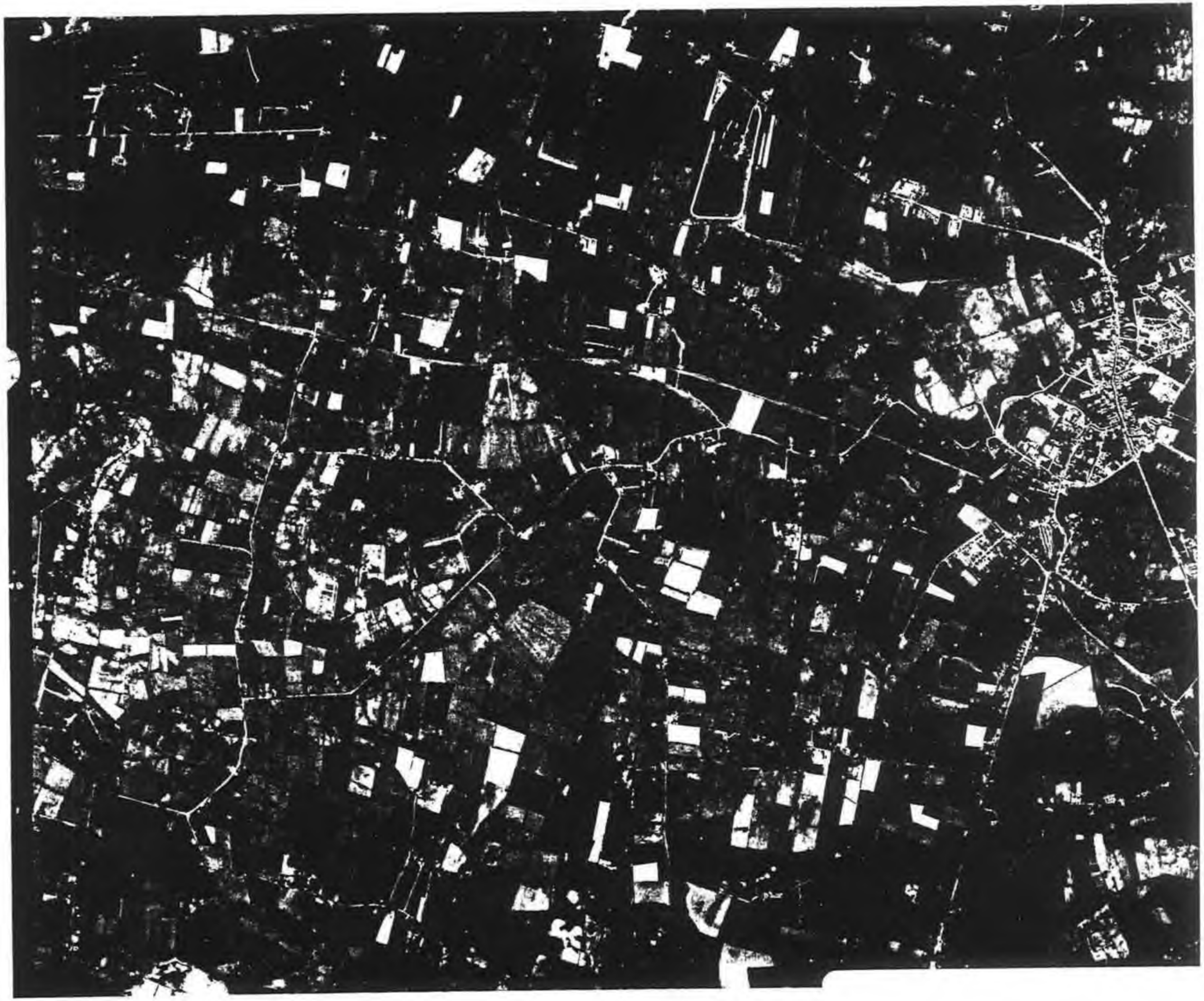


PHOTO 2
Aerial Photograph of the Ballinagard area

At a meso scale, low relief drumlins (trending NW/SE) lie near the spring. There are few drains or streams within the proposed spring catchment since the soils are relatively free draining and the bedrock has fissure/conduit permeability. Any streams that do occur are very short, rising at springs which occur at the break in slope of the uplands 3km to the NW. They flow SE to the Hind River. A swallow hole and associated sinking stream lies 4km WNW of the spring (Photo 3).

Land use in the area is mainly livestock farming, both dairy and drystock.

4 GEOLOGY

4.1 Bedrock Geology

The dominant rock type is Pure Limestone (shallow water limestone;Upper Dinantian) and forms the upland topography around Roscommon town. A south westerly trending fault lies 2km west of the springs. As an aquifer the Pure limestone has locally productive zones particularly if the zone is fissured or karstified.

4.2 Subsoils Geology

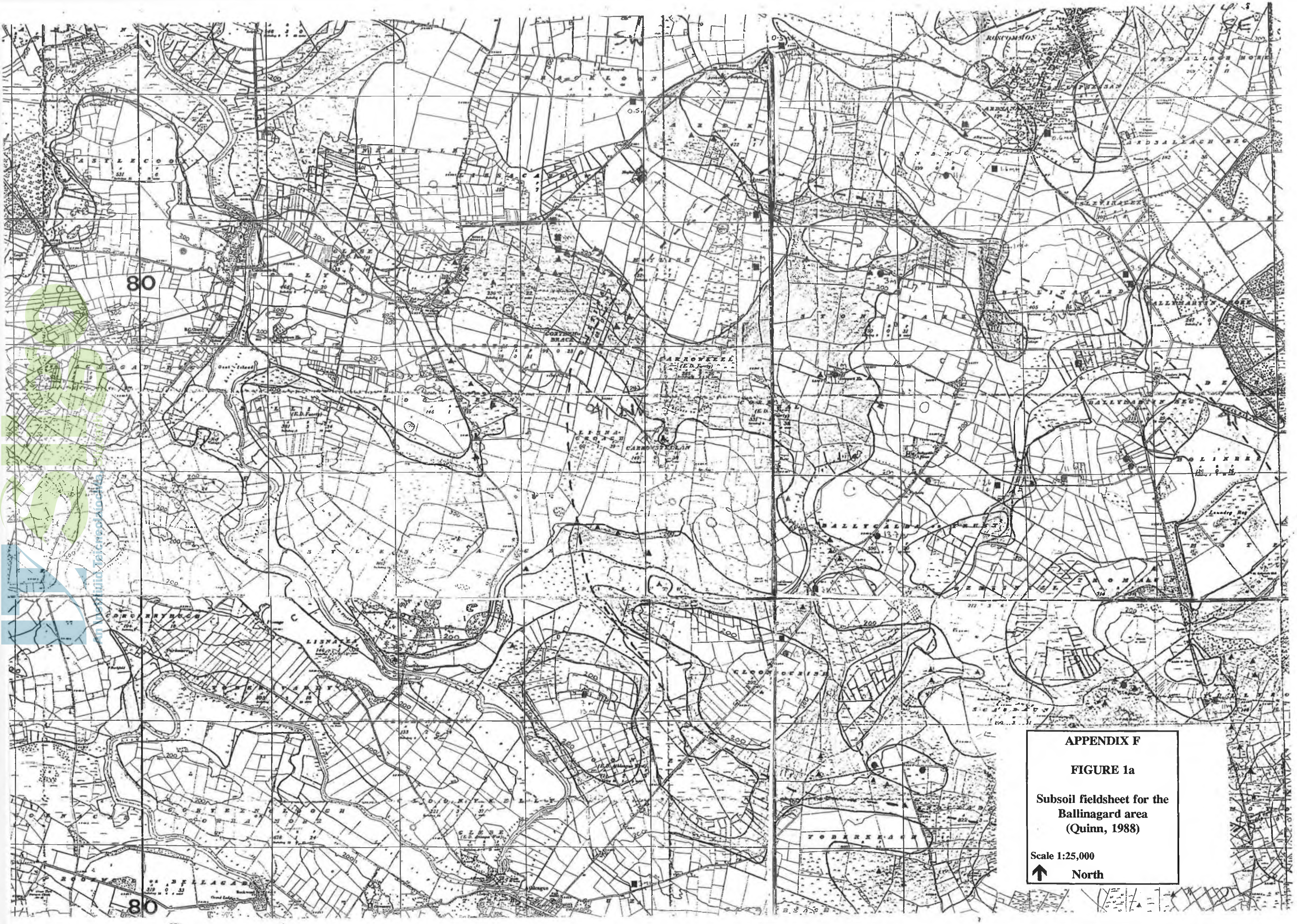
A copy of the 1:25,000 scale subsoil field sheet for the area, carried out by I. Quinn (1988) appears in Figure 1a and a digitised copy of the area (17/25 NE) at the 1:25,000 scale appears at the back of this appendix (Figure 1b). Generally within the zone of proposed catchment and 1km outside it, there are two subsoil types: Limestone till and Raised bog.

4.2.1 Limestone Till

The area around the source is dominated by a clayey diamicton which contains striated subangular limestone clasts. It also contains some angular sandstone erratics, occasional very rounded quartz clasts, jasper clasts and conglomerate clasts. Their origin is probably from the Mount Mary ORS inlier 10km SW, or Slieve Bawn 13km NE. Stonefree silt and fine sand is found 0.5km NE of source in an interdrumlin low.

4.2.2 Raised Bog

Peat is concentrated in the relatively low lying areas, at Lisnamult townland NW of the spring and along the floodplains of the Hind River. Peat formation is thought to have occurred after periods of marl accumulation which was deposited at local groundwater discharge points.



APPENDIX F

FIGURE 1a

Subsoil fieldsheet for the Ballinagard area (Quinn, 1988)

Scale 1:25,000

North

4.3 Depth-to-rock

Trial pitting indicates that depth-to-bedrock within 1km of the spring is greater than 3m. Three pits within 20m of the spring encountered peat to 1.9m below surface underlain by shell marl and clays.

Outside this area there are several outcrops as marked on the 1:25,000 scale field map. Boreholes show that depth-to-bedrock ranges from 1m to 11.6m below surface. Mean recorded depth to bedrock is 9.5m.

5 METEOROLOGY

Daily rainfall data for the October 1992 to September 1993 period, were taken directly from the Roscommon Vocational School rainfall station (58m OD), which is 2.5km N of the source. Rainfall was 1027mm. Potential Evapotranspiration (PE) at Claremorris was 365.5mm for the same period. AE for the area was estimated at 365.5mm, the same value as PE, since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures potential recharge was taken to be approximately 661.5mm for the October 1992 to September 1993 field season (see Figure 2).

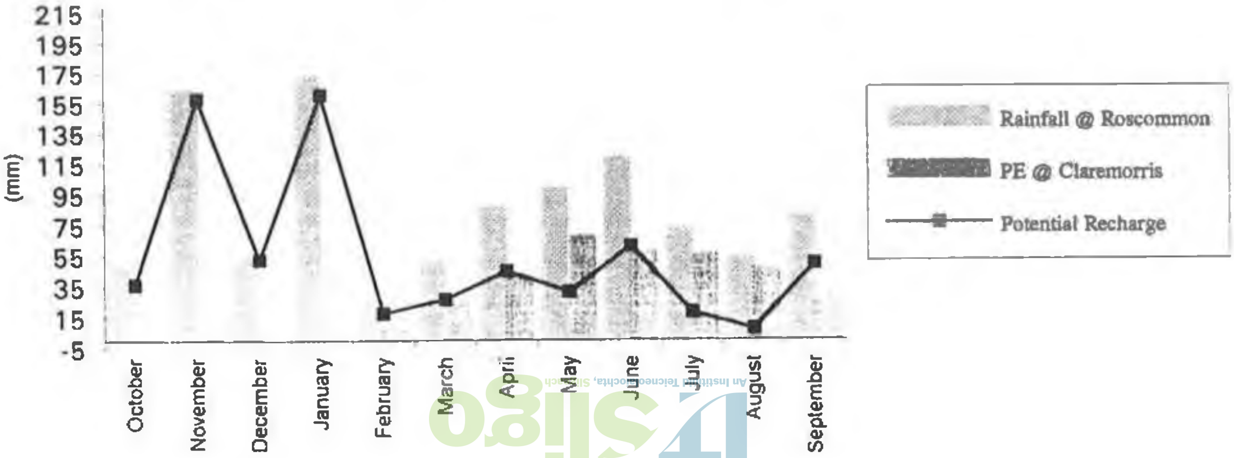
These calculations are summarised below:

Precipitation	1027mm
P.E.	365.5mm
Estimated A.E. (100% P.E.)	365.5mm
Potential recharge	661.5mm

6 WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed in the spring area an understanding of the size of the spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies was to occur within the spring recharge zone. It was decided that as an initial step the spring catchment area would be *estimated* by a water balance. Hydrogeological techniques and water tracing were carried out later to confirm the estimated catchment area. This work is described in Section 7.

FIGURE 2
1992-93 Meteorology for Ballinagard with calculated Potential Recharge



The recharge area required to supply the October 1992 to September 1993 discharge levels of this spring was calculated by:

$$\left(\begin{array}{c} \textbf{Outflows} \\ \text{Total Spring Output} \\ + \text{Abstraction} \\ + \text{Flow to other} \\ \text{aquifers} \end{array} \right) / \left(\begin{array}{c} \textbf{Inflows} \\ \text{Direct Recharge} \\ + \text{Indirect Recharge} \\ + \text{Flow from other aquifers} \\ + \text{Urban Recharge} \end{array} \right) = \begin{array}{c} \textbf{Catchment} \\ \textbf{Area} \end{array}$$

Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

Total Spring Output

Overflow from the spring and total pumping rates at the pumphouse were needed to find the total spring output for the October 1992 to September 1993 period. A staff gauge at the rectangular thin plate weir was used to determine the spring overflow. Water levels were converted to discharge with a British standards equation. It was found that overflow at the weir averaged 9,200m^3/d. Total pumping rates at the spring were 2,176m^3/d. Therefore, the total spring output for Ballinagard is 11,376m^3/d.

$\Rightarrow$ 11,376m^3/d

Abstraction

Disregarded, see Chapter 3.

Flow to other aquifers

Disregarded, see Chapter 3.

Total outflows from the Ballinagard Source $\Rightarrow$ 11,376m^3/d

Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

Direct Recharge

As there are relatively high permeability subsoils in the area and there are few drainage features, a relatively large proportion of potential recharge, determined in Section 5, infiltrates to the water table. Estimating runoff to be in the order of 15% of potential recharge, direct/actual recharge to the aquifer was taken to be 562mm.

$\Rightarrow 1.53 \times 10^{-3}$m/d

Indirect recharge

Nil

Flow from other aquifers

See Chapter 3. —

Urban Recharge

Up to 0.1 l/sec./km^2 of urban runoff and pipe leakage theoretically recharges the underlying aquifer. $\Rightarrow 8.64 \times 10^{-6}$ m/d

Total inflows to the aquifer at Ballinagard $\Rightarrow 1.538 \times 10^{-3}$m/d

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

$$\frac{\text{Total outflows from the Ballinagard Source}}{\text{Total inflows to the aquifer at Ballinagard}} = \frac{11{,}376\text{m}^3\text{/d}}{1.538 \times 10^{-3}\text{m/d}} = 7.4\text{km}^2$$

7 HYDROGEOLOGY

7.1 Data Availability

A watertable map exists for the area (Figure 3). Several boreholes were levelled in by Roscommon Co. Co. in 1987, and tracing was carried out in 1991.

7.2 Groundwater flow direction

Regional groundwater flows from the NW to the ESE in the Pure Limestone. Recharge occurs in the uplands to the NW and regional groundwater discharge occurs at Lough Ree.

A tracer Leucophor STA was introduced into the Fuerty swallow hole by Roscommon Co. Co. (5th July, 1991) 4km WNW of source, where it disappeared below ground with the flow of its sinking stream. All possible outflow points were monitored for the tracer using a fabric detector constructed of sterile unbleached cotton gauze. Evaluation of the presence of the dye on the detector was visual, with a hand-held ultraviolet source. A positive trace occurred at the spring 7 days later.

7.3 Physical Demarcation of the Catchment Area

The catchment boundaries for this source were principally determined by topography, tracing and results from the watertable map, keeping in mind that the water balance method estimates the size of the catchment to be 7.4km^2. The resultant catchment boundaries appear in Figures 3.

The physically determined catchment area for the spring was judged to be 7.9km^2. This may be used as a starting indicator that the physically determined catchment area recharges the Ballinagard source.

8 VULNERABILITY ASSESSMENT

A vulnerability map (Figure 4) was prepared for the catchment and peripheral areas at the 1:25,000 scale by the GIS group at TCD, from Quinn's field maps, using the "minimum standard vulnerability mapping" GSI Guidelines (Daly and Warren, 1994). The vulnerability map appears at the back of this report.


80
S.M.
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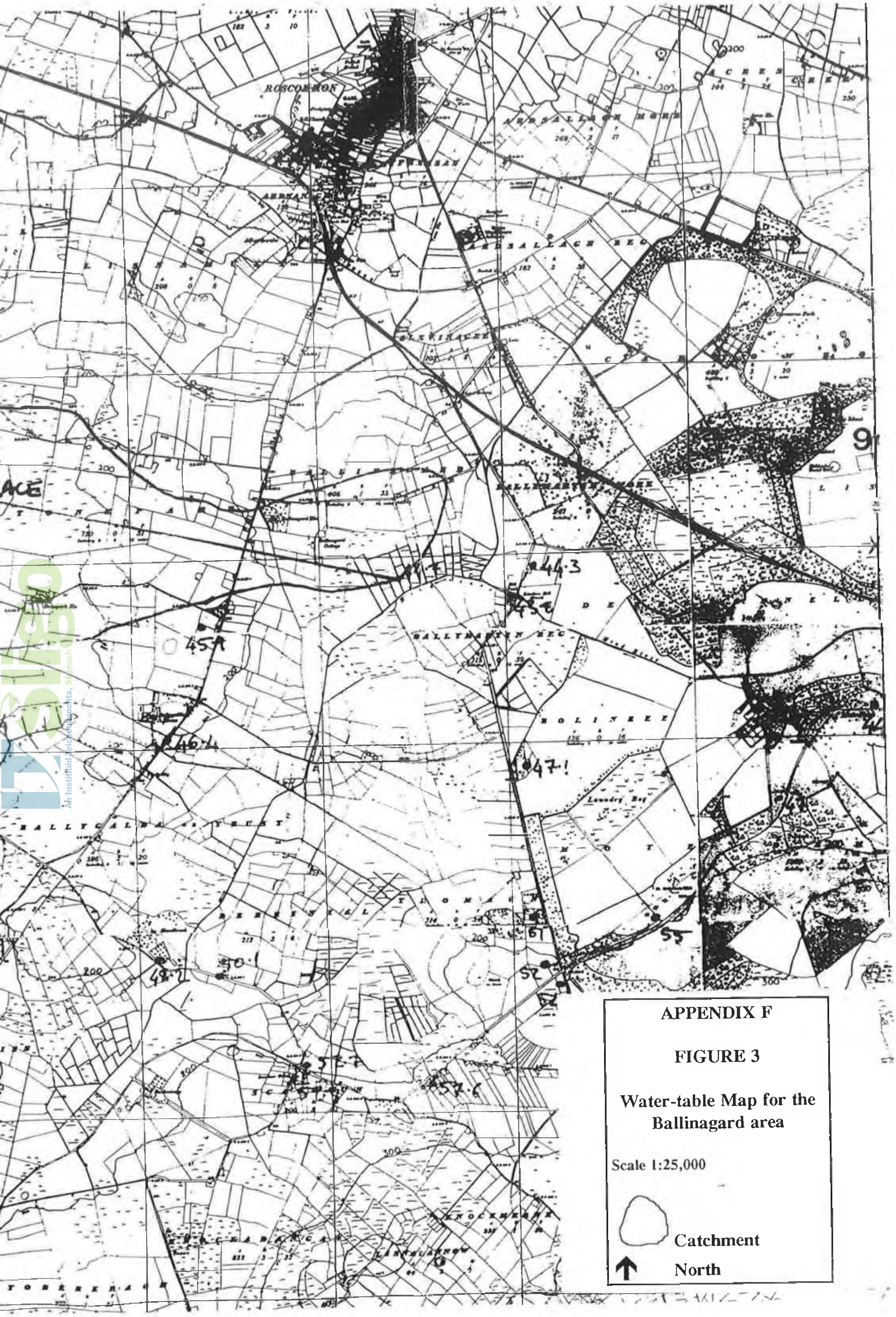
50.2
49
200



APPENDIX F

FIGURE 3

Water-table Map for the Ballinagard area

Scale 1:25,000

Catchment

North

The spring catchment at Ballinagard is considered to be both highly and extremely vulnerable to pollution. The coefficient of variation in the year round electrical conductivity measurements was 9.2%.

The mapped vulnerabilities for this source's catchment area are presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), that occur within the confines of the catchment.

The % values are: 33% Extreme
67% High.

9 POTENTIAL POLLUTION SOURCES

The area within the proposed source catchment consists entirely of farmland, where livestock farming is the dominant activity. Farm yards, silage clamps and landspreading of animal wastes are the main threat to the source since the subsoils are thin and limestone outcrop is common. Landspreading should be avoided along both sides of the stream that sinks into the Fuerty swallow hole.

The Co. Co. pumphouse and spring is clean, secure and well fenced off.

The 7.9km^2 ZOC should be treated as a Zone 1 protection zone.

APPENDIX G

BALLINDINE PUBLIC SUPPLY

1 SPRING DETAILS

GSI No.	: 11/25NE W---		
Grid Ref.	: 13622 26983		
6" Sheet	: Mayo		
Townland	: Ballindine North		
Elevation	: ~ 60m OD		
Depth to Rock	: ~ 7.7m		
Average Spring Discharge	: (i) Abstraction Rate		
	(a) to Claremorris		$981m^3/d$
	(b) to Ballindine		$808m^3/d$
		Total	$1,789m^3/d$
	(ii) Spring Overflow Average:		$2,000m^3/d$
	(iii) TOTAL Spring Discharge(i+ii):		$3,789m^3/d$

2 SPRING LOCATION AND SITE DESCRIPTION

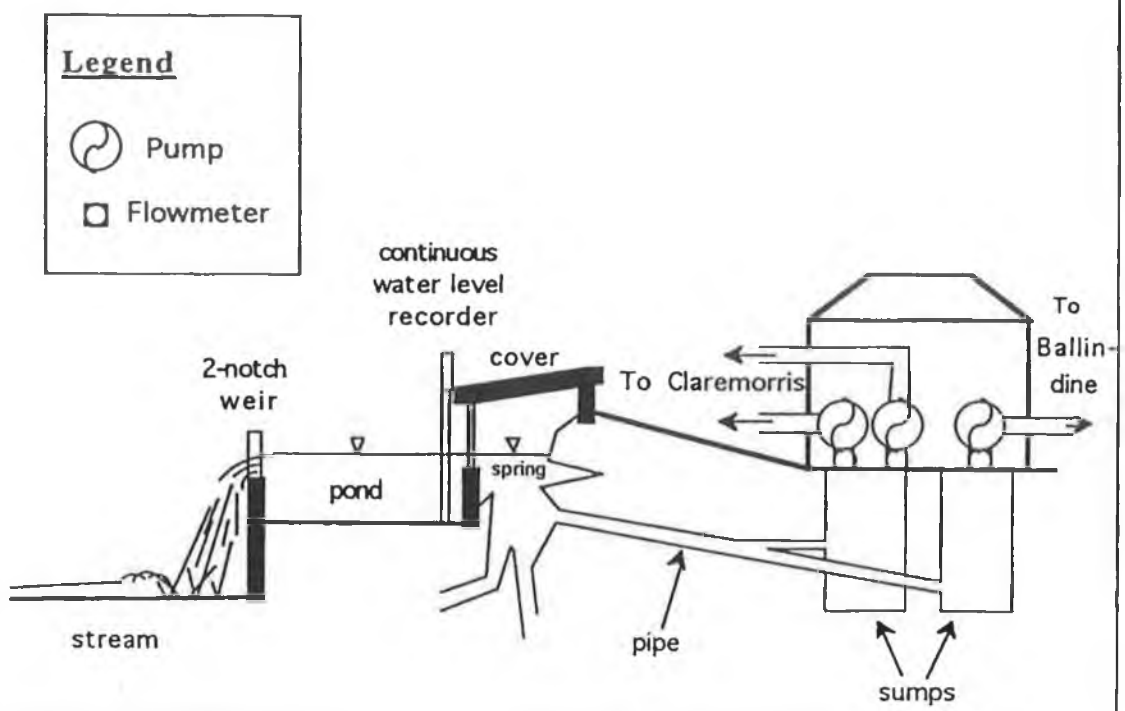
This public supply spring is located 5km SE of Claremorris and 1km NW of Ballindine town off the N 17 road, in a relatively isolated field beside a disused train track. The spring at an elevation of about 60m OD, is situated 1.6km SW of the Robe River.

The spring is enclosed in a circular concrete chamber which gravity feeds water to sumps at the pumphouse which is 100m north (Figure 1). Spring overflow is to a pond which is backed up by a non-standard two-notch rectangular weir (Photo 1). A continuous water level recorder was installed inside the pond by the GSI, 1993, in order to determine the rate of overflow from the spring. The overflow flows into a tributary of the Robe River.

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

This spring is situated just west of low relief drumlins (98m OD) that trend NW/SE (Photo 2). Drains are common in the depressions between the drumlins but there are few drains on the drumlins since they are relatively free draining. Often turloughs or raised bogs occur between

FIGURE 1
Plan of Ballindine Spring works



FROM PRICE (1995)

PHOTO 1
Ballindine Spring and weir

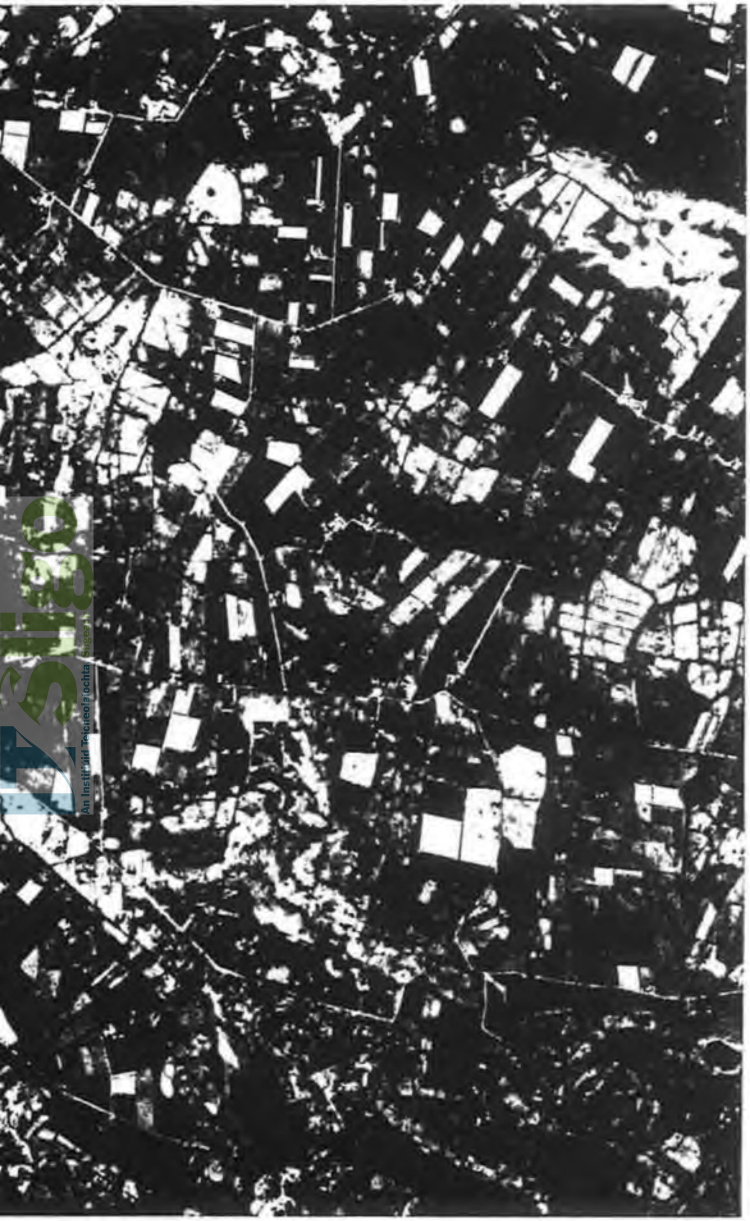


PHOTO 2
Aerial Photograph of the Ballindine area

the drumlins. In winter the inter-drumlin/turlough areas are frequently flooded as the regional water-table rises.

At the meso scale the spring lies directly in the break of slope of a low relief drumlin which has a maximum height of 78m OD.

Land use in the area is livestock farming, both dairy and drystock.

4 GEOLOGY

4.1 Bedrock Geology

In geneal the area is underlain by Pure Limestone (shallow water limestone; Burren). It is Upper Dinantian in age. However a recent borehole carried out for a related STRIDE study indicates that the spring is situated in fractured Bank limestone which is a pale grey fossiliferous limestone. Mr C. McDermott (GSI) recognises a fault to run NE/SW through Ballindine town separating the clean pure limestones from the bank limestone.

As an aquifer the Bank limestone has locally productive zones particularly if the zone is fractured/faulted.

4.2 Subsoils Geology

A copy of the 11/25NE 1:25,000 scale subsoil sheet for the area, mapped by this author appears at the back of this Appendix.

To the east of the spring (uphydraulic-gradient of the spring) the area is dominated by a clayey/silty lodgement till with angular/sub-angular limestone clasts. The drumlin immediately upslope of the spring beside the Ballindine graveyard has a bedrock core (from trial pitting).

Gravelly till and till with gravels occur to the SE of the proposed catchment. This area is marked by hummocky ground and small disused gravel pits.

Fen peat/raised bog occurs in the depressions/turloughs between the drumlins.

At the spring itself, trial pits carried out for this study suggest that the subsoil is sandier nearer to rockhead. A log of the borehole carried out by this author and drilled by the GSI

(1993) 10m distance from the spring appears at the back of this report. It indicates that a black impermeable clay 50cm thick (Photo 3) lies immediately above the bedrock (7.7m b.gl.) which probably acts as the confining layer for the groundwater.

4.3 Depth-to-rock

The borehole at the spring indicates that depth-to-bedrock is 7.7m below ground level (Photo 4). Trial pits carried out by this author within a 1km grid of the spring indicate that depth-to-bedrock is ~2m at the apex of a drumlin, but >3m between the drumlins.

There is some limestone outcrop at Ballindine town as marked on the 1:25,000 scale subsoil map.

5 METEOROLOGY

Daily rainfall and evaporation data for the October 1992 to September 1993 period, were taken directly from the Claremorris synoptical weather station (71m OD) since it is only 5km north-west of the spring, and at a similar ordnance datum. Rainfall was 1245mm and PE was 365.5mm. AE for the area was estimated at 365.5mm, the same value as PE, since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures potential recharge was taken to be approximately 879.5mm for the October 1992 to September 1993 field season (see Figure 2).

These calculations are summarised below:

Precipitation	1245mm
P.E.	365.5mm
Estimated A.E. (100% P.E.)	365.5mm
Potential recharge	879.5mm

6 WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed in the spring area an understanding of the size of the spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies was to occur within the spring recharge zone. It was decided that, as an initial step, the spring catchment area would be *estimated* by a water balance, the principles which have been discussed in Chapter 3. Hydrogeological techniques were carried out later to confirm the estimated catchment area. This work is described in Section 7.

FIGURE 2
1992-93 Meteorology for Ballindine with calculated Potential Recharge

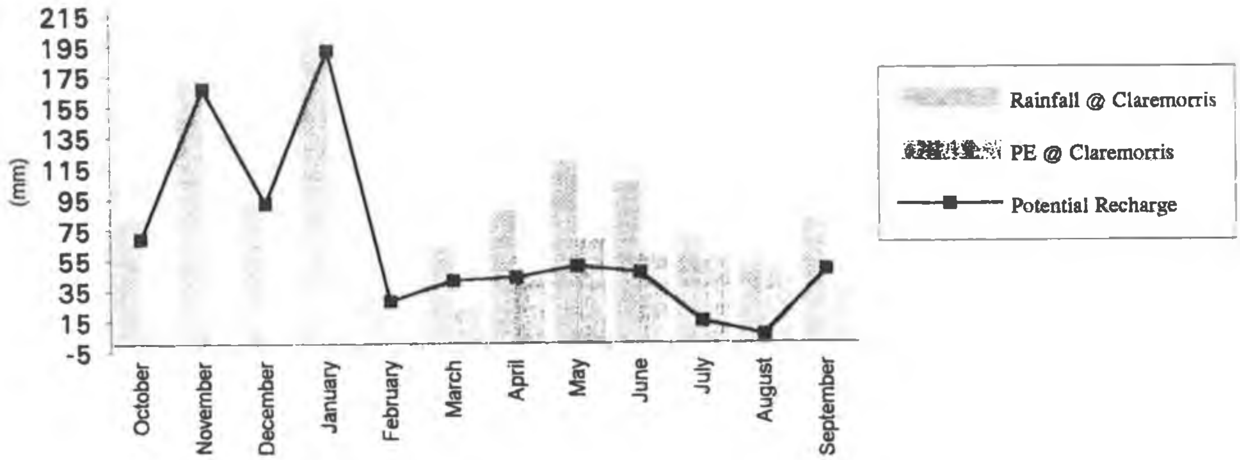


PHOTO 3
The black clay believed to be a confining layer

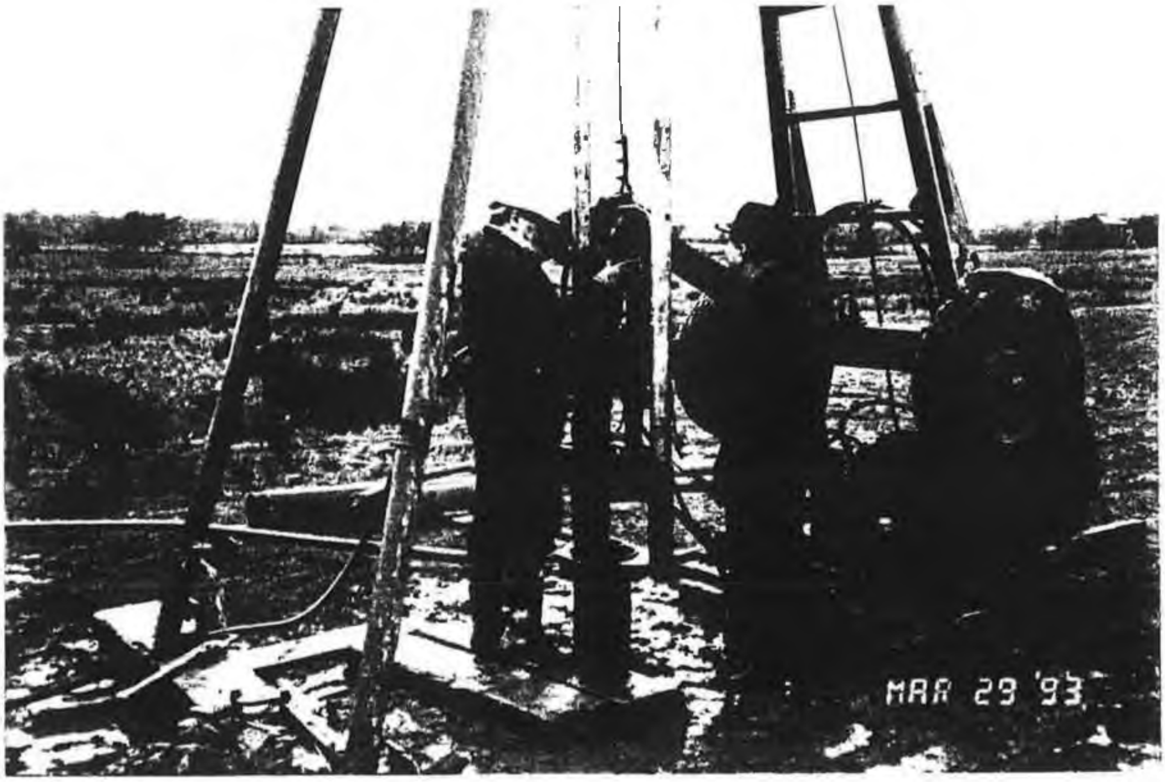


PHOTO 4
Drilling with the GSI at Ballindine

The recharge area required to supply the October 1992 to September 1993 discharge levels of this spring was calculated by:

(**Outflows**: Total Spring Output + Abstraction + Flow to other aquifers) / (**Inflows**: Direct Recharge + Indirect Recharge + Flow from other aquifers + Urban Recharge) = **Catchment Area**

Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

Total Spring Output

Overflow from the spring and total pumping rates at the pumphouse were needed to find the total spring output. A continuous water level recorder was installed at the weir to determine the spring overflow. Water levels were converted to discharge with a rating curve developed by this author and Price (see Figure 3), by salt dilution gauging or a bucket. It was found that overflow at the weir averaged 2,000m^3/d. Total pumping rates at the spring were 1,789m^3/d.

Therefore, the total spring output for Ballindine is 3,789m^3/d $\Rightarrow$ 3,789m^3/d

Abstraction

Disregarded, see Chapter 3.

Flow to other aquifers

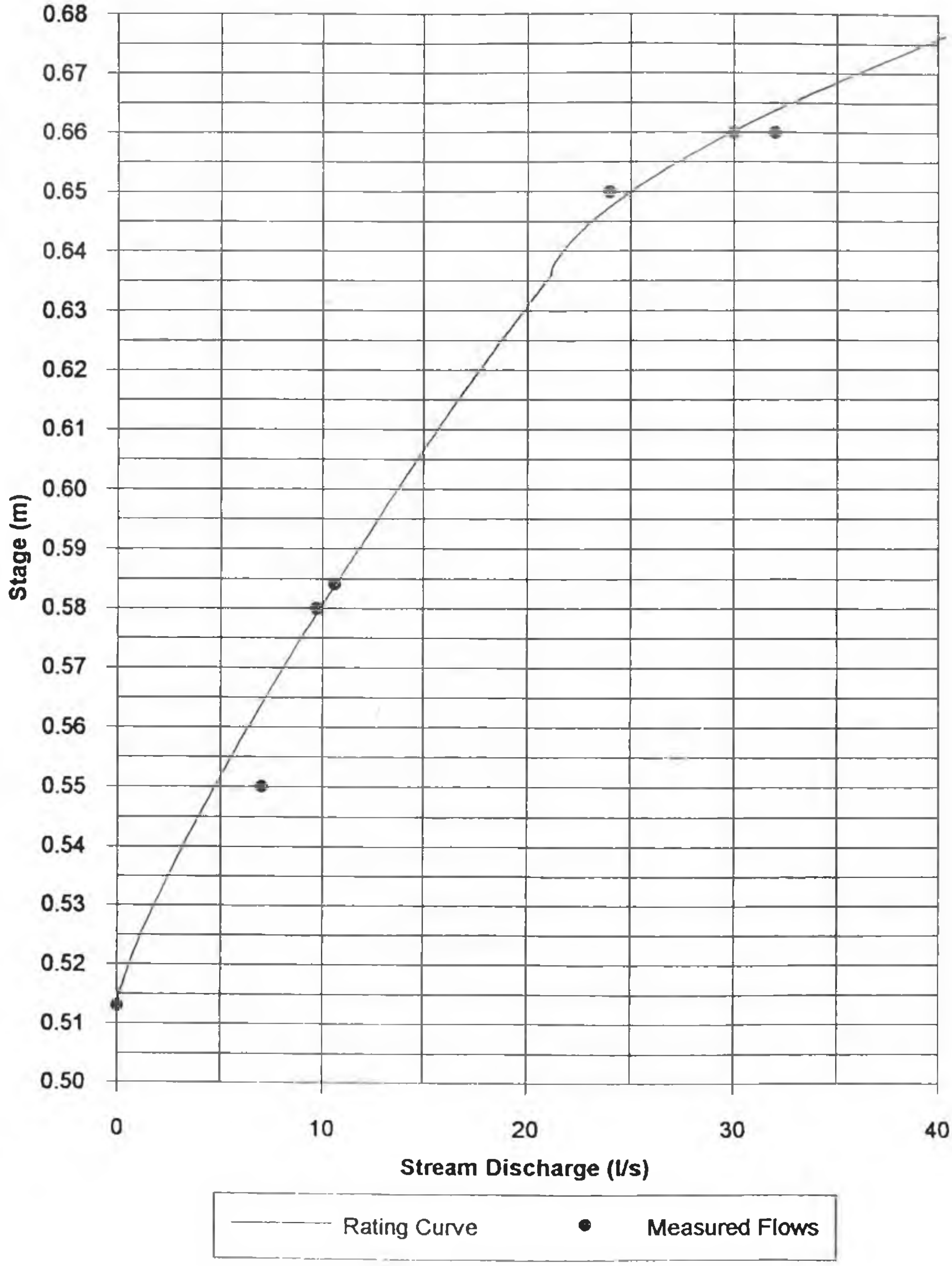
Disregarded, see Chapter 3.

Total outflows from the Ballindine Spring $\Rightarrow$ 3,789m^3/d

Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

FIGURE 3
Rating curve for the weir at Ballindine



Direct Recharge

Generally there are relatively moderate permeability subsoils in the area with few drainage features, except between drumlins. A confining layer of dense low permeability clay lies near the spring. It is believed that only a moderate to low proportion of potential recharge, recharges the aquifer because of the confining clays. Estimating runoff to be in the order of 60% of potential recharge, direct/actual recharge to the aquifer was taken to be 352mm.

$\Rightarrow$ 9.64×10^{-4} m/d

Indirect recharge

Nil

Flow from other aquifers

See Chapter 3. —

Urban Recharge

Up to 0.1 l/sec./km^2 of urban runoff and pipe leakage theoretically recharges the underlying aquifer. $\Rightarrow$ 8.64×10^{-6} m/d

Total inflows to the aquifer at Ballindine $\Rightarrow$ 9.7×10^{-4} m/d

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

$$\frac{\text{Total outflows from the spring}}{\text{Total inflows to the aquifer}} = \frac{3{,}789\text{m}^3/\text{d}}{9.7 \times 10^{-4}\ \text{m/d}} = 3.9\text{km}^2$$

7 HYDROGEOLOGY

7.1 Groundwater levels

Groundwater data is sparse for the Ballindine area. Turloughs are common in the area.

7.2 Groundwater flow direction

The movement of regional groundwater is east to west under hydraulic gradients of 0.8 - 1.75m/km (Drew and Daly 1994). It discharges at the Robe River.

7.3 Physical Demarcation of the Catchment Area

The catchment boundaries for this spring were principally determined by topography. It was judged to be 4.3km². The resultant catchment map appears in the 1:25,000 subsoils sheet at the back of this appendix.

The estimated catchment area, determined by the water balance technique, was calculated to be 3.9km². Price and Johnston (1995) with a spring recession analysis technique concluded that the catchment area for Ballindine spring was 3.7km². These figures may be used as a starting indicator that the physically determined catchment area recharges the spring at Ballindine.

8 VULNERABILITY ASSESSMENT

A vulnerability map (Figure 4) was prepared for the catchment and peripheral areas at the 1:25,000 scale from this author's field maps. The "improved and achievable vulnerability mapping" GSI guidelines(Daly and Warren, 1994) were the main rules used since much of the catchment was mapped at reconnaisance level with trial pitting.

The spring catchment at Ballindine is considered to be both highly and extremely vulnerable to pollution. The coefficient of variation in the year round electrical conductivity measurements was 9.5%.

The mapped vulnerabilities for this source's catchment area are presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), that occur within the confines of the catchment.

The % values are: 10% Extreme
90% High.

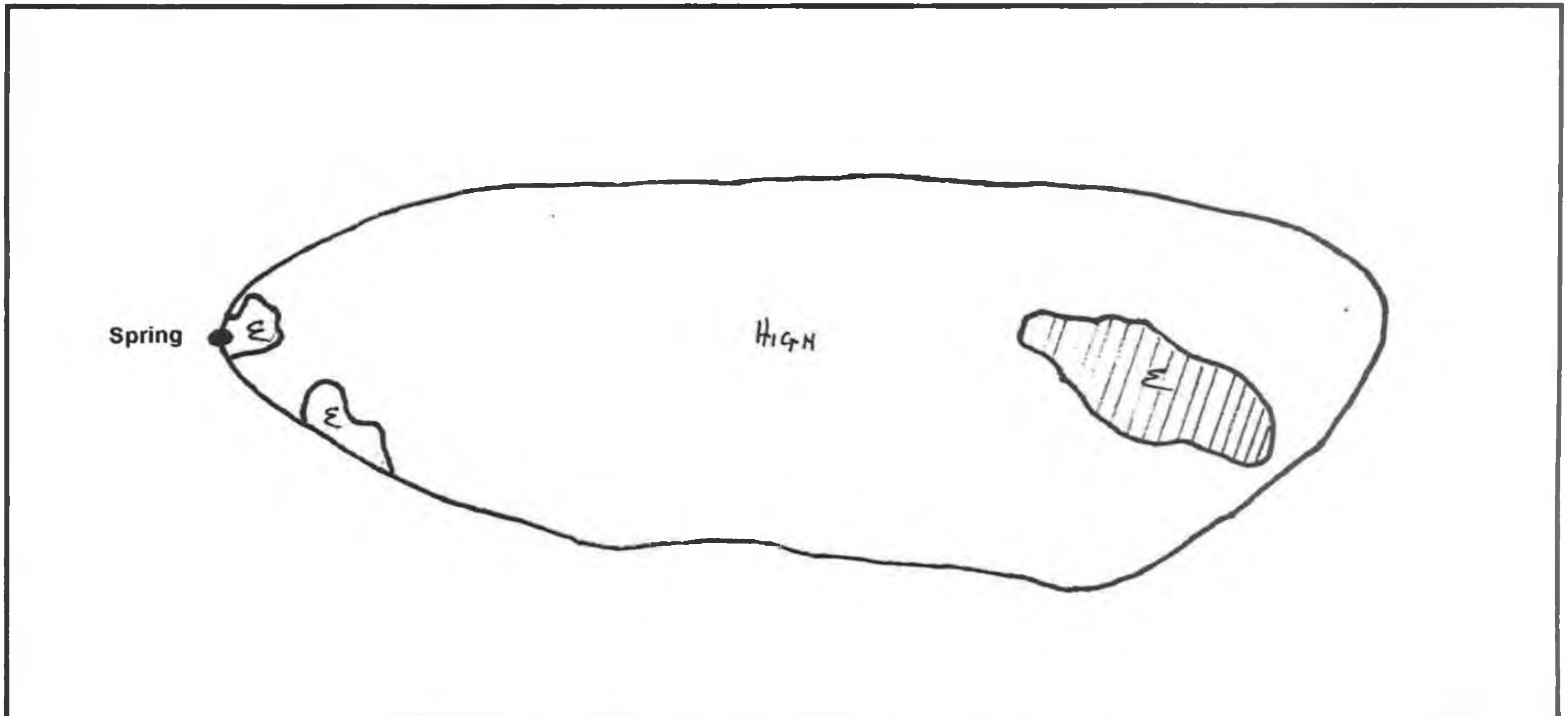


FIGURE 4

Ballindine

Groundwater Vulnerability

Extreme Vulnerability

High Vulnerability

Catchment

North

Scale 1:25,000

9 POTENTIAL POLLUTION SOURCES

The majority of the area within the proposed spring catchment consists of farmland, where livestock farming is the dominant activity. Farm yards, silage clamps and landspreading of animal wastes are the main threat to the source since certain parts of the catchment have turloughs. Often their large bodies of surface water may become polluted by run-off from the local drumlins where landspreading is practised. The surface water at the turloughs may in turn pollute the Ballindine spring as it could sink at the swallow holes and flow east/west to the spring as groundwater.

The main N 17 road lies along the apex of the drumlin which is adjacent to the spring. Trial pits show that bedrock along the road is not greater than 2m deep. Run-off (contaminants) from the road are likely to recharge the Ballindine spring.

Similarly, run-off from both Ballindine town and its graveyard are likely to recharge the spring at Ballindine.

The Co. Co. pumphouse and spring are clean, secure and well fenced off.

Borehole name: BALLINDINE No: 1

11/25 VE

County: MAYO 6" sheet No: 111

Date Logged: 29/3/93 Type: Shell + auger

Remarks: Shell + auger. Generally limestone silt → clay diamict, more clay the deeper the hole. little clast content generally weathered out. 5 – 6.5m interval there are clasts in clay diamict, assorted ie schist, qtzite, SST. Confining clay inter. @ 7.5 → 7.7m, Bedrock @ 7.6/7.7m

LOG

Depth below well head in m	Diameter (ins) / Apparent fluid resistance	LOG
0.5m → 1m	Clay Sand in	
	upper layer w/grass	
Sandy LST Dm	Light brown SST till	
	or diamict, sub-	10 m
	angular limestone	
	clasts	
1m – 1.5m	Mid Grey heavy	
	clay/silt matrix	
	No clasts, all	
Silt SST Dm	weathered out, and	
	break @ touch.	
	SST clasts are	20 m
	weathered out	
1.5m – 2m	Darker grey silt –	
Silt Sst Dm	clay matrix Clasts	
	weathered out (SST)	
2 – 3m	Grey Dm	
	LST & Clasts sub-	
	angular Clay	
Clay LST Dm	Matrix, some silt	30 m
	LST Clasts not	
	weathered out	
3 – 4m	Grey colored Dm	
	Silt Matrix	
	Subangular LST	
Silt LST Dm	Clasts with purer	
	silt lenses. fess	
	linear structure	40 m
4 – 5m	Clay Dm Ang LST	
	Clasts heavy dense	
Clay LST Dm	clay grey → brown	
	Dense clay matrix	
	support	

Geological Survey
of Ireland

Borehole name: Ballindine ..... No: 1

County: MAYO .... 6" sheet No: 111

Date Logged: 29/3/93 Type: Shell+Auger

Remarks:

Bedrock at 7.5 → 7.6m

fractured B/R @ 7.8m with veinqtz.

LOG

Depth below well head in m	Diameter (ins) / Apparent fluid resistance
5-6m	Clay Dn
	Assorted Clasts
Clay LST Dn	schist, lst, sst
	Clay matrix,
	typical clay lst
	till
6.5m → 7.5m	Dark Black Clay
	Homogeneous.
	Some fine layers
	of Qtz rich sand
	Very fine-marble
	→ Lake Sediment
7.5m	Bedrock Buried
	Limestone.
7.5m 15cm	Qtz vein fractured
	lst.

10 m

20 m

30 m

40 m

APPENDIX H

MOUNT TALBOT PUBLIC SUPPLY

1 SPRING DETAILS

GSI No.	: 17/25SW W --	
Grid Ref.	: 18203 25232	
6" Sheet	: Roscommon 44	
Townland	: Cloonlaughan	
Elevation	: 46.85m OD	
Depth of Spring	: < 2m	
Depth to Rock	: 2.5m	
Average Spring Discharge	: (i) Abstraction Rate (66l/s x 13.5hrs)	3200m³/d
	(ii) Spring Overflow Average:	3370m³/d
	(iii) TOTAL Spring Discharge(i+ii):	6570m³/d

2 SPRING LOCATION AND SITE DESCRIPTION

This public supply source is located 750m southeast of Mount Talbot village in a boggy field adjacent to a small tributary of the River Suck. The River Suck is 350m west of the source.

The source consists of two springs that feed a small a dug out channel which flows south into a small westward flowing stream. The channel is about 20m long to a weir and is 4m wide; its surface water level is kept at a stable height by a broad crested concrete weir 0.8m high on the upsteam side (Photos 1 and 2). An intake mid-way along the 20m stretch of channel, flows water to the pumphouse sumps which are 5m away. The two pumps operate for 13 hours per day, abstracting a maximum of 3200m³/d.

The source is well fenced off and access can only be gained from the main road via a locked gate 200m north.

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

The springs, at an elevation of 46.5m OD, lie in the River Suck valley. Several NW/SE trending low relief drumlins lie north and south of the springs. A north/south trending limestone ridge with a maximum height of 150m OD, lies 2.5km east of the source. The

PHOTO 1
Mount Talbot Springs and weir

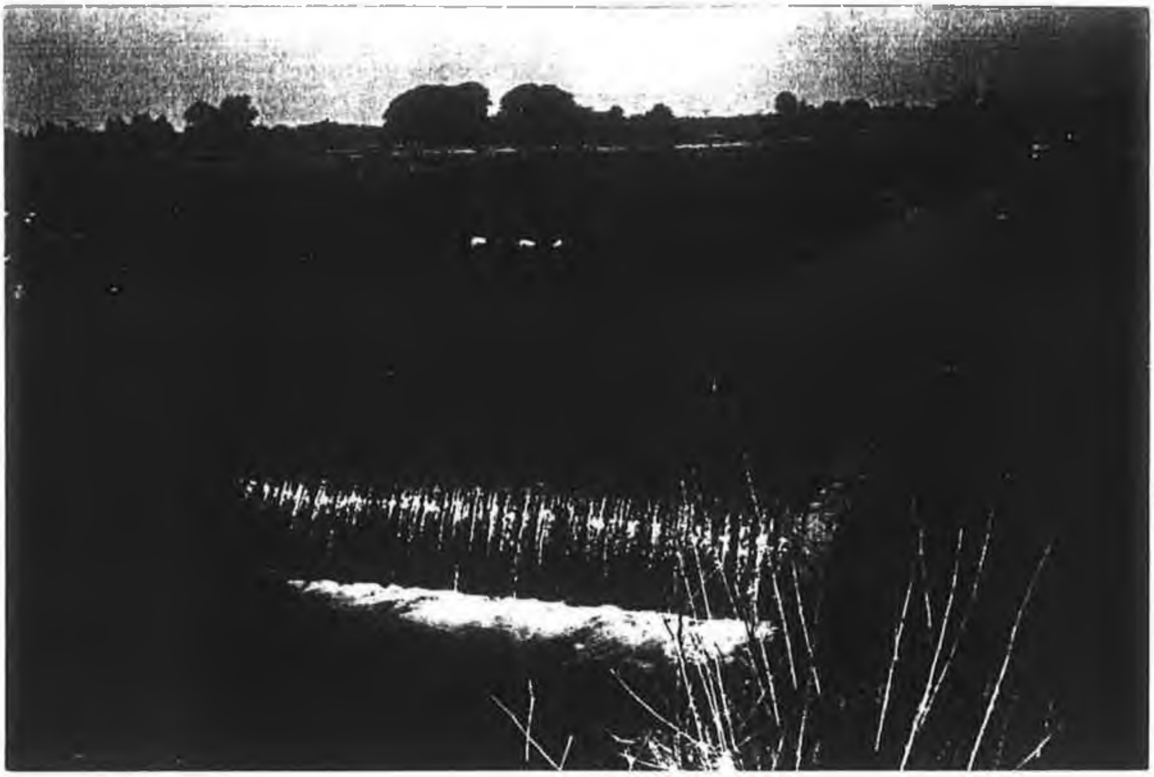


PHOTO 2
Mount Talbot spring weir

ridge acts as the regional watershed; the River Suck lies to the west and the River Shannon lies to the east.

The limestone ridge is free draining. Minor tributaries run west from the ridge to the River Suck. They run between the drumlins where there are several raised bogs. Regional groundwater discharges into the tributaries since ECs were not less than 600 μS/cm. There are several turloughs which lie E/NE of the source. The nearest turlough is 1.5km ESE of the source which lies at the foot of the limestone ridge; it has two swallow holes.

Land use in the area is mainly livestock farming, both dairy and drystock.

4 GEOLOGY

4.1 Bedrock Geology

The dominant rock type in the area is Pure Limestone (shallow water limestone; Burren, Chevron 1992). It is from this rock that the springs draw their water.

As an aquifer the Pure limestone has locally productive zones particularly if the zone is fissured or karstified.

4.2 Subsoils Geology

Part of the 1:25,000 (17/25SW) subsoil sheet for the area (40km^2), carried out by this author appears in Figure 1 at the back of this Appendix. The area within 1km of the source is dominated by a fine grey clay lodgement till with angular/sub-angular limestone clasts. Trial pits carried out for this study suggest that the subsoil is sandier nearer to rockhead. Fen peat is widespread at the springs and is up to 1m deep. There are no glacial related gravels in the area, but there is a suggestion of alluvial gravels near the River Suck and along its larger tributaries.

Within the 40km^2 area, outside the proposed catchment, clayey limestone till is the dominant subsoil type which is often interbedded with silt. The limestone clasts in the till tend to be relatively angular with maximum clast size at 30cm. Morphologically the till is a grey boulder clay deposited as ice moved west from the 150m high limestone plateau 2/3km from source. Raised bog, cut-away in parts is common in the inter-drumlin areas where it overlies clays or clayey tills.

4.3 Soils

Degraded brown podzolics with low infiltration rates are common in the limestone till areas. Often gleys are found in the inter-drumlin areas where there is poor draining and overlying peat. This soil type normally has a low permeability. Raised bog (often cut-away in parts) is widespread where it covers up to one third of the area that was mapped.

4.4 Depth-to-rock

Within the source enclosure depth-to-bedrock ranges from 1.6m to 4.7m below surface; further details may be found in the consulting engineers report carried out in 1982, at Roscommon Co. Co. Courthouse.

Borehole information for the lowland valley area suggests that the subsoil is 1.5m to 5m deep. Limestone outcrop is common at the N/S limestone ridge and subsoils here are a maximum of 1m deep. The drumlins are believed to be bedrock cored.

5 METEOROLOGY

Daily rainfall data for the October 1992 to September 1993 period, were taken directly from the Ballygar rainfall station (61 m OD), which is 3km to the west of the source. Rainfall was 1038.5mm. Potential Evapotranspiration (PE) at Claremorris was 365.5mm for the same period. AE for the area was estimated at 365.5mm, the same value as PE, since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures potential recharge was taken to be approximately 673mm for the October 1992 to September 1993 field season (see Figure 2).

These calculations are summarised below:

Precipitation	1038.5mm
Estimated A.E. (100% P.E.)	365.5mm
Potential recharge	673mm

6 WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed in the spring area an understanding of the size of the spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies

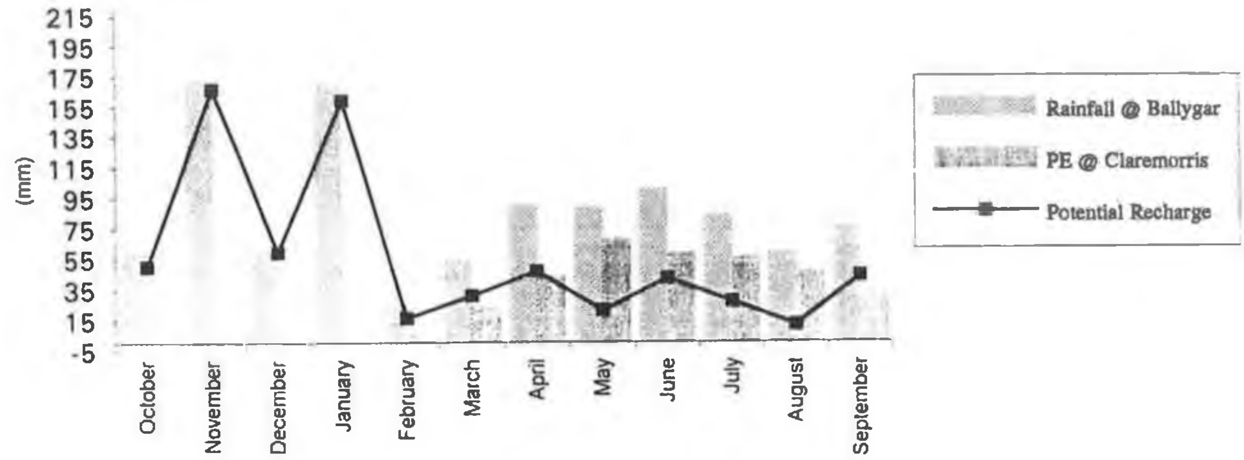

215
195
175
155
135
115
95
75
55
35
15
-5
(mm)
October
November
December
January
February
March
April
May
June
July
August
September
Rainfall @ Ballygar
PE @ Claremorris
Potential Recharge

FIGURE 2
1992-93 Meteorology for Mount Talbot with calculated Potential Recharge

was to occur within the spring recharge zone. It was decided that, as an initial step, the spring catchment area would be ***estimated*** by a water balance. Hydrogeological techniques were carried out later to confirm the estimated catchment area. This work is described in Section 7.

The recharge area required to supply the October 1992 to September 1993 discharge levels of this spring was calculated by:

$$\left(\begin{array}{c}\textbf{Outflows}\\ \text{Total Spring Output}\\ + \text{Abstraction}\\ + \text{Flow to other}\\ \text{aquifers}\end{array}\right) / \left(\begin{array}{c}\textbf{Inflows}\\ \text{Direct Recharge}\\ + \text{Indirect Recharge}\\ + \text{Flow from other aquifers}\\ + \text{Urban Recharge}\end{array}\right) = \begin{array}{c}\textbf{Catchment}\\ \textbf{Area}\end{array}$$

Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

Total Spring Output

Overflow from the springs and total pumping rates at the pumphouse were needed to find the total spring output for the October 1992 to September 1993 period. A staff gauge at the weir was used to determine the spring overflow. Water levels were converted to discharge with a rating curve developed by this author, with a midget current meter and dye dilution gauging. It was found that overflow at the weir averaged 3370m^3/day. Total pumping rates at the spring were (66l/s x 13.5hrs) 3200m^3/day. Therefore, the total spring output for Mount Talbot is 6570m^3/day.

$\Rightarrow$ 6570m^3/d

Abstraction

Disregarded, see Chapter 3.

Flow to other aquifers

Disregarded, see Chapter 3.

Total outflows from the Mount Talbot Source $\Rightarrow$ 6570m^3/d

Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

Direct Recharge

As there are relatively low permeability subsoils and peat in the area, and there are several drainage features, a relatively low proportion of potential recharge, determined in Section 5, infiltrates to the water table. Estimating runoff to be in the order of 50% of potential recharge, direct/actual recharge to the aquifer was taken to be 334mm.

$\Rightarrow$ 9.15×10^{-4} m/d

Indirect recharge

Nil

Flow from other aquifers

See Chapter 3. —

Urban Recharge Nil

Total inflows to the aquifer at Mount Talbot $\Rightarrow$ 9.15×10^{-4} m/d

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

$$\frac{\text{Total outflows from the Mount Talbot Source}}{\text{Total inflows to the aquifer at Mount Talbot}} = \frac{6{,}570 \text{ m}^3/\text{d}}{9.15 \times 10^{-4} \text{ m/d}} = 7.2 \text{ km}^2$$

7 HYDROGEOLOGY

7.1 Data Availability

Groundwater data is sparse for the Mount Talbot area; no open file or borehole records were encountered for the general area.

Before this public supply was constructed, seven trial holes were carried out at the Mount Talbot source (11/1982) by the group of consulting engineers previously mentioned in Section 4.4. However, none of the holes penetrated bedrock. Falling head tests were carried out to determine the permeability of a gravel layer overlying the bedrock. Roscommon Co. Co. may be contacted for further information.

7.2 Groundwater levels

The trial holes at the source show that the static water level is 1m b.gl. mainly at the peat/clay till boundary. The two springs are believed to act as overflow valves. The pumphouse intake therefore only receives spring overflow.

7.3 Groundwater flow direction, gradient and time of travel

Regional groundwater flows from east to west in limestone bedrock. Recharge occurs in the limestone uplands to the east and regional groundwater discharge occurs at the River Suck. There was no information on the gradient or TOT of the groundwater since no tracing could be carried out. Tracing could not be carried out over the field period at the two swallow holes in the turlough 1.5km ESE of the source since it was flooded and there appeared to be no inflow to the swallow holes.

7.4 Physical Demarcation of the Catchment Area

The catchment boundaries for this spring were principally determined by topography, keeping in mind that the water balance method estimates the size of the catchment to be 7.2 km^2. The proposed catchment boundaries appear in Figure 1.

Since groundwater flow is east to west and the River Suck and its tributaries are discharge zones for regional groundwater, the catchment area for the Mount Talbot source was judged to be upgradient in an easterly direction towards the N/S trending limestone ridge. The eastern catchment boundary for the source is coincident with the watershed/surface/groundwater catchment divide of the limestone ridge. The southern and northern catchment boundaries lie on the apexes of NW/SE trending drumlin ridges which are limestone bedrock cored. A groundwater fed stream (EC > 670μS/cm) lies south of the southern catchment divide; a large spring lies at its headwater. The Cloonalin River lies north of the northern catchment boundary. It is groundwater fed since EC mid-way along the river was in excess of 650μS/cm and four springs form its headwater. The northern and southern catchment boundaries merge to form the western boundary as marked in Figure 1.

The estimated catchment area determined by the water balance technique was calculated to be 7.2 km^2. This figure agrees well with the proposed physically determined catchment area.

8 VULNERABILITY ASSESSMENT

A vulnerability map (Figure 3) was prepared for the catchment and peripheral areas at the 1:25,000 scale by the GIS group at TCD, from this author's subsoils maps, using the "minimum standard vulnerability mapping" GSI Guidelines (Daly and Warren, 1994) since much of the area was only mapped at reconnaisance level, but with detailed aerial photography analysis. The vulnerability map appears at the back of this report.

The 7.3km^2 spring catchment at Mount Talbot is considered to be both highly and extremely vulnerable to pollution. The limited subsoil extent, although dominantly composed of clayey till, causes groundwater to be highly vulnerable to pollution since it is generally less than 3m thick. Outcrop is common along the eastern catchment boundary. The coefficient of variation in the year round electrical conductivity measurements was relatively high at 10% suggesting extreme vulnerability.

The mapped vulnerabilities for this source's catchment area are presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), that occur within the confines of the catchment.

The % values are: 47% Extreme
53% High.

9 POTENTIAL POLLUTION SOURCES

The area within the proposed source catchment area consists entirely of farmland, where livestock farming is the dominant activity. Farm yards, silage clamps and landspreading of animal wastes are the main threat to the source since the subsoils are thin and limestone outcrop is common. The turlough with two swallow holes, 1.2km SE of the source, covers nearly 1km^2 of the catchment. This large body of surface water may become polluted by run-off from the local drumlins where landspreading is practised. The surface water may in turn pollute the Mount Talbot springs as it could sink at the swallow holes and flow east/west to the springs as groundwater.

The Co. Co. pumphouse is clean, secure and well fenced off.

APPENDIX I

KILLEGLAN PUBLIC SUPPLY

1 SPRING DETAILS

GSI No.	: 17/23NE W --		
Grid Ref.	: 18864 24047		
6" Sheet	: Roscommon 50		
Townland	: Rockland		
Elevation	: 49.91m OD		
Depth to Rock at Spring	: <3m		
Average Spring Discharge	:	(i) Abstraction Rate (80l/s x 19hrs)	5,470m³/d
		(ii) Spring Overflow Average:	1,440m³/d
		(iii) TOTAL Spring Discharge(i+ii):	6,910m³/d

2 SPRING LOCATION AND SITE DESCRIPTION

The Killeglan source is located 10km NNE of Ballinasloe, along the L 12 road to Thomas Street. It is about 20m from the road in a boggy field.

The source consists of a deepened spring that is surrounded by a concrete enclosure. The spring outlet is via two gaps in the concrete wall (Photo 1). Two pipes move water to two large pumps in the pumphouse which is 18m from the spring. Access to the source can only be gained via a locked gate.

A sister untapped spring lies immediately NW of the concrete chamber (Photo 2).

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

The spring, at an elevation of 49.91m OD, lies in the River Suck valley. It forms the headwaters for the south-west flowing Killeglan River which discharges to the River Suck 4.2km away.

Limestone uplands (90-120m OD) lie N and SE of the source which act as the regional watersheds; the River Suck lies to the west and the River Shannon lies to the east. Four short-lived surface streams flow northward from the bog covered uplands in the SE and rapidly disappear down swallow holes as they hit the valley floor. The acidic surface water

PHOTO 1
Killeglan spring enclosed in a concrete chamber

PHOTO 2
Sister (untapped spring) beside Killeglan spring

running off the bogs appear to have been the prerequisite for the formation of the swallow holes.

At a meso scale there are few surface drains or streams in the area since the soils are relatively free draining and the bedrock which has a fissure/conduit permeability is close to the surface. There are several small-scale surface depressions which run along a northerly line from two swallow holes in the townland of Taghmaconnell. A second cluster of depressions are concentrated in the townland of Onagh. These depresssions are attributed to karstic collapse features.

Land use in the area is mainly livestock farming, both dairy and drystock.

4 GEOLOGY

4.1 Bedrock Geology

The rock type over the whole area is Pure Limestone (Burren; shallow water limestone).

As an aquifer the Pure limestone has locally productive zones particularly if the zone is fissured or karstified.

4.2 Subsoils Geology

A copy of the 1:25,000 scale subsoil sheet for the area, appears in Figure 1 at the back of this Appendix. Generally within the zone of proposed catchment and 1km outside it, there are three subsoil types: Peat; sorted and stratified sands and gravels; and Limestone till.

4.2.1 Peat

Raised bog and fen peat are concentrated in the relatively low lying areas immediately beside the spring to the east and south. The peat is underlain by low permeability clayey tills. Peat formation is thought to have occurred in the topographic low points which were at one stage intersected by a relatively high water-table.

4.2.2 Sands and Gravels

Sands and gravels were recorded at 13 localities by Quinn, around the source. They are esker and glaciofluvial/glaciolacustrine related. Over 20% of the proposed catchment contains sands and gravels.

The esker ridges show a WNW-E orientation and rise to approximately 5m above the surrounding plateau; sections show that they consist of a coarse boulder/cobble gravel with a sandy matrix. The eskers may often overly limestone tills or boulder clay.

4.2.3 Limestone Till

Limestone till overlies much of the proposed catchment. These sediments are characterised by their bimodal particle size distribution. Angular to sub-angular striated clasts of limestone are supported by a sandy matrix with small amounts of silt and clay. There are occasional rounded gravel clasts. Quinn (1988) interprets that the till is largely a product of the reworking of the local glaciofluvial esker sediments.

4.3 Depth-to-rock

Trial pitting carried out for this study, indicates that depth-to-bedrock within 20m of the spring ranges from 1.5-3m. All pits encountered peat to 1.8m below surface underlain by shell marl and clays.

Mean recorded depth-to-bedrock throughout Figure 1, from borehole records, is 14.9m. However depth-to-rock is considered to be < 2m wherever springs, swallow holes and shallow surface depressions are located.

5 METEOROLOGY

Daily rainfall data for the October 1992 to September 1993 period, were taken directly from the Ballygar rainfall station (61m OD), which is 15km to the north west of the source. Rainfall was 1038.5mm. AE for the area was estimated at 359.5mm, the same value as PE at Birr, since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures potential recharge was taken to be approximately 679mm for the October 1992 to September 1993 field season (see Figure 2).

These calculations are summarised below:

Precipitation	1038.5mm
P.E.	359.5mm
Estimated A.E. (100% P.E.)	359.5mm
Potential recharge	679mm

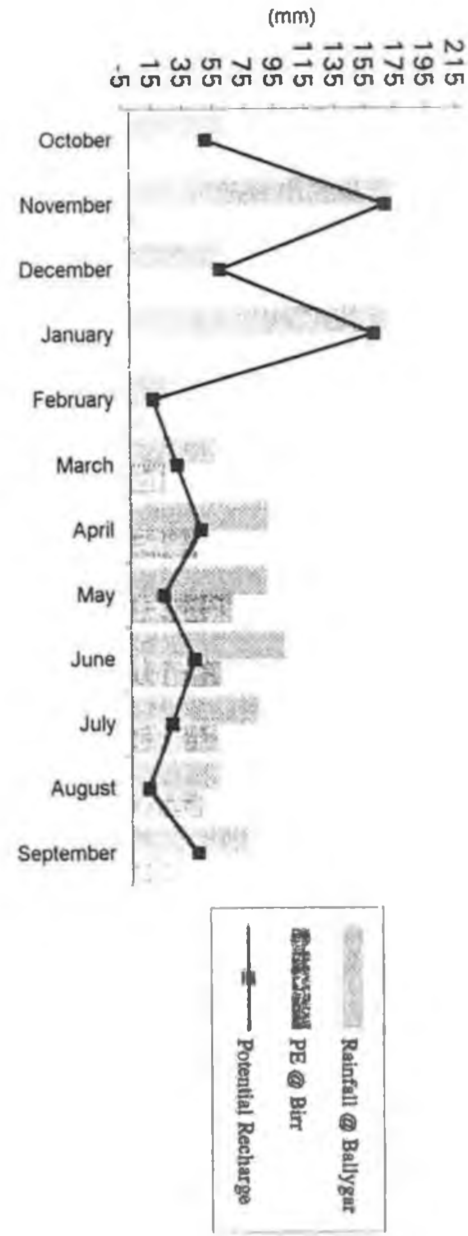

(mm)
-5
15
35
55
75
95
115
135
155
175
195
215
October
November
December
January
February
March
April
May
June
July
August
September
Rainfall @ Ballygar
PE @ Birr
Potential Recharge

FIGURE 2
1992-9
FIGURE 2
1992-93 Meteorology for Killeglan with calculated Potential Recharge

6 WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed in the spring area an understanding of the size of the spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies was to occur within the spring recharge zone. It was decided that, as an initial step, the spring catchment area would be *estimated* by a water balance. Hydrogeological techniques and water tracing were carried out later to confirm the estimated catchment area. This work is described in Section 7.

The area required to supply the annual discharge of this spring was calculated by:

$$\left(\begin{array}{c} \textbf{Outflows} \\ \text{Total Spring Output} \\ + \text{Abstraction} \\ + \text{Flow to other} \\ \text{aquifers} \end{array} \right) / \left(\begin{array}{c} \textbf{Inflows} \\ \text{Direct Recharge} \\ + \text{Indirect Recharge} \\ + \text{Flow from other aquifers} \\ + \text{Urban Recharge} \end{array} \right) = \begin{array}{c} \textbf{Catchment} \\ \textbf{Area} \end{array}$$

Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

Total Spring Output

Overflow from the springs and total pumping rates at the pumphouse were needed to find the total spring output for the October 1992 to September 1993 period. A staff gauge along the spring overflow channel had to be used to determine the spring overflow, since the spring is totally enclosed in concrete. Water levels were converted to discharge with a rating curve developed by this author, with a midget current meter and dye dilution gauging. It was found that overflow at the weir averaged 1,440m^3/d. Total pumping rates at the spring were 5,470m^3/d. Therefore, the total spring output for Killeglan is 6,910m^3/d.

$\Rightarrow$ 6,910m^3/d

Abstraction

Disregarded, see Chapter 3.

Flow to other aquifers

Disregarded, see Chapter 3.

Total outflows from the Killeglan Source $\Rightarrow$ 6,910m^3/d

Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

Direct Recharge

As there are relatively high permeability subsoils in the area and there are few drainage features, a relatively high proportion of potential recharge, determined in Section 5, infiltrates to the water table. Estimating runoff to be in the order of 15% of potential recharge, direct/actual recharge to the aquifer was taken to be 577mm.

$\Rightarrow 1.58 \times 10^{-3}$m/d

Indirect recharge

Nil

Flow from other aquifers

See Chapter 3. —

Total inflows to the aquifer at Killeglan $\Rightarrow 1.58 \times 10^{-3}$m/d

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

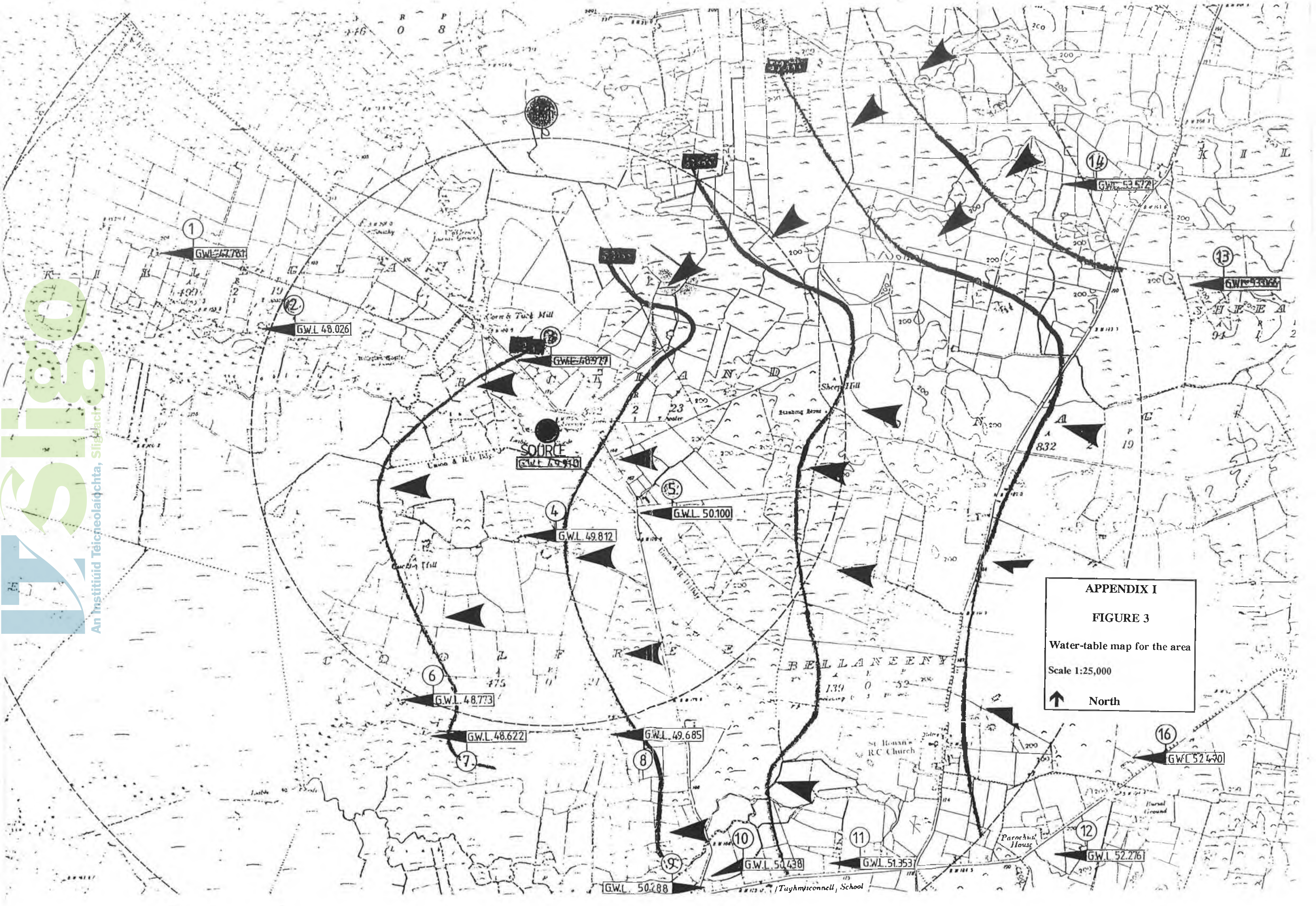
$$\frac{\text{Total outflows from the Killeglan Source}}{\text{Total inflows to the aquifer at Killeglan}} = \frac{6{,}910\text{m}^3/\text{d}}{1.58 \times 10^{-3}\text{m/d}} = 4.4\text{km}^2$$

7 HYDROGEOLOGY

7.1 Data Availability

Several boreholes were levelled to ordnance datum by Roscommon Co. Co. in 1987, and tracing was carried out in 1991 and 1994.

A watertable map of groundwater exists for the area (Figure 3). This map has relatively widely spaced contours which may indicate that the aquifer at Killeglan is quite permeable.



APPENDIX I

FIGURE 3

Water-table map for the area

Scale 1:25,000

↑ North

7.2 Groundwater flow direction, gradient and time of travel

Regional groundwater flows from east to west in the Pure Limestone recharging in the uplands to the NE and SW, and discharging at the River Suck.

Two traces using Leucophor STA were carried out in the area in 1991 and 1994 by Roscommon Co. Co. and this author, respectively. Tracer was introduced to two swallow holes, one in the turlough at Glennanea (2.6km SSW of source) and one at Carrowduff (3.9km SW of source). All possible outflow points were monitored for the tracer using a fabric detector constructed of sterile unbleached cotton gauze. Evaluation of the presence of the dye on the detector was visual, with a hand-held ultraviolet source. For both swallow holes a positive trace occurred at the spring 1.5 days later. For the Glennanea trace in 1991, the dye was detected first in a stream at Dundonnell townland and then at a spring in Bellaneeny townland before it appeared at the main Killeglan spring.

Surface water entering the swallow holes appears to flow at shallow depths in the subsurface to the Killeglan spring via conduits, emerging at local topographic lows where the water-table intercepts the surface.

The real flow direction of groundwater deduced by tracing was not the same as the flow direction indicated by the water table map. because a fissure/conduit system did not permit flow in the direction of the contour map's flow line.

7.3 Physical Demarcation of the Catchment Area

The physically determined catchment area for the main Killeglan spring was judged to be 25km^2 by D. Daly (GSI) in previous work. This estimate is thought to be rather large particularly to the north and east. The 1992-93 water budget for the Killeglan spring suggests that a maximum of 4.4km^2 is needed to fulfil the total spring output. However this figure could be doubled to 8.8km^2 since there is an equally large spring 20m from the main Killeglan source which is untapped and in its natural state (Photo 2).

8 VULNERABILITY ASSESSMENT

A vulnerability map was prepared for Daly's catchment and peripheral areas at the 1:25,000 scale by the GIS group at TCD, from Quinn's maps, using the "minimum standard vulnerability mapping" GSI Guidelines (Daly and Warren. 1994) since much of the area was only mapped at reconnaisance level, but with detailed aerial photography analysis. The vulnerability map appears at the back of this appendix (Figure 4).

The spring catchment at Killeglan is considered to be both highly and extremely vulnerable to pollution. The coefficient of variation in the year round electrical conductivity measurements was 12.6%.

The mapped vulnerabilities for this source's catchment area are presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low), that occur within the confines of the catchment.

The % values are: 50% Extreme
50% High.

9 POTENTIAL POLLUTION SOURCES

The area within the proposed source catchment area consists entirely of farmland, where livestock farming is the dominant activity. Farm yards, silage clamps and landspreading of animal wastes are the main threat to the source since the subsoils are thin, and karstic collapse features are common. Landspreading should be avoided over the underground routes of both traces since their flow has been proved to be extremely shallow.

The Co. Co. pumphouse and spring is clean, secure and well fenced off.

APPENDIX J

BELMONT GROUP SCHEME

1 SPRING DETAILS

GSI No.	: 1125NE W---	
Grid Ref.	: 13543 26225	
6" Sheet	: Galway	
Townland	: Belmont	
Elevation	: ~ 43m OD	
Depth to Rock at Spring	: < 3m	
Average Spring Discharge	: (i) Abstraction Rate	182m^3/d
	(ii) Spring Overflow Average:	128m^3/d
	(iii) TOTAL Spring Discharge(i+ii):	310m^3/d

2 SPRING LOCATION AND SITE DESCRIPTION

This group scheme spring is located 5km west of Miltown and 13km north-west of Tuam in a relatively isolated field. The source supplies 500 persons with water. Daily output is 185m^3/d which is pumped to a 182m^3 (40,000 gallon) reservoir tank (92m OD) on top of a steep ridge.

In reality the spring is a dug out well. It is 5m in diameter and is enclosed by an earth embankment. Two small pumps at about 0.5-1m depth below water level extract water from the dug out. Spring overflow, although rare, is via a narrow wavin pipe which has a diameter of 50cm. Any overflow water flows to a sink-hole/turlough, 400m west.

3 TOPOGRAPHY, SURFACE HYDROLOGY AND LAND USE

The spring is situated just west of an upland area (98m OD) where bedrock cored drumlins/ridges trend NW/SE (Photo 1). Drains are common in the depressions between the drumlins but there are few drains on the ridges since they are relatively free draining. Often turloughs and raised bogs occur in the inter-drumlin depressions. In winter the inter-drumlin/turlough areas are frequently flooded as the regional water-table rises.

At the meso scale the spring lies directly in the break of slope of a high relief limestone ridge at about 43m OD. The limestone ridge has a maximum height of 92m OD.

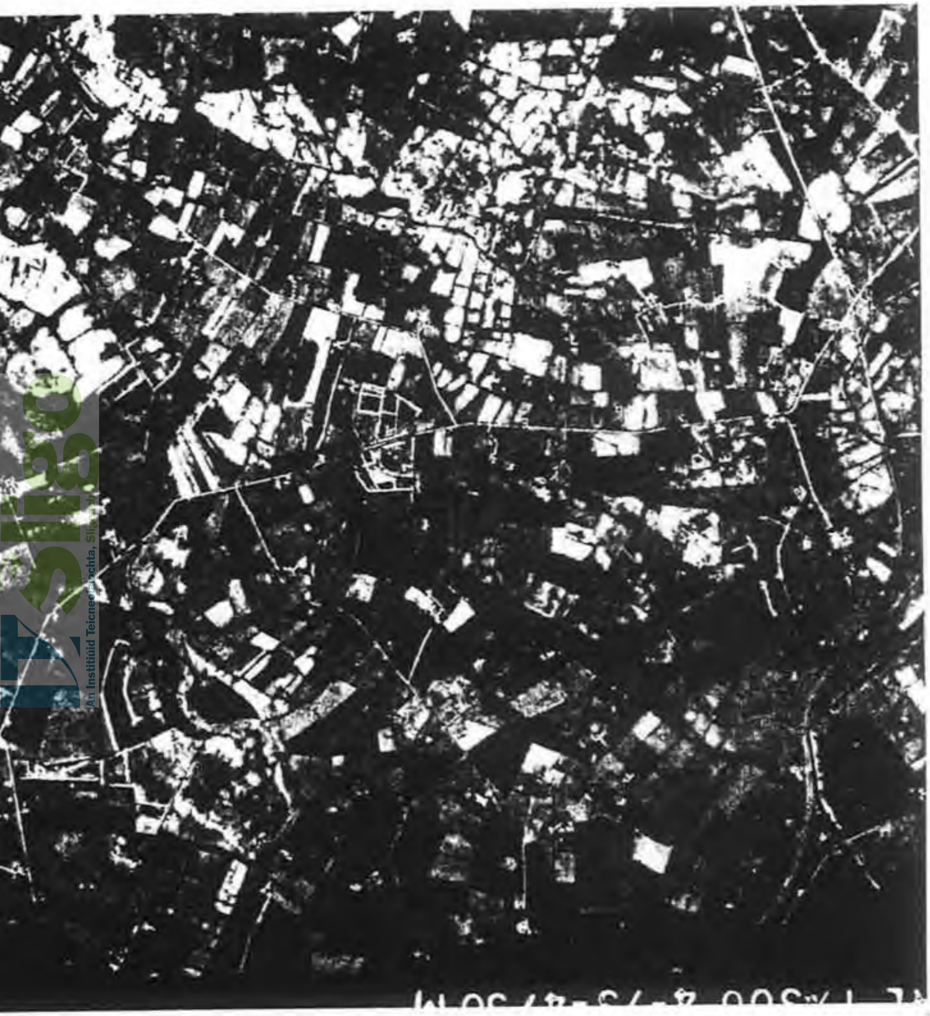


PHOTO 1
Aerial Photograph of the Belmont area

Land use in the area is livestock farming, both dairy and drystock.

4 GEOLOGY

4.1 Bedrock Geology

In general the area is underlain by Bank limestone which is a pale grey, unbedded but fossiliferous limestone.

As an aquifer the Bank limestone has locally productive zones particularly if the zone is faulted or dolomitised.

4.2 Subsoils Geology

A digitised copy of the 11/25NE 1:25,000 scale subsoil sheet for the area, mapped by this author appears at the back of Appendix G.

To the east of the spring (uphydraulic-gradient of the spring) the area is dominated by a clayey/silty lodgement till with sub-rounded limestone clasts up to 0.25m in diameter.

Fen peat/raised bog occurs in the depressions/turloughs between the drumlins.

At the spring itself, trial pits carried out for this study suggest that the subsoil is sandier nearer to rockhead with large limestone clasts.

4.3 Depth-to-rock

Trial pits carried out by this author near the spring and within a 1km grid indicate that depth-to-bedrock is <3m.

The limestone ridge immediately upslope of the spring shows considerable outcrop.

5 METEOROLOGY

Daily rainfall and evaporation data for the October 1992 to September 1993 period, were taken directly from the Claremorris synoptical weather station (71m OD) which is 12km north of the spring. It is the nearest station with information available for this period. Rainfall was 1245mm and PE was 365.5mm. AE for the area was estimated at 365.5mm, the same value as PE, since there were a relatively high number of rain days in an area where the soils must have been consistently at field capacity, in an unusual rainfall regime, when it was in excess of PE each month. Using these figures potential recharge was taken to be approximately 879.5mm for the October 1992 to September 1993 field season (see Figure 1).

These calculations are summarised below:

Precipitation	1245mm
P.E.	365.5mm
Estimated A.E. (100% P.E.)	365.5mm
Potential recharge	879.5mm

6 WATER BALANCE

As the subsoils and hydrogeological mapping programme progressed in the spring area an understanding of the size of the spring catchment was needed during the October 1992 to September 1993 field season, since detailed reconnaissance mapping for vulnerability studies was to occur within the spring recharge zone. It was decided that, as an initial step, the spring catchment area would be *estimated* by a water balance, the principles which have been discussed in Chapter 3.

The recharge area required to supply the October 1992 to September 1993 discharge levels of this spring was calculated by:

$$\left(\begin{array}{c} \textbf{Outflows} \\ \text{Total Spring Output} \\ + \text{Abstraction} \\ + \text{Flow to other} \\ \text{aquifers} \end{array} \right) \Big/ \left(\begin{array}{c} \textbf{Inflows} \\ \text{Direct Recharge} \\ + \text{Indirect Recharge} \\ + \text{Flow from other aquifers} \\ + \text{Urban Recharge} \end{array} \right) = \textbf{Catchment Area}$$

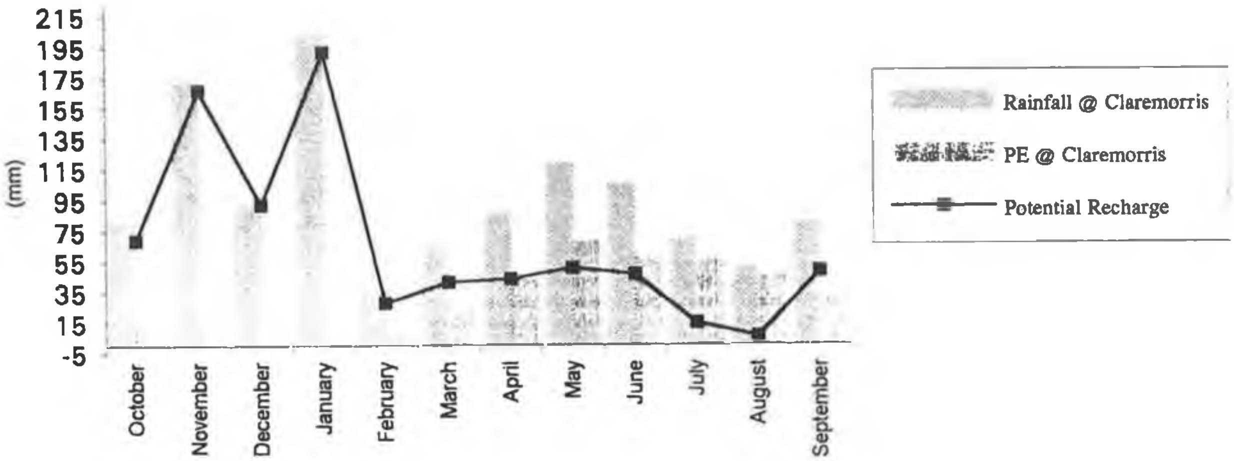
Outflow Calculations

- Total Spring Output
- Abstraction
- Flow to other aquifers

Total Spring Output

Overflow from the spring and total pumping rates at the pumphouse were needed to find the total spring output. The dimensions of the overflow wavin pipe were used to determine the spring overflow. It was found that overflow through the pipe averaged $128m^3/d$, although occasionally the overflow flowed over the pipe. Total pumping rates at the spring were $182m^3/d$.

FIGURE 1
1992-93 Meteorology for Belmont with calculated Potential Recharge



Therefore, the total spring output for Belmont is $310m^3/d$ $\Rightarrow 310m^3/d$

Abstraction

Disregarded, see Chapter 3.

Flow to other aquifers

Disregarded, see Chapter 3.

Total outflows from the Belmont spring $\Rightarrow 310m^3/d$

Inflow Calculations

- Direct Recharge
- Indirect Recharge
- Flow from other aquifers
- Urban Recharge

Direct Recharge

Generally there are moderate permeability subsoils in the area with few drainage features, except between drumlins. There is also limestone outcrop near to the spring. Estimating runoff to be in the order of 20% of potential recharge, direct/actual recharge to the aquifer was taken to be 704mm.

$\Rightarrow 1.93 \times 10^{-3}$ m/d

Indirect recharge

Nil

Flow from other aquifers

See Chapter 3. —

Total inflows to the aquifer at Belmont $\Rightarrow 1.93 \times 10^{-3}$ m/d

Estimated Catchment Area

Outflows/Inflows = Catchment Area [(iv), from Chapter 3]

$$\frac{\text{Total outflows from the spring}}{\text{Total inflows to the aquifer}} = \frac{310m^3/d}{1.93 \times 10^{-3}\ m/d} = 0.16km^2$$

7 HYDROGEOLOGY

7.1 Groundwater levels

Groundwater data is sparse for the Belmont area. Two turloughs lie immediately SW of the spring. Rathbaun turlough is 1.5km distance and a smaller one is only 400m away.

7.2 Hydrogeological regime

The movement of regional groundwater in this area is east to west under hydraulic gradients of 0.8 - 1.75m/km (Drew and Daly 1994).

At Liskeevy Bridge 3.7km east of Belmont spring, the River Clare is influent. It is presumed that the influent zone corresponds to a zone of very high permeability in the underlying aquifer (Drew and Daly *op. cit.*). Discharge of this groundwater is understood to occur at springs SW of Liskeevy Bridge in the townland of Ardour (Millburn), 7km SW of the influent zone and 4.3km SW of the Belmont source.

7.3 Physical structure of the spring catchment area

In summary the Belmont source is a dug out hole which sits at the foot of a Bank limestone scarp where topography intersects the shallow flow of groundwater. This shallow water-table is mirrored at the two turloughs previously described which are only a short distance from the spring. It is believed that a zone of high permeability fissures runs east/west through the Belmont area from the River Clare. The dug out hole at Belmont spring is thought to be a 'window' into an underground drainage system/conduit system.

7.4 Physical Demarcation of the Catchment Area

It is clear that the physical catchment area of Belmont spring is potentially very large. It is probable that the easterly catchment boundary is within the vicinity of the River Clare.

However, the estimated catchment area, determined by the water balance technique, was calculated to be only 0.16km² since the two pumps and overflow only extract a small amount of water at a shallow level from a deeper underground channel.

As a result it was not possible to delineate the catchment area of this source.

8 VULNERABILITY ASSESSMENT

The area immediately around Belmont source (1km^2) is considered to be extremely vulnerable to pollution since the subsoils here are < 3m deep and there is much outcrop. The coefficient of variation in the year round electrical conductivity measurements at the spring was 12.6%.

The mapped vulnerability for the 1km^2 grid around the source is presented as a percentage (%) vulnerability in order to indicate the areal extent of the four main classes of vulnerability (Extreme, High, Moderate, and Low).

The % value is: 100% Extreme

9 POTENTIAL POLLUTION SOURCES

The majority of the mapped area consists of farmland, where livestock farming is the dominant activity. Farm yards, silage clamps and landspreading of animal wastes are the main threat to the source since bedrock is shallo and so is the water-table.

The pumphouse and source are dirty and poorly fenced off.

APPENDIX K

ROCKINGHAM PUBLIC SUPPLY

1 SPRING DETAILS

GSI No. : 17/29NW W--
Grid Ref. : 18498 30278
6" Sheet : Roscommon 06
Elevation : 48m OD
Depth to Rock at Spring : 0 - 0.5m
TOTAL Spring and borehole discharge: 13,100m^3/d

2 SPRING LOCATION AND SITE DESCRIPTION

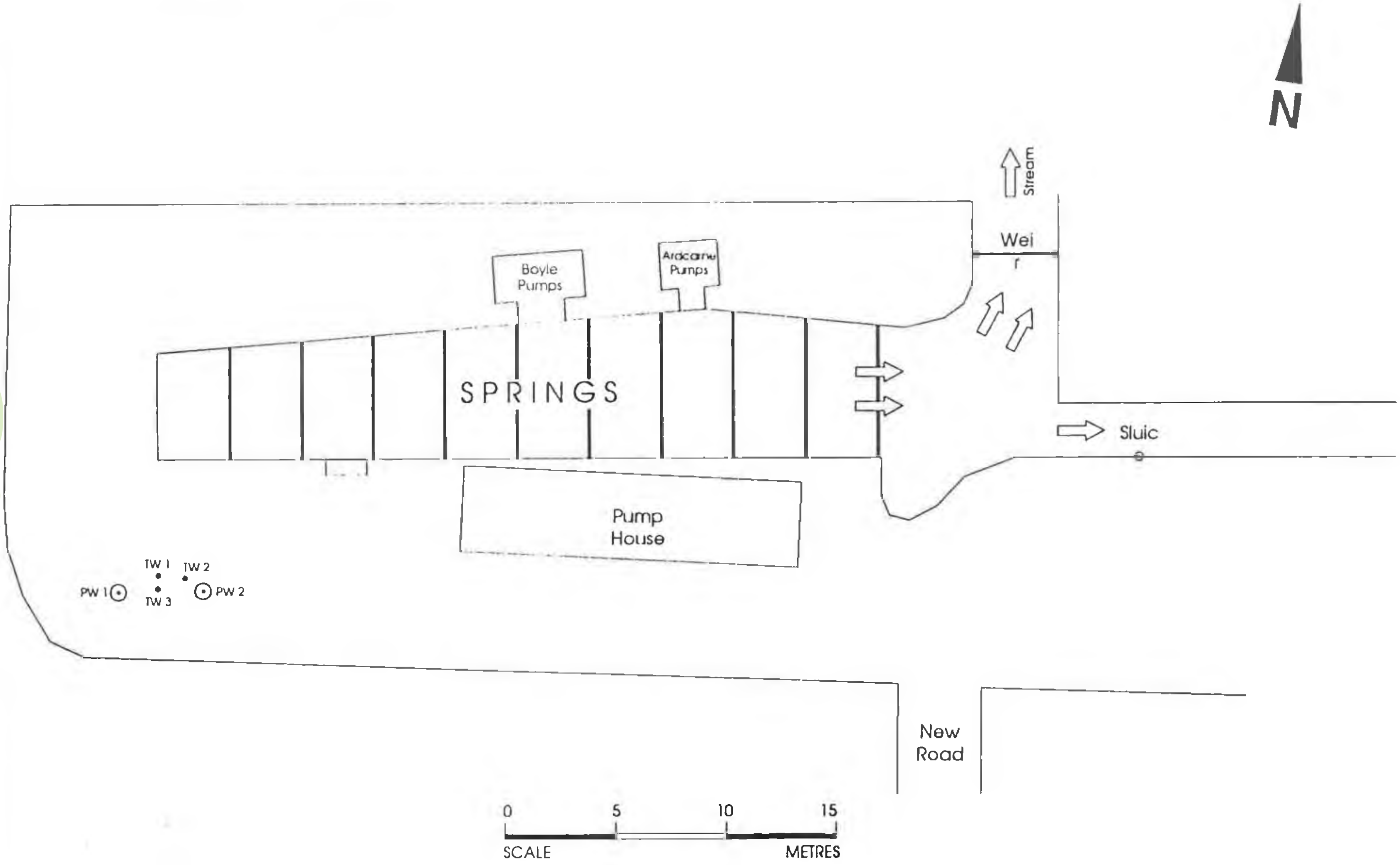
This public supply source is located 5km ENE of Boyle within the Lough Key forest park. Lough Key lies 400m north of the source (Photo 1).

The Rockingham source is a public supply that has a complicated hydrogeology. It is both spring and borehole fed. Much work has been done on the supply over the last nine years by K. Longworth (1987) and K. Cullen and Co. (1990-91). H. Price and P. Johnston carried out further full investigations on the source over the same 1992/93 period as this study, as part of their STRIDE contract.

Only certain sections of the source report appear below. Details on the hydrogeology and catchment of the springs/borehole occur in Price (1995). The reader is asked to study the texts mentioned above for a comprehensive description of the Rockingham public supply.

The Rockingham public supply consists of several springs that feed a sump and two production wells (Figures 1 and 2). For most of the year there is surplus discharge of groundwater from the springs, but in the late summers this flow usually stops. Two production wells which lie 5m SW of the springs were completed by K. Cullen and Co. in 1990. They provide the extra depth that is needed to extract groundwater in the summer when the water-table is lower. Inflow occurs between 7.6-12.5m below ground level at fissures in limestone, and static water level is 4m below ground level. A log of Production Well 1 appears in Figure 3.

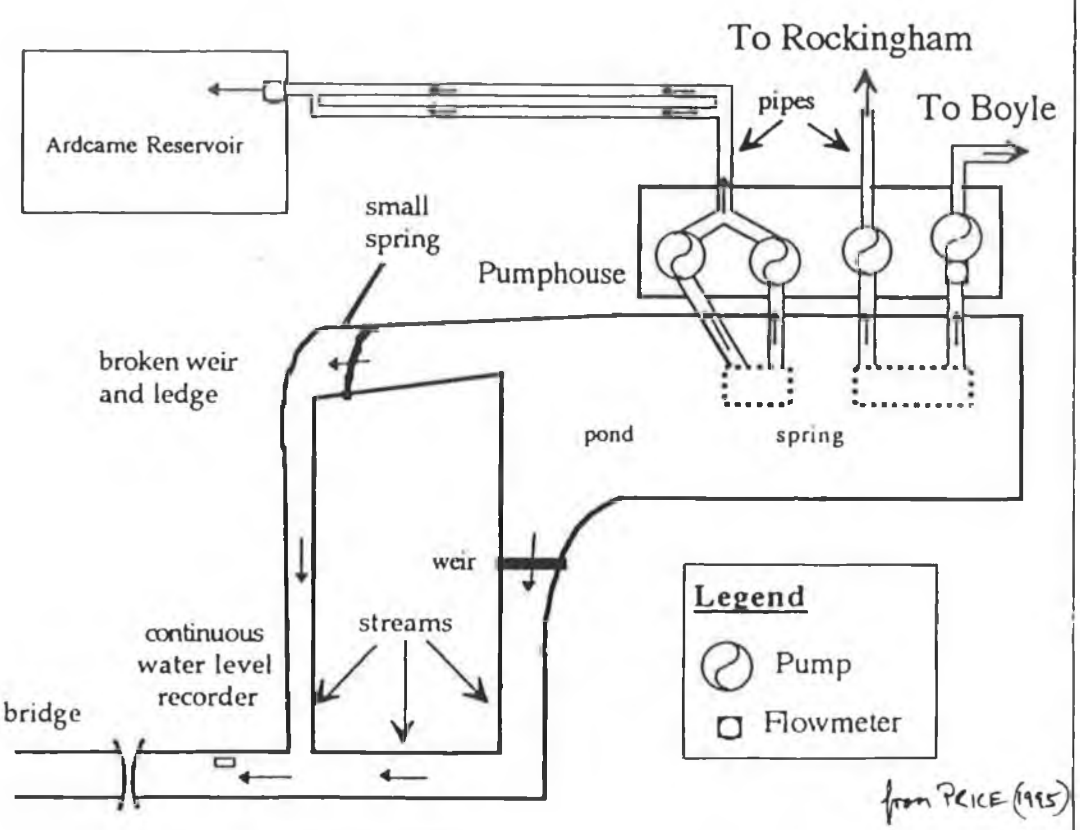
PHOTO 1
Aerial Photograph of Lough Key Forest Park and Rockingham springs



SKETCH MAP OF ROCKINGHAM SITE - HYDROGEOLOGICAL STUDY *from KT CULLEN+CO.*

FIGURE 1

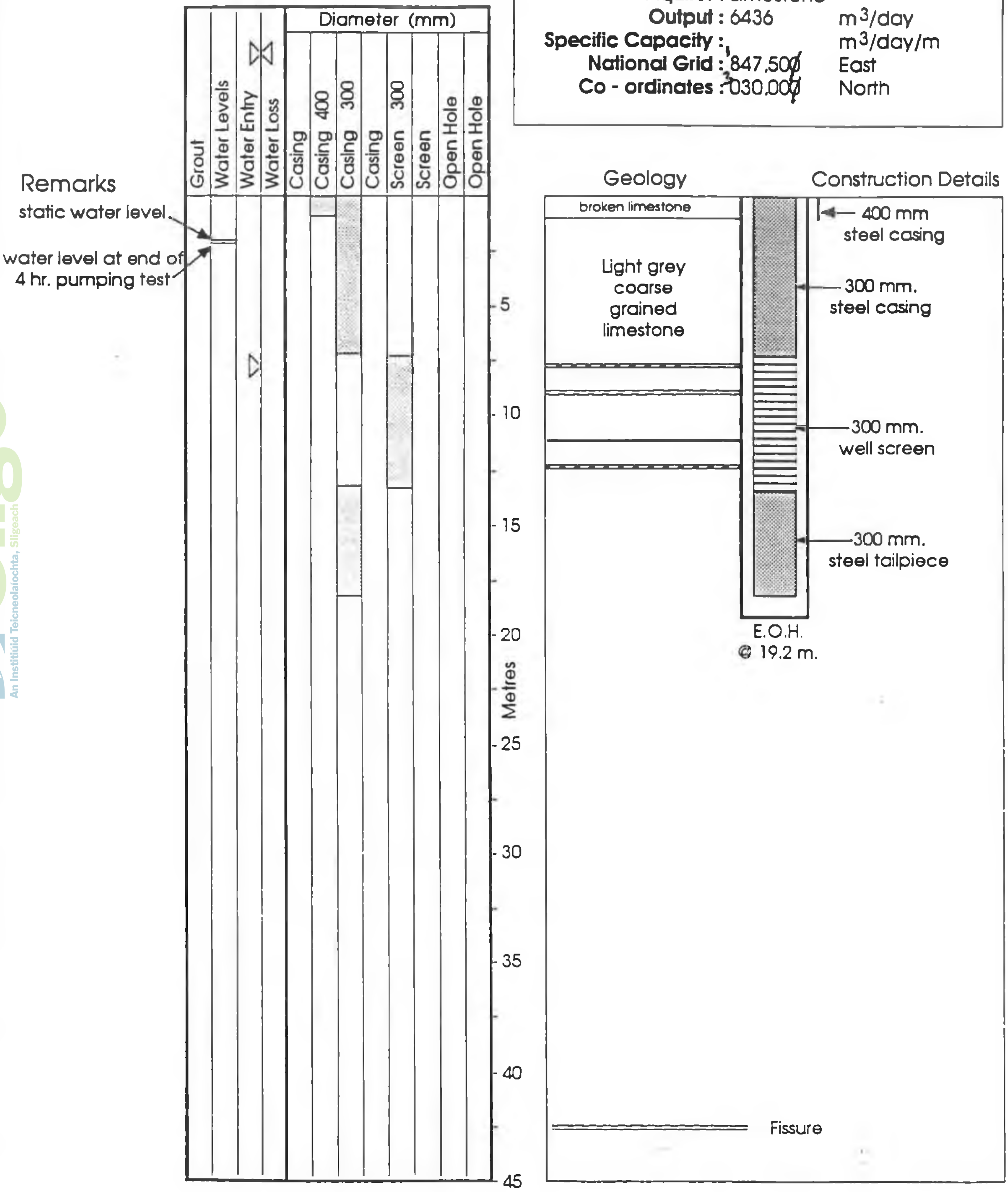
FIGURE 2 Schematic Diagram of Rockingham Water Supply (Plan)



Completed Well Design

Production Well
PW No. 1

Client : Roscommon Co. Co.
Project : Boyle RWSS
Location : Rockingham
County : Roscommon
Date : November 1990
Driller : Dunnes Water Services Ltd.
Aquifer : Limestone
Output : 6436 m^3/day
Specific Capacity : m^3/day/m
National Grid : 847,500 East
Co - ordinates : 030,000 North



K.T.Cullen & Co. Ltd.
Hydrogeological & Environmental Consultants

FIGURE 3

3 GEOLOGY

3.1 Bedrock Geology

The dominant rock type in the area is the Ballyshannon Limestone Formation which is pure and karstified. It covers approximately 50% of Longworth's original study area (1987) and outcrops extensively. The Rockingham member of the Ballyshannon Formation provides the water for the Rockingham springs.

3.2 Subsoils Geology

A copy of the 1:25,000 subsoil field sheet for the area, appears at the back of this report. It is dominantly the digitised version of Longworth's original field sheets. Some updating was carried out by this author. The area within 1km of the source consists of outcrop and only a thin patchy cover of clayey/silty tills with sub-angular limestone clasts.

3.4 Depth-to-rock

Within the spring enclosure depth-to-bedrock is 0.5-0m below surface; further details may be found in the reports mentioned in Section 2. The drumlins are believed to be bedrock cored.

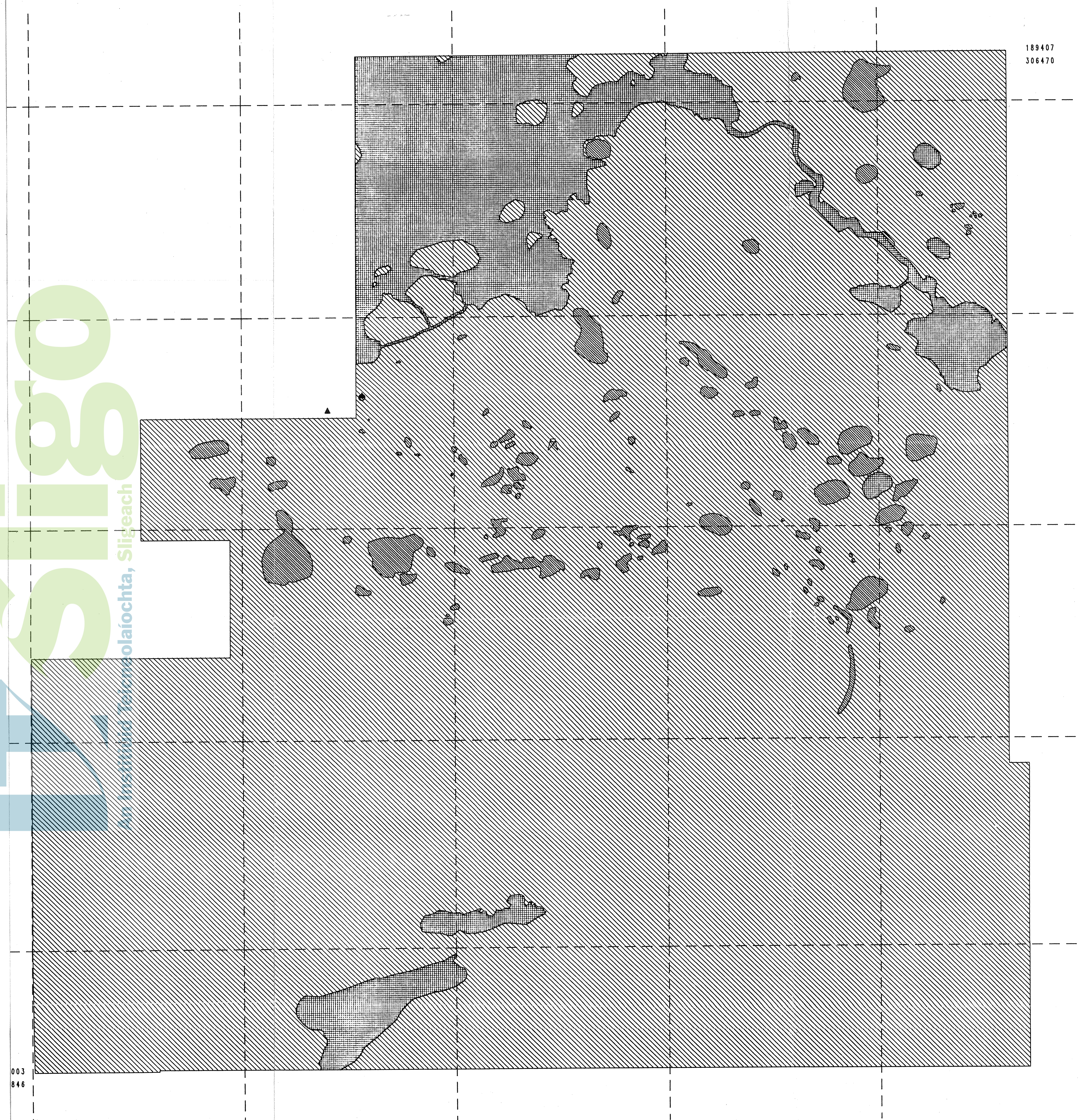
4 Physical Demarcation of the Catchment Area

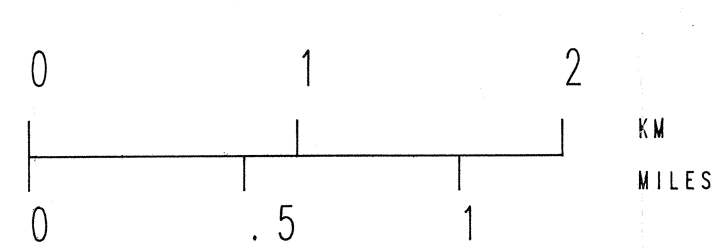
The catchment boundaries for this source are detailed in Price (1995). At time of writing the catchment area for the springs was believed to be greater than $8km^2$.

5 VULNERABILITY ASSESSMENT

A vulnerability map (Figure 4) was prepared for the area at the 1:25,000 scale by the GIS group at TCD using mainly the "minimum standard vulnerability mapping" guidelines, since much of the area was only mapped at reconnaisance level, without trial pitting. This map appears at the back of this report.

The area around Rockingham spring (and proposed catchment) is considered to be extremely vulnerable to pollution. The limited subsoil extent, causes groundwater to be extremely vulnerable to pollution since it is generally less than 3m thick. Outcrop is common in many parts of the catchment. The coefficient of variation in the year round electrical conductivity measurements was relatively high at 17.9% suggesting short residence times for recharge.





ROCKINGHAM

FIGURE 4

GROUNDWATER VULNERABILITY

- EXTREME VULNERABILITY
- PROBABLY EXTREME VULNERABILITY
- LAKE

- SOURCE

Extreme Vulnerability

- Losing/Sinking Stream
- Stream Network Above Losing Reach
- Swallow Hole

Based on the Catchment Subsoils (Quaternary Geology) map and Geological Survey of Ireland vulnerability guidelines.

Generated using GIS techniques by S Pipes(3), with technical support from J Gillmor(3), directed by C Coxon(3), P Mills(3) and K Rybaczuk(3).

(3) Trinity College Dublin

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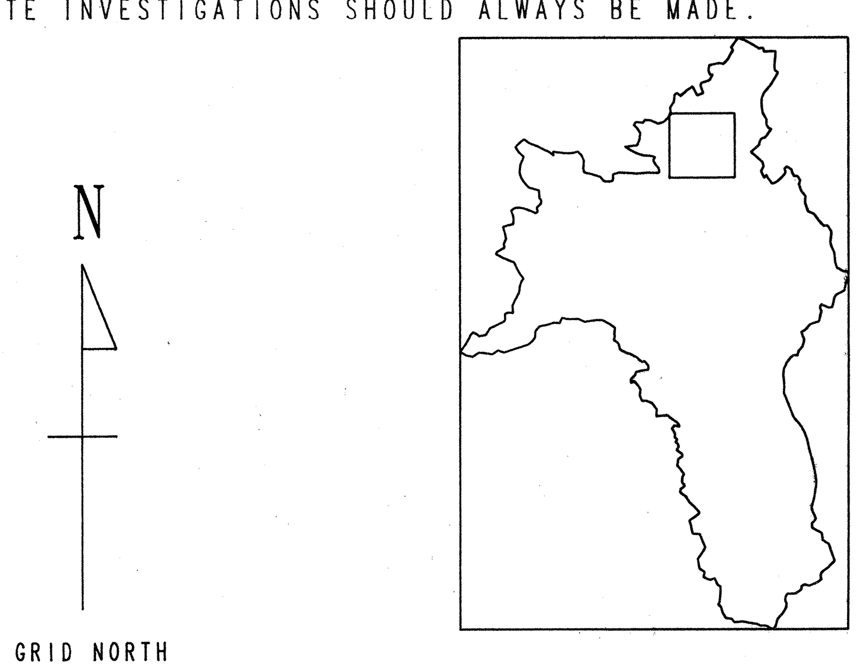
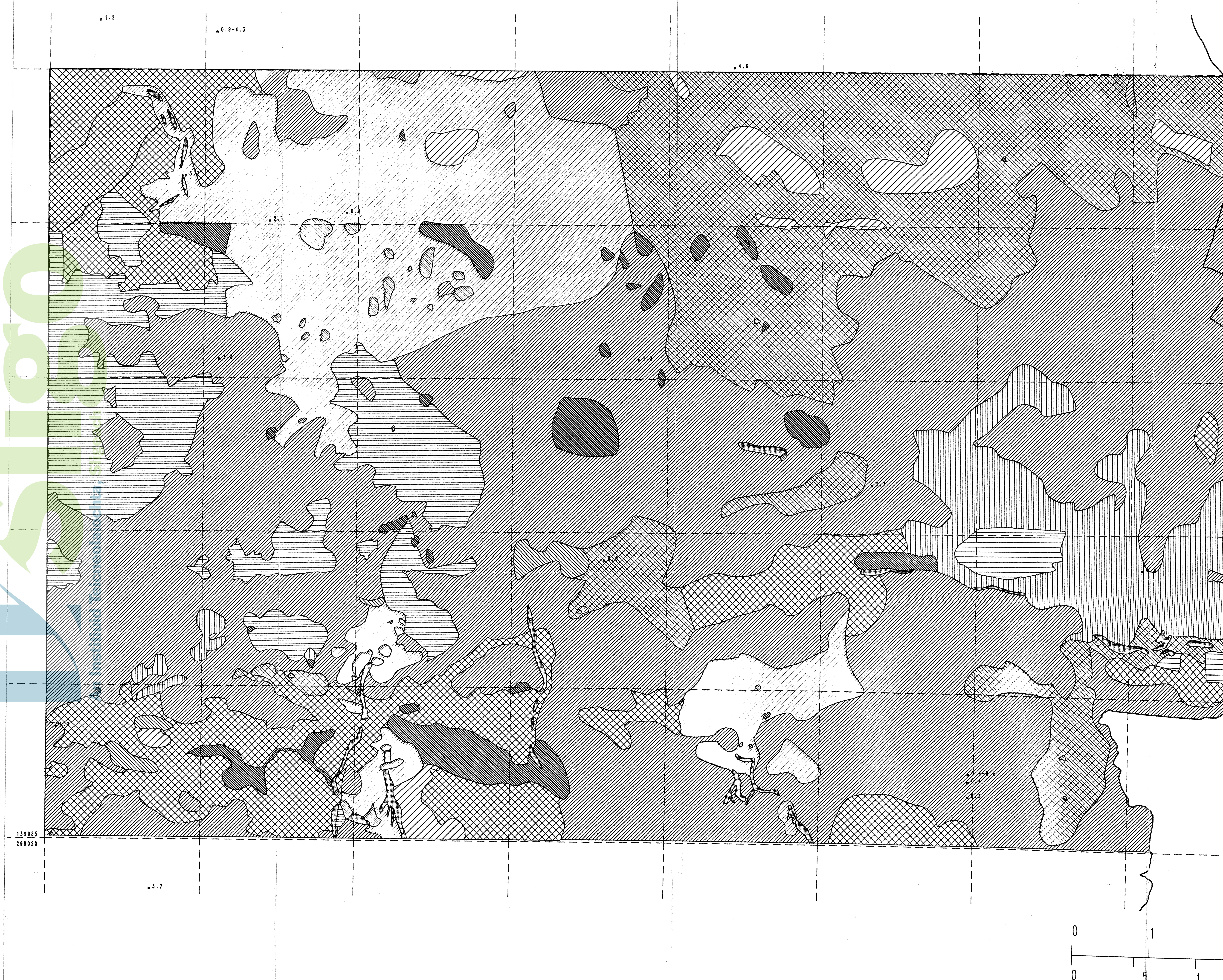


KILKELLY

FIGURE 1 b

SUBSOILS (QUATERNARY GEOLOGY)



- ALLUVIUM
- RAISED BOG
- RAISED BOG INTACT
- BLANKET BOG
- GRAVELLY TILL
- CLAYEY TILL
- SANDY TILL
- UNDIFFERENTIATED TILL
- SAND & GRAVEL
- ESKER (SAND & GRAVEL)
- GRAVEL PIT
- BEDROCK NEAR SURFACE
- BEDROCK OUTCROP
- TURLOUGH

- SOURCE
- DRUMLIN
- Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)

- Accuracy 10 - 100 M
- Accuracy 100 - 500 M
- Accuracy 500 - 2000 M

Mapped and compiled by M. Doak (2).
Supervised by by W P Warren (1), and D. Daly (1).
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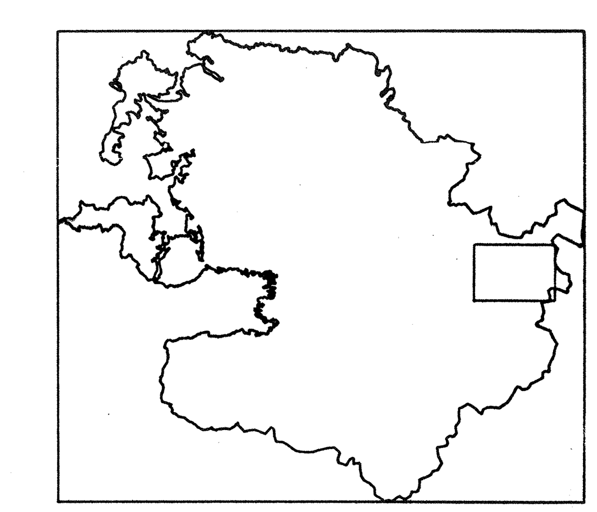
N

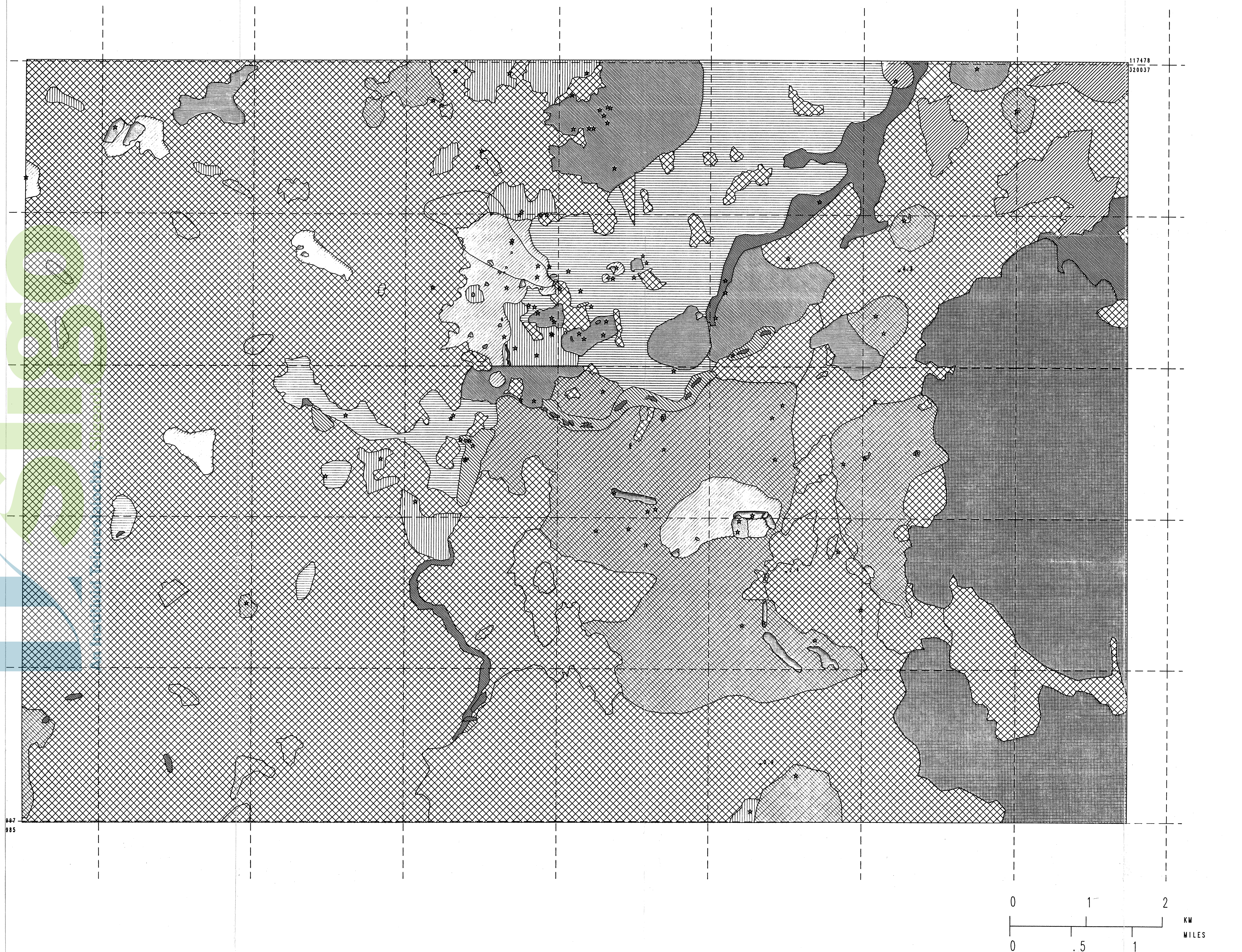
GRID NORTH



CROSSMOLINA

FIGURE

SUBSOILS (QUATERNARY GEOLOG



- ALLUVIUM
- RAISED BOG
- RAISED BOG INTACT
- BLANKET BOG
- STONY TILL
- GRAVELLY TILL
- CLAYEY TILL
- SILTY TILL
- SANDY TILL
- UNDIFFERENTIATED TILL
- SAND & GRAVEL
- ESKER (SAND & GRAVEL)
- GRAVEL PIT
- BEDROCK NEAR SURFACE
- BEDROCK OUTCROP
- LAKE

- SOURCE

- DRUMLIN
- Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)

- Accuracy 10 - 100 M
- Accuracy 100 - 500 M
- Accuracy 500 - 2000 M

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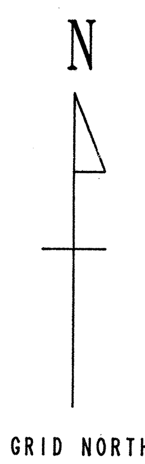
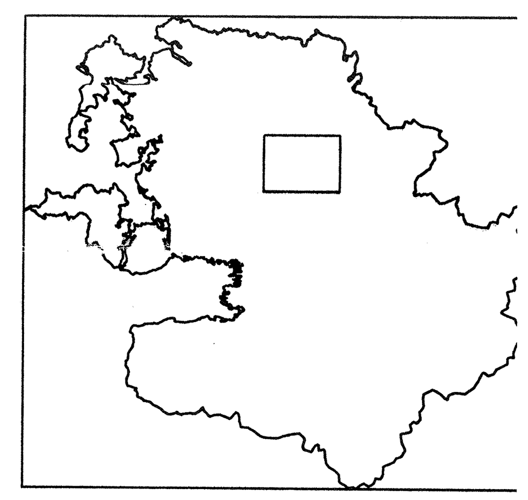
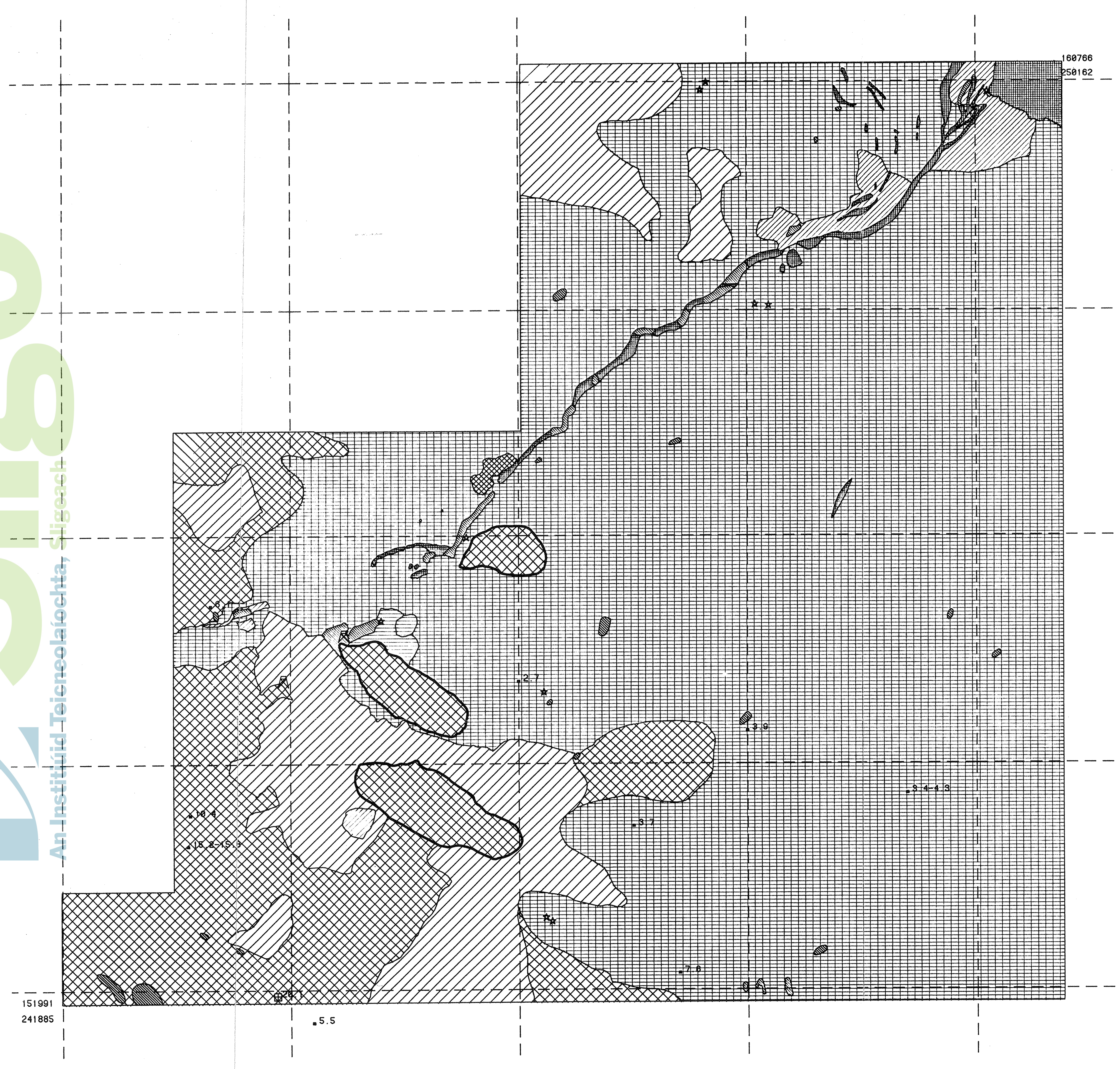




BARNADERG-MID. GALWAY

SUBSOILS (QUATERNARY GEOLOGY)

FIGURE 2 b



- RAISED BOG
- TILL WITH GRAVEL
- CLAYEY TILL
- SILTY TILL
- UNDIFFERENTIATED TILL
- SAND & GRAVEL
- ESKER (SAND & GRAVEL)
- GRAVEL PIT
- BEDROCK OUTCROP
- TURLOUGH
- LAKE

- SOURCE
- DRUMLIN
- Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)

- Accuracy 10 - 100 M
- Accuracy 100 - 500 M
- Accuracy 500 - 2000 M

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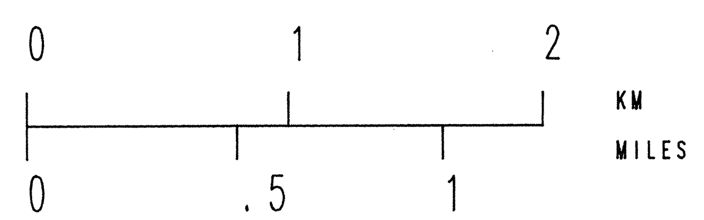

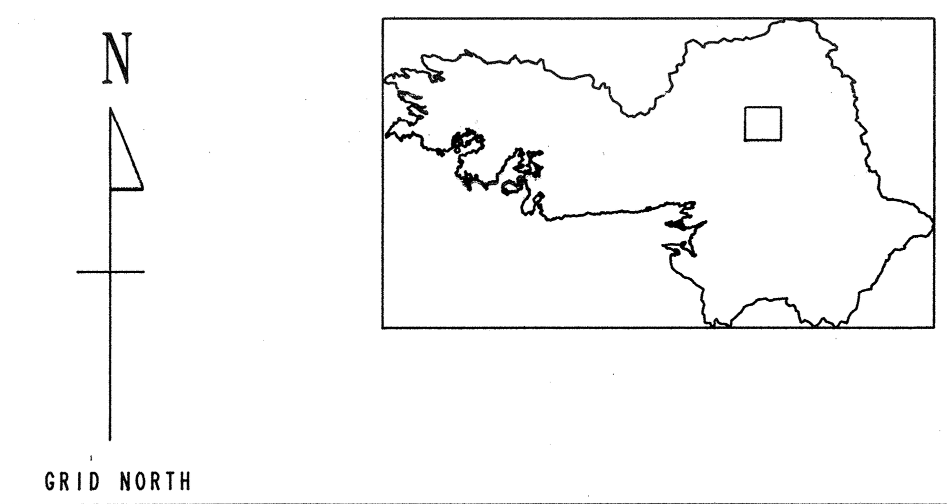

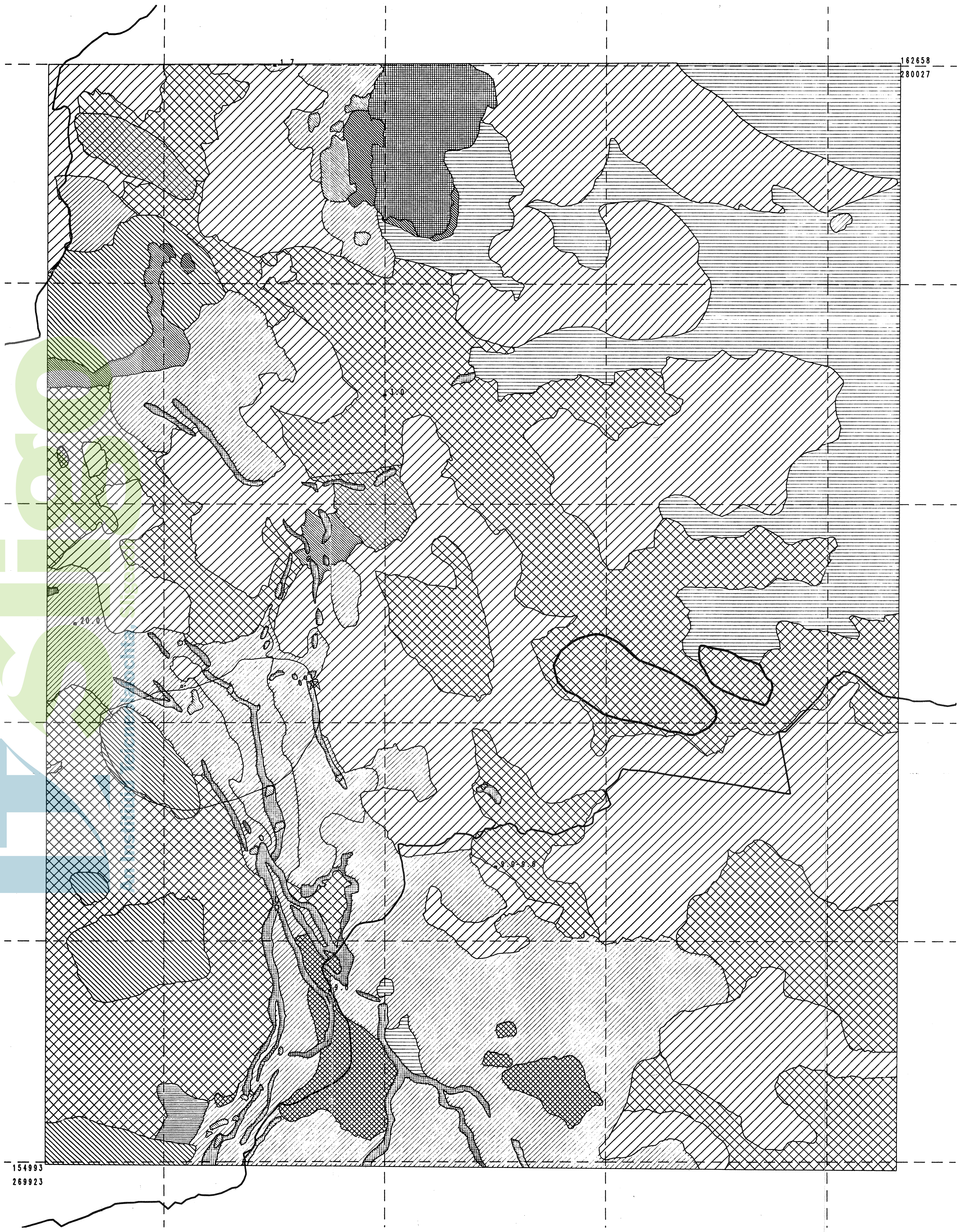

BALLINLOUGH

FIGURE 2 b

SUBSOILS (QUATERNARY GEOLOGY)

- ALLUVIUM
- RAISED BOG
- STONY TILL
- GRAVELLY TILL
- CLAYEY TILL
- SILTY TILL
- UNDIFFERENTIATED TILL
- SAND & GRAVEL
- ESKER (SAND & GRAVEL)
- GRAVEL PIT
- BEDROCK NEAR SURFACE
- BEDROCK OUTCROP
- TURLOUGH
- LAKE

- SOURCE
- DRUMLIN
- Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)

- Accuracy 10 - 100 M
- Accuracy 100 - 500 M
- Accuracy 500 - 2000 M

0 1 2 KM

0 .5 1 MILES

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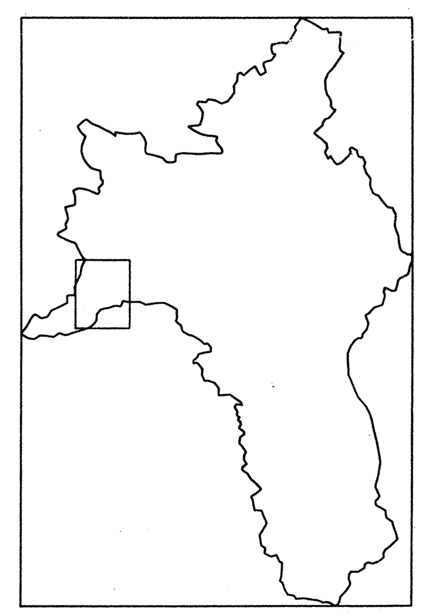
N

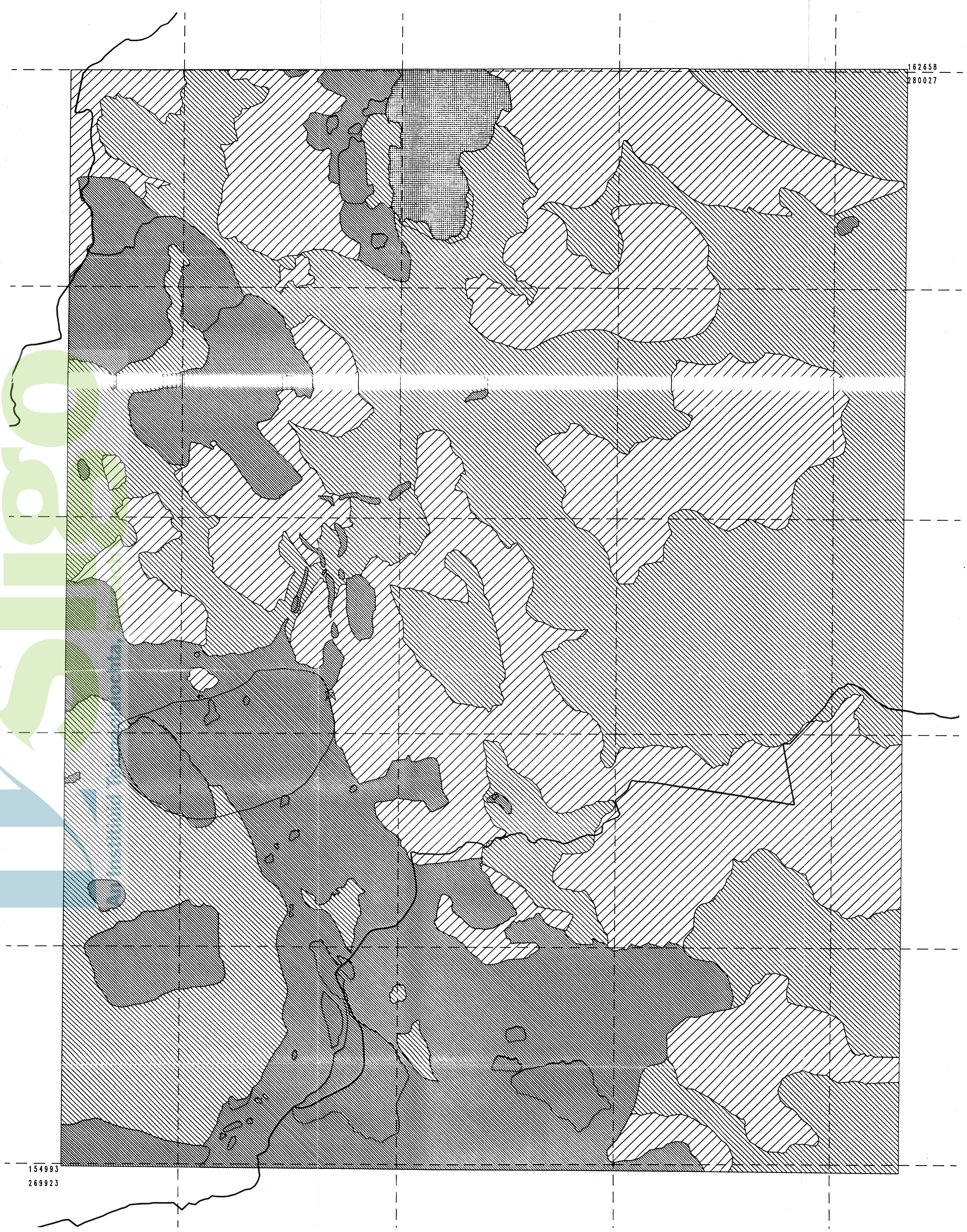
GRID NORTH



BALLINLOUGH

FIGURE 7

GROUNDWATER VULNERABILITY

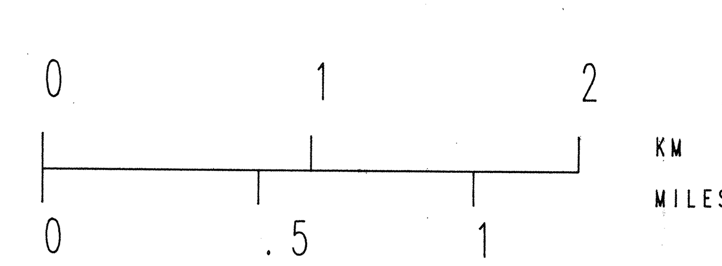


- EXTREME VULNERABILITY
- PROBABLY EXTREME VULNERABILITY
- HIGH VULNERABILITY
- PROBABLY HIGH VULNERABILITY
- PROBABLY MODERATE VULNERABILITY
- LAKE

- SOURCE

Extreme Vulnerability

- Losing/Sinking Stream
- Stream Network Above Losing Reach
- Swallow Hole



Based on the Catchment Subsoils (Quaternary Geology) map and Geological Survey of Ireland vulnerability guidelines.

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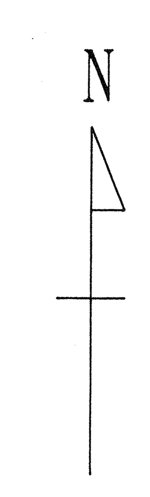
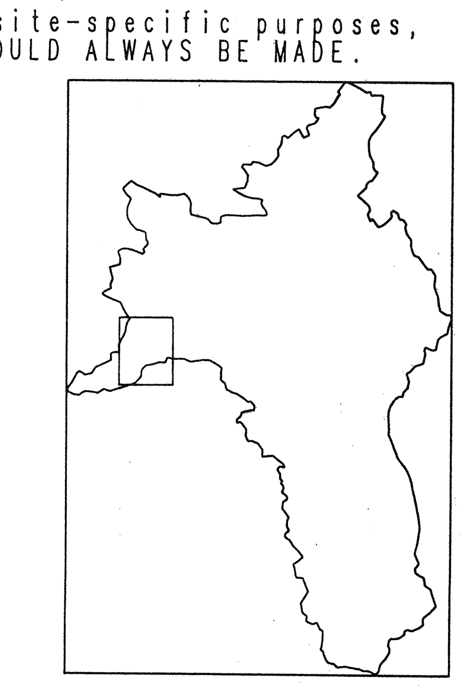


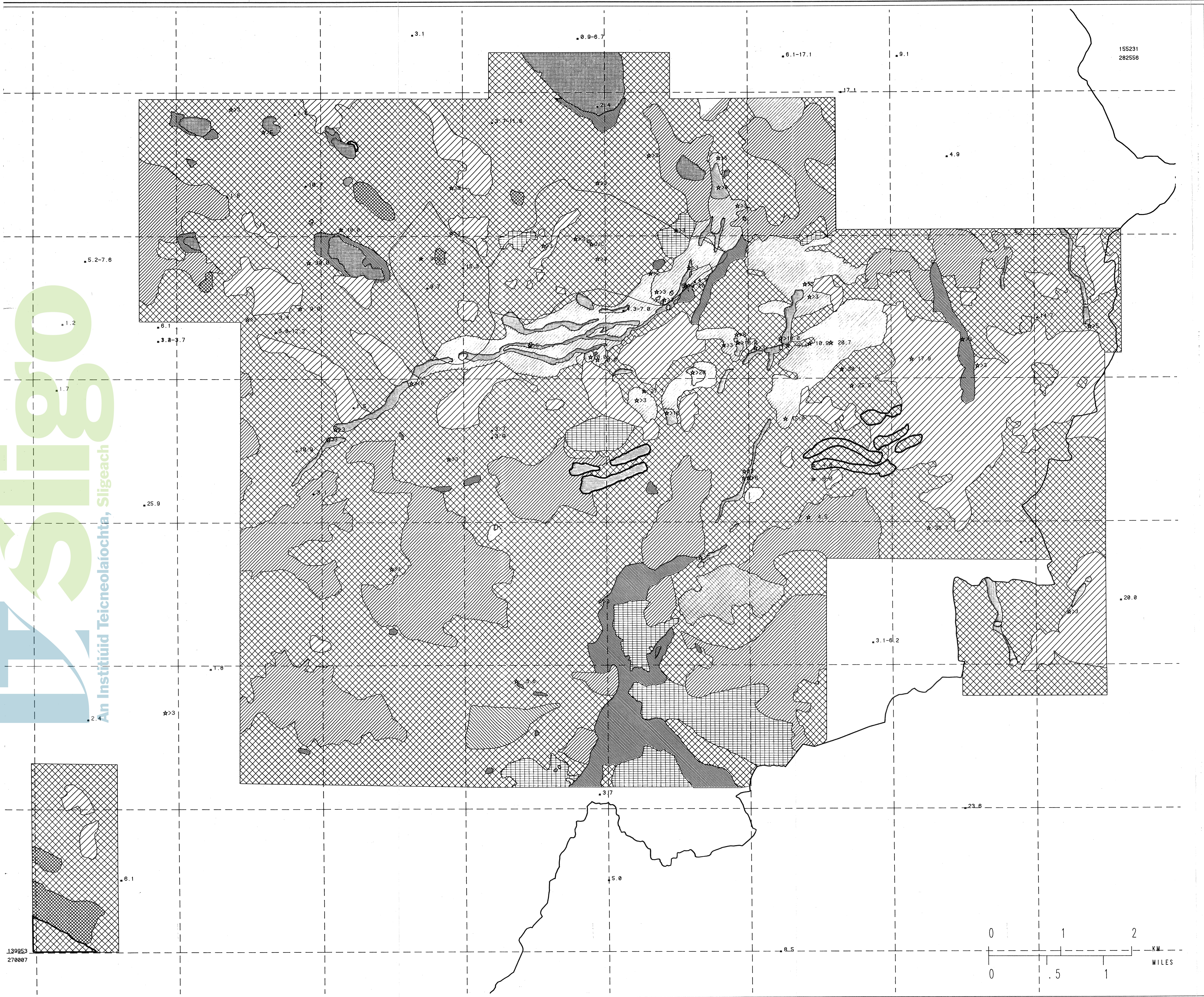


m024614

BALLYHAUNIS

FIGURE 3 b

SUBSOILS (QUATERNARY GEOLOGY)



- ALLUVIUM
- RAISED BOG
- RAISED BOG INTACT
- STONY TILL
- GRAVELLY TILL
- TILL WITH GRAVEL
- UNDIFFERENTIATED TILL
- SAND & GRAVEL
- ESKER (SAND & GRAVEL)
- GRAVEL PIT
- BEDROCK NEAR SURFACE
- BEDROCK OUTCROP
- TURLOUGH
- LAKE

- SOURCE
- DRUMLIN
- Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)

- Accuracy 10 - 100 M
- Accuracy 100 - 500 M
- Accuracy 500 - 2000 M

Mapped and compiled by M. Doak (2).
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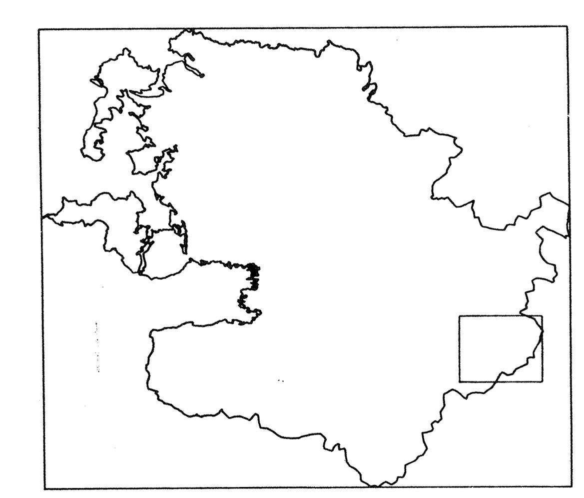
N

GRID NORTH

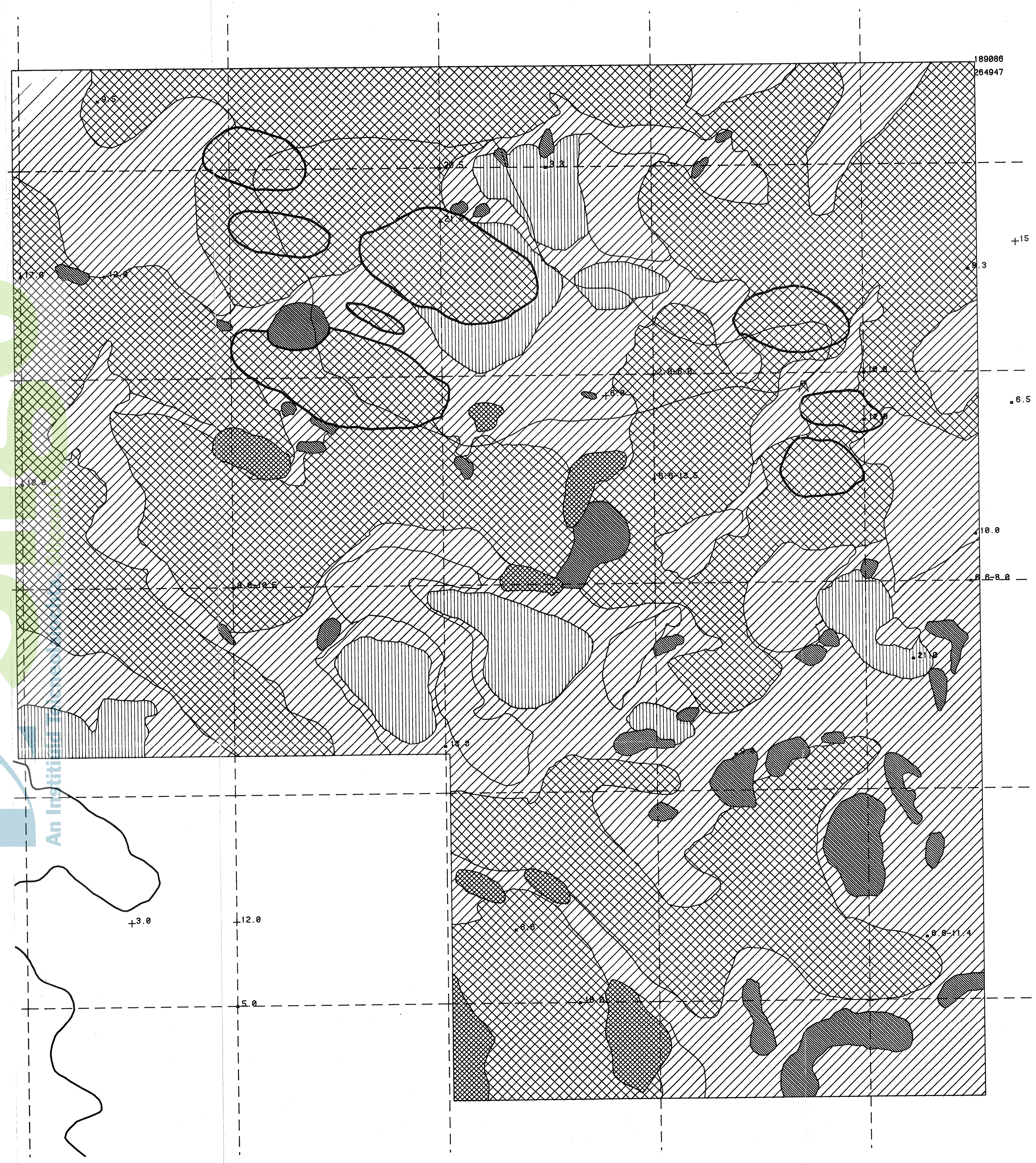


m027617

BALLINAGARD

FIGURE 1 b

SUBSOILS (QUATERNARY GEOLOGY)



- RAISED BOG
- SANDY TILL
- SHALLOW TILL
- UNDIFFERENTIATED TILL
- BEDROCK OUTCROP
- TURLOUGH

- SOURCE
- DRUMLIN
- Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)

- Accuracy 10 - 100 M
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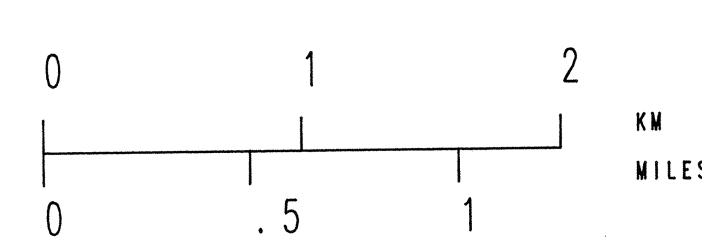

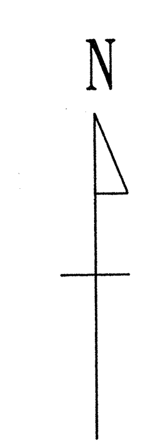

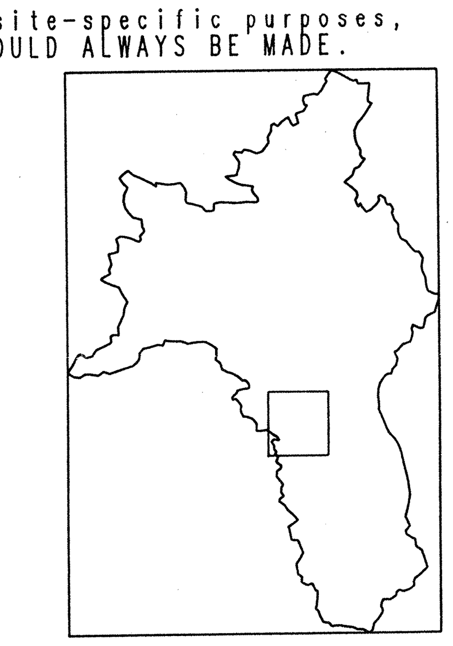

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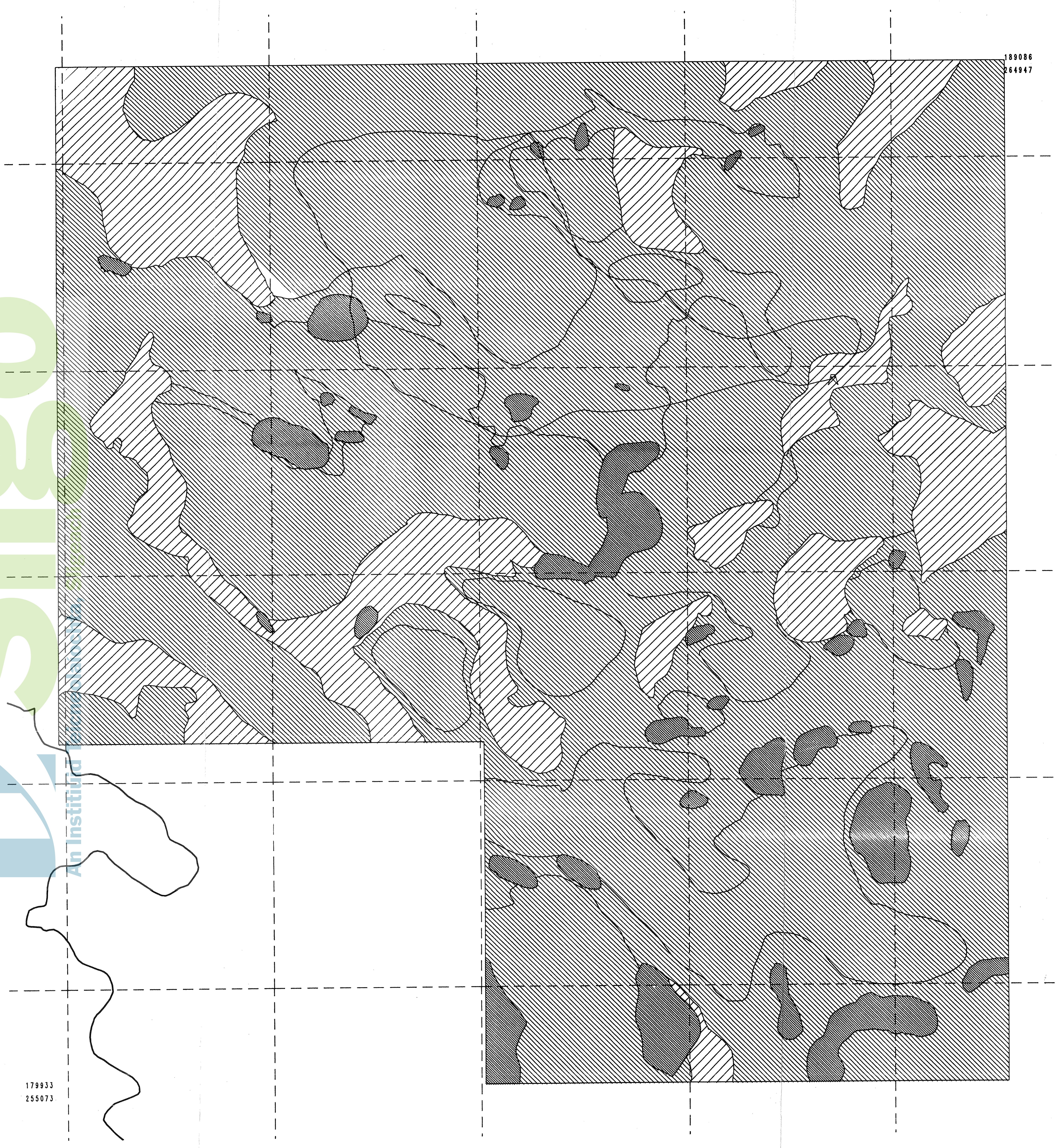
BALLINAGARD

FIGURE 4

GROUNDWATER VULNERABILITY



- EXTREME VULNERABILITY
- PROBABLY HIGH VULNERABILITY
- PROBABLY MODERATE VULNERABILITY

- SOURCE

Extreme Vulnerability

- Losing/Sinking Stream
- Stream Network Above Losing Reach
- Swallow Hole

Based on the Catchment Subsoils (Quaternary Geology) map and Geological Survey of Ireland vulnerability guidelines.

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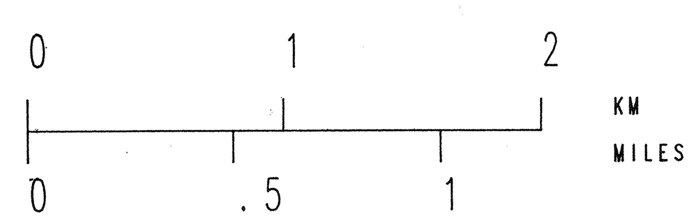

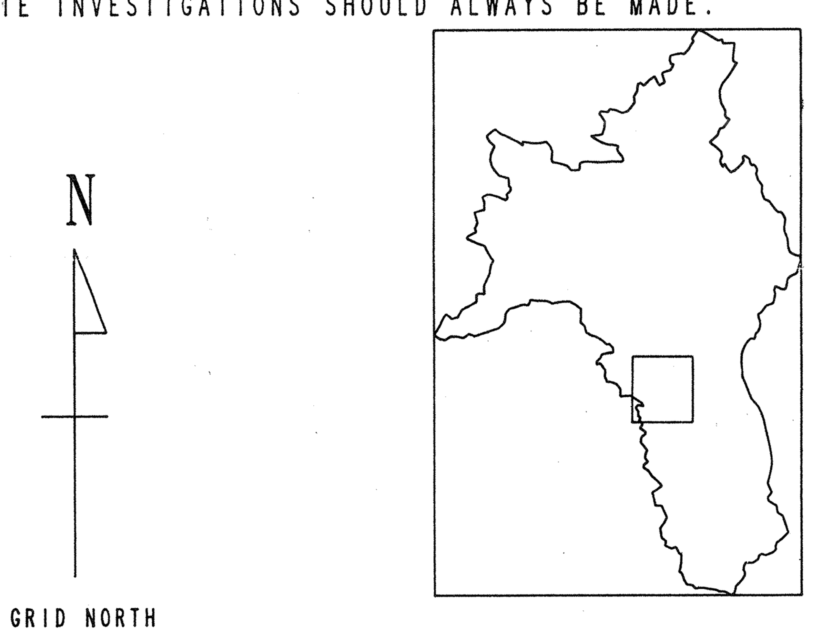

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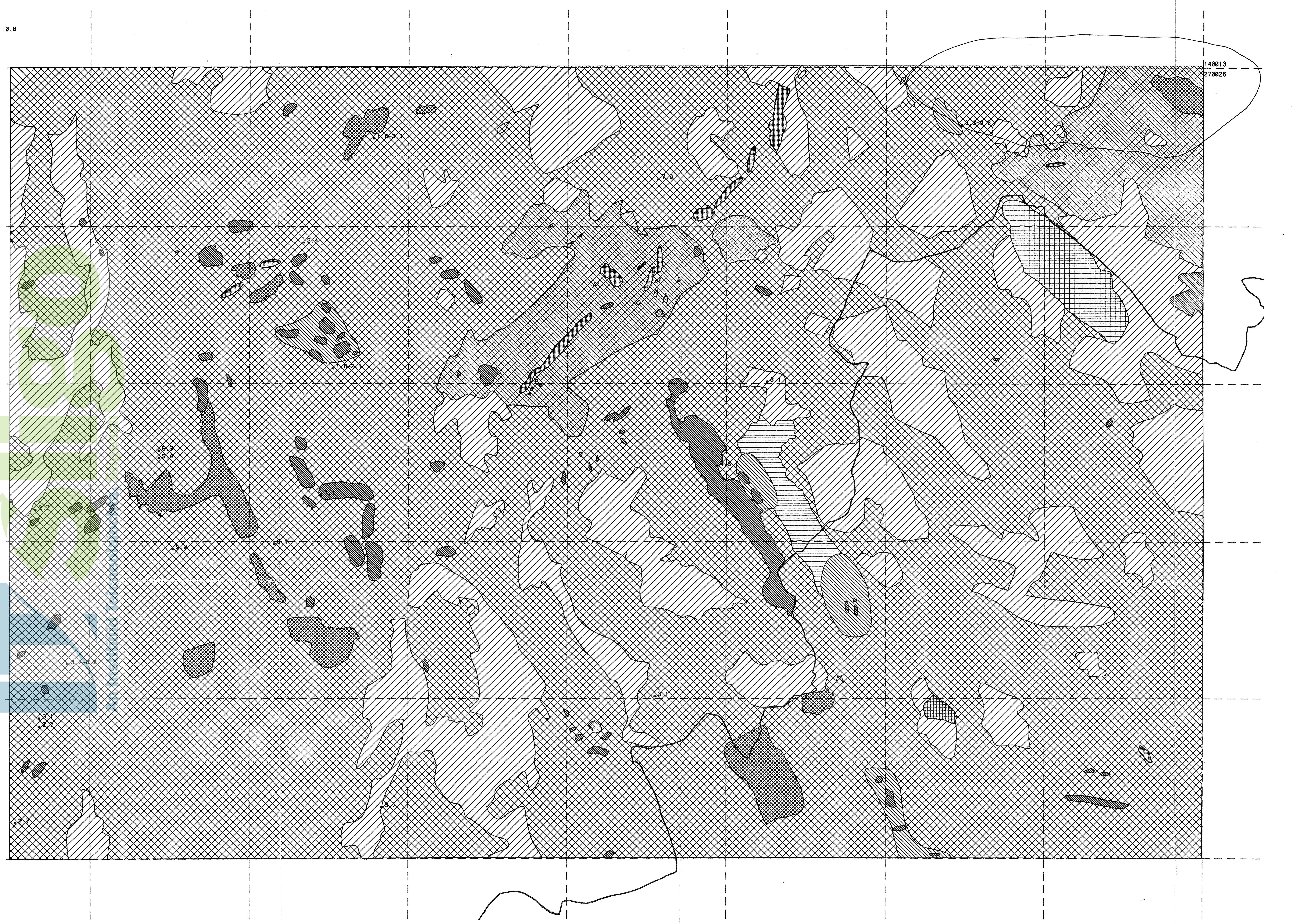
BALLINDINE-BELMONT

SUBSOILS (QUATERNARY GEOLOG



0 1 2 KM
0 .5 1 MILES

- ALLUVIUM
- RAISED BOG
- GRAVELLY TILL
- TILL WITH GRAVEL
- CLAYEY TILL
- SILTY TILL
- UNDIFFERENTIATED TILL
- SAND & GRAVEL
- ESKER (SAND & GRAVEL)
- GRAVEL RIDGE
- GRAVEL PIT
- BEDROCK NEAR SURFACE
- BEDROCK OUTCROP
- TURLOUGH
- LAKE

- SOURCE

- DRUMLIN
- Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)
- Accuracy 10 - 100 M
- Accuracy 100 - 500 M
- Accuracy 500 - 2000 M

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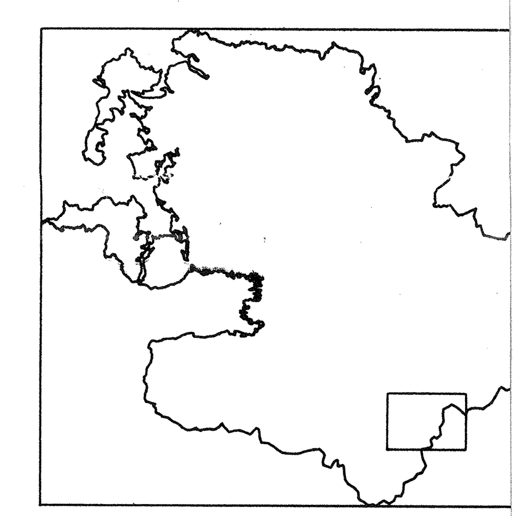
N

GRID NORTH



MOUNT . TALBOT

FIGURE 1

SUBSOILS (QUATERNARY GEOLOGY)

- RAISED BOG
- UNDIFFERENTIATED TILL
- BEDROCK NEAR SURFACE
- BEDROCK OUTCROP
- TURLOUGH

- SOURCE
- DRUMLIN
- Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)

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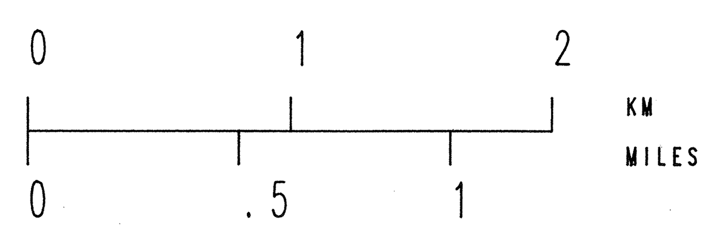
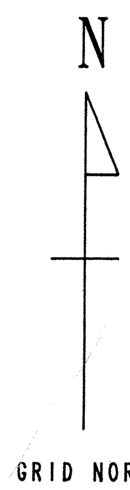
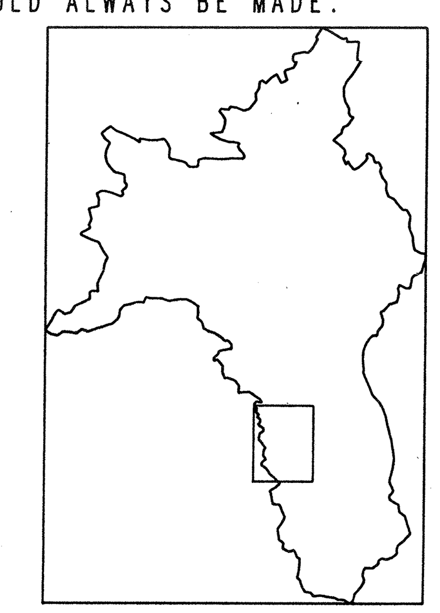






m027617

MOUNT . TALBOT

FIGURE 3

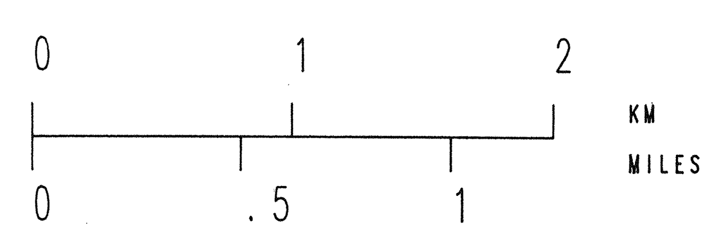
GROUNDWATER VULNERABILITY

- EXTREME VULNERABILITY
- PROBABLY HIGH VULNERABILITY
- PROBABLY MODERATE VULNERABILITY

- SOURCE

Extreme Vulnerability

- Losing/Sinking Stream
- Stream Network Above Losing Reach
- Swallow Hole



Based on the Catchment Subsoils (Quaternary Geology) map and Geological Survey of Ireland vulnerability guidelines.

Generated using GIS techniques by S Pipes(3), with technical support from J Gillmor(3), directed by C Coxon(3), P Mills(3) and K Rybaczuk(3).

(3) Trinity College Dublin

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The project was co-ordinated by R Thorn Sligo RTC.

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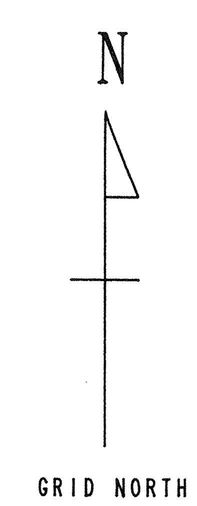
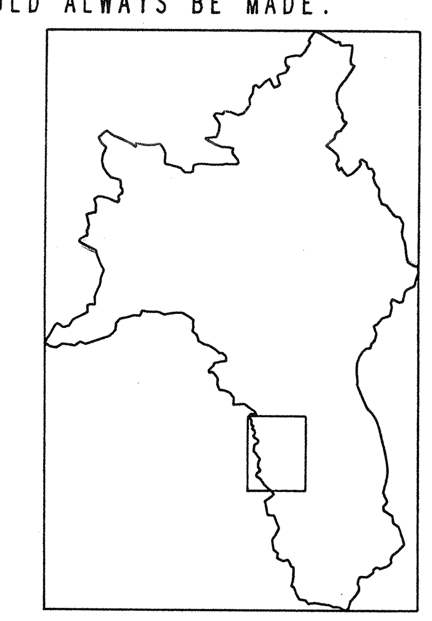


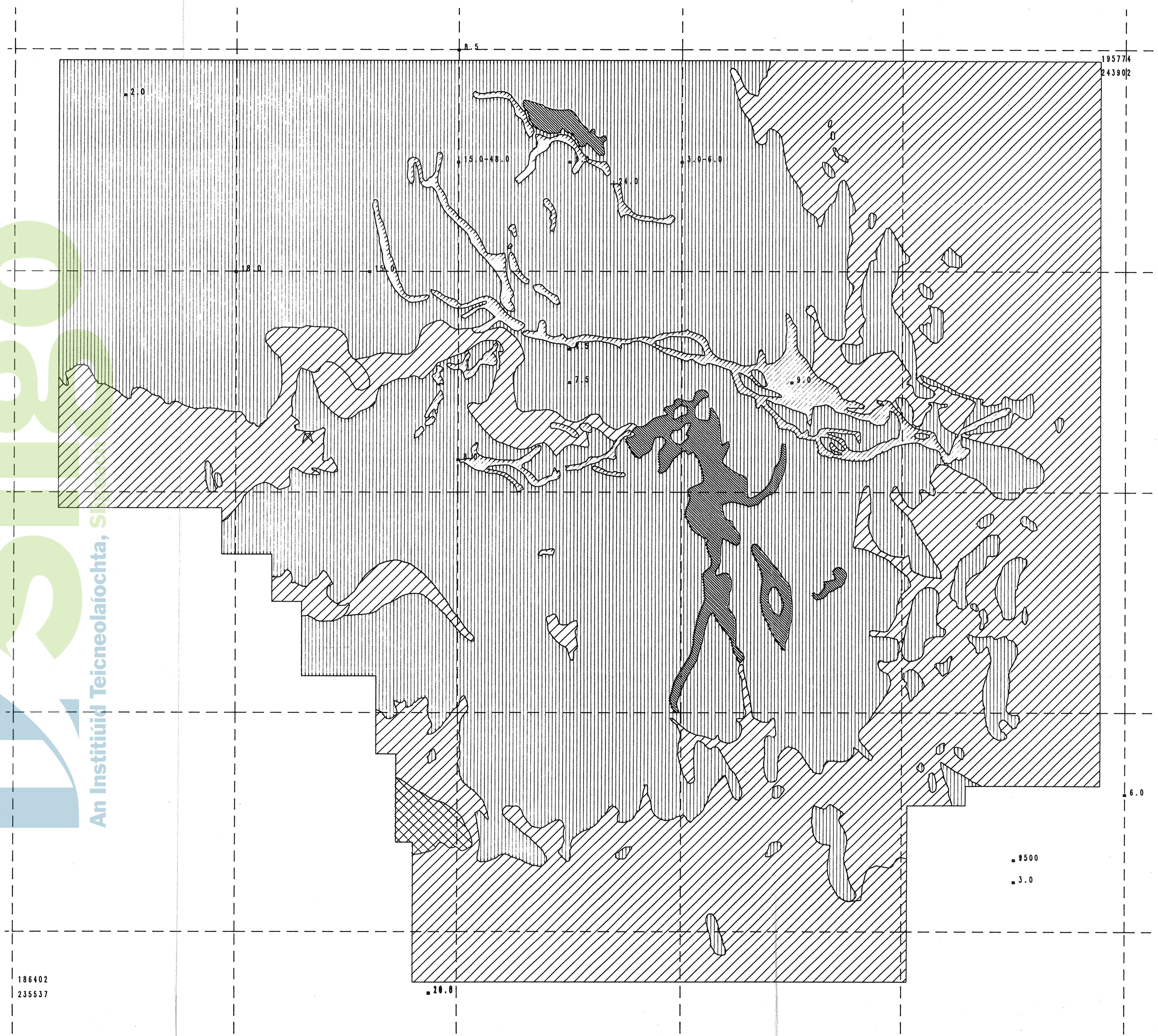


m027614

KILLEGLAN

FIGURE 1

SUBSOILS (QUATERNARY GEOLOGY)



- RAISED BOG
- ALLUVIUM
- SANDY TILL
- SHALLOW TILL
- UNDIFFERENTIATED TILL
- SAND & GRAVEL

- SOURCE
- DRUMLIN
- Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)

- Accuracy 10 - 100 M
- Accuracy 100 - 500 M
- Accuracy 500 - 2000 M

Mapped and compiled by M. Doak (2).
Supervised by by W P Warren (1), and D. Daly (1).
Based on Geological Survey of Ireland archival data, air photo interpretation and field mapping.

Digitised by M. Doak (2). Edited by H. MacMahon (3) and P. Keane (3). GIS processing and map production by S. Pipes (3), with technical support from J. Gillmor (3), supervised by C. Coxon (3) P. Mills (3) and K. Rybaczuk (3).

(1) Geological Survey of Ireland (2) Sligo RTC
(3) Trinity College Dublin

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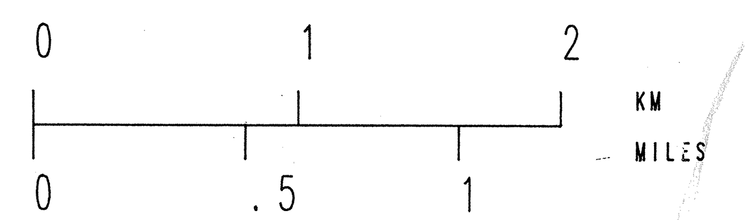
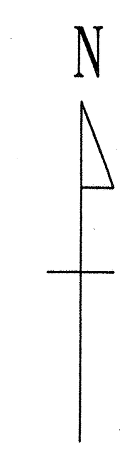
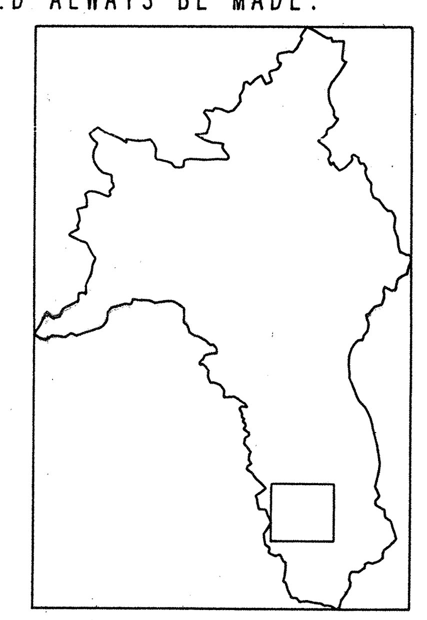


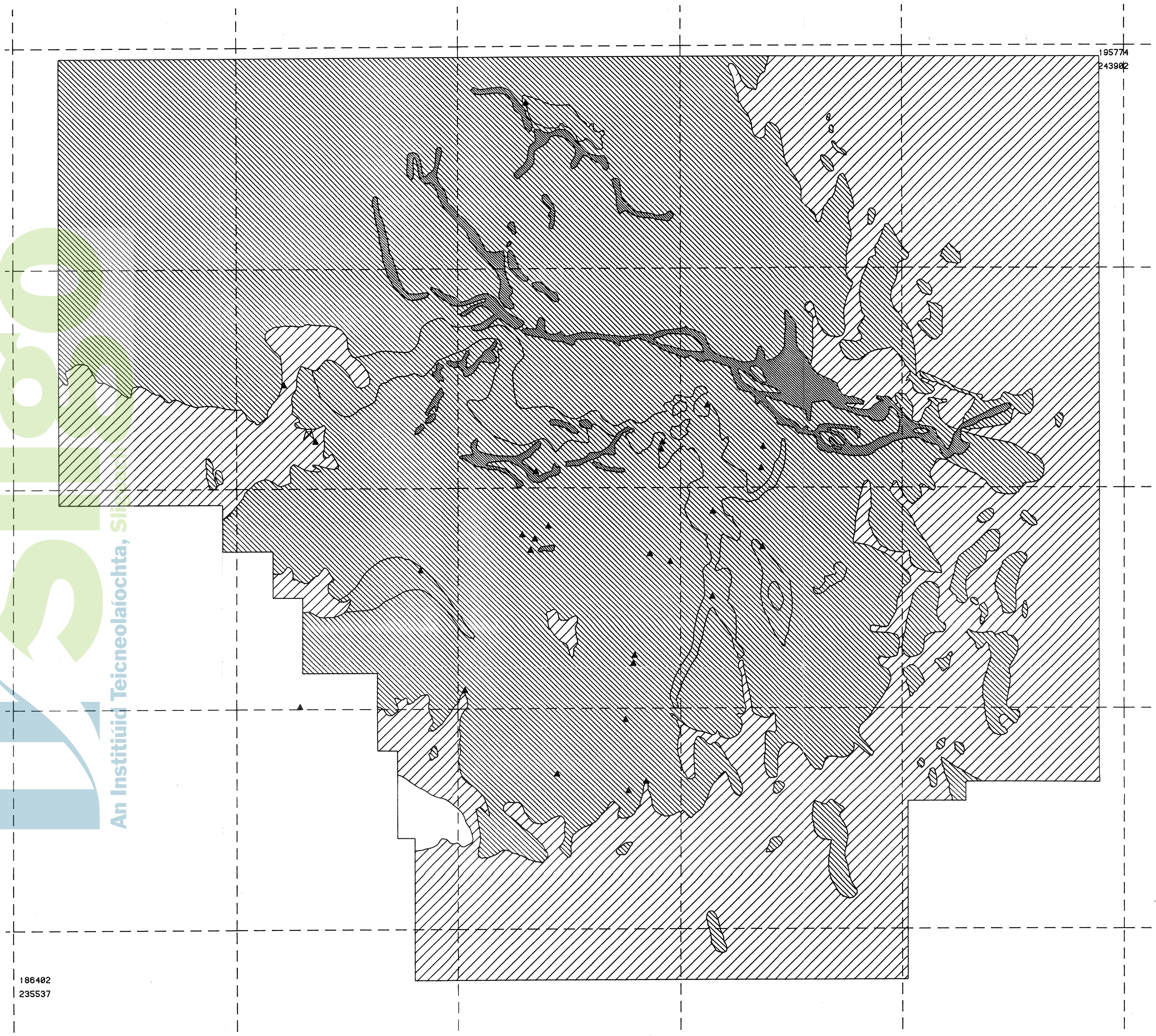




KILLEGLAN

FIGURE 4

GROUNDWATER VULNERABILITY



0 1 2 KM
0 .5 1 MILES

PROBABLY EXTREME VULNERABILITY
HIGH VULNERABILITY
PROBABLY HIGH VULNERABILITY
PROBABLY MODERATE VULNERABILITY

SOURCE

Extreme Vulnerability

Losing/Sinking Stream
Stream Network Above Losing Reach
Swallow Hole

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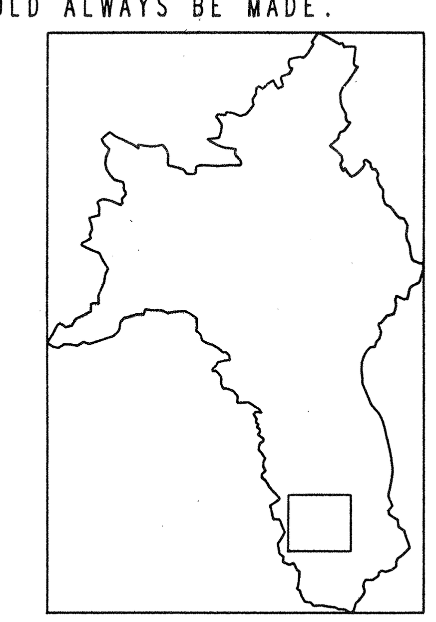
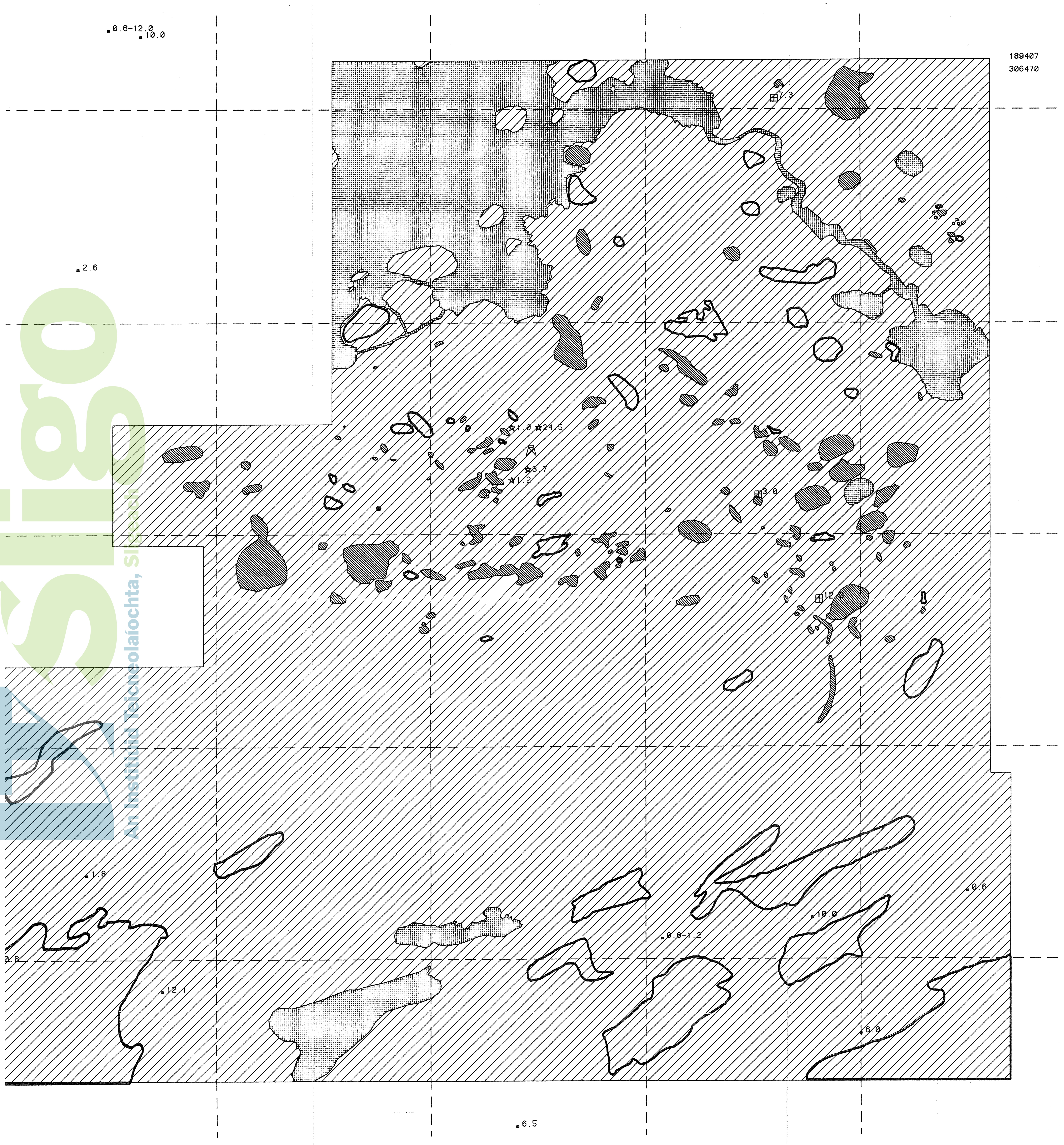
N

GRID NORTH



ROCKINGHAM

SUBSOILS (QUATERNARY GEOLOGY)



SHALLOW TILL
BEDROCK OUTCROP
LAKE

SOURCE

DRUMLIN

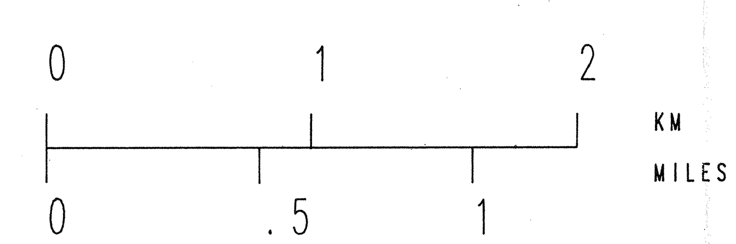
Field-mapped Depth to Bedrock (Metres)

G.S.I. Archive Data Depth To Bedrock (Metres)

Accuracy 10 - 100 M

Accuracy 100 - 500 M

Accuracy 500 - 2000 M



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