National Development Plan 2007 - 2013

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

STRIVE

Report Series No. 6

WATER FRAMEWORK DIRECTIVE – Recharge and Groundwater Vulnerability

STRIVE

Environmental Protection Agency Programme

2007-2013

Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government

Environmental Protection Agency

The Environmental Protection Agency (EPA) is a statutory body responsible for protecting the environment in Ireland. We regulate and police activities that might otherwise cause pollution. We ensure there is solid information on environmental trends so that necessary actions are taken. Our priorities are protecting the Irish environment and ensuring that development is sustainable.

The EPA is an independent public body established in July 1993 under the Environmental Protection Agency Act, 1992. Its sponsor in Government is the Department of the Environment, Heritage and Local Government.

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The EPA is assisted by an Advisory Committee of twelve members who meet several times a year to discuss issues of concern and offer advice to the Board.

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Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail.

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- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
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- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

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- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

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- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

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- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

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- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

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Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

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WATER FRAMEWORK DIRECTIVE – Recharge and Groundwater Vulnerability

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STRIVE Report

End of Project Report available for download on http://erc.epa.ie/safer/reports

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The EPA STRIVE Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

The aim of the project was to develop a quantified link between groundwater vulnerability and recharge. Based on a review of previous work on this topic, it was recognised that the most important linkage to investigate was that between subsoil permeability and recharge, since subsoil permeability has the greatest influence over the recharge coefficient. Other influences on the recharge coefficient include subsoil thickness, soil type and the ability of the aquifer to accept the available recharge.

Four areas were selected for detailed study, representing different subsoil permeability and aquifer types:

1. the Curragh gravel aquifer in County Kildare (an area of high permeability subsoils)

2. the Callan–Bennettsbridge lowlands in County Kilkenny (moderate permeability subsoils)

3. the Galmoy area of County Kilkenny (moderate permeability subsoils)

4. and the Knockatallon aquifer in County Monaghan (low permeability subsoils).

Regarding aquifer category, the focus of the project was on regionally important aquifers. Given the relatively short project time frame, the case studies relied mainly on existing hydrological and hydrogeological records, augmented by supplementary data collection, including samples for chlorofluorocarbon (CFC) analyses (Curragh, Galmoy and Knockatallon) and installation of automatic groundwater monitoring loggers (Knockatallon).

The recharge coefficient values obtained from the case studies were:

- 81–85% for the high permeability subsoils of the Curragh gravel aquifer

- 41–54% for the moderate permeability subsoils within the Callan–Bennettsbridge lowlands (or 36–60% for the full sub-catchment areas, which include high and low permeability subsoils as well as moderate permeability subsoil)

- 55–65% for the moderate permeability subsoils of the Galmoy mine area

- less than 17% (and probably less than 5%) for the low permeability subsoils of the Knockatallon aquifer.

The results of the case studies, together with recharge coefficient values obtained from previous studies, were used to develop a quantified link between subsoil permeability, aquifer vulnerability, recharge and run-off. Recharge and run-off coefficients are each classed into three groupings: High, Intermediate and Low. A High recharge coefficient equates to a Low run-off coefficient, and *vice versa*. The range of recharge coefficients in each grouping are: High: 70–90%, Intermediate: 30–70%, and Low: 5–30%.

A GIS-based tool is proposed that will enable the estimation of recharge using recharge coefficient values. Potential recharge is calculated as the product of effective rainfall and recharge coefficient. The actual recharge is then calculated taking account of the ability of the aquifer to accept the available recharge. Recharge caps (existing values) are applied to poor and locally important aquifers. Run-off (including interflow) is calculated from the effective rainfall that does not become potential recharge, plus any rejected recharge. Peat deposits are assigned to the Low recharge coefficient grouping.

1 Introduction

1.1 Project Background

Until relatively recently, recharge estimation was not given a high priority by water resources legislators and managers in Ireland because groundwater abstractions for water supplies represented only a tiny fraction of the available resource. Now, however, owing to growing awareness of the importance of groundwater contributions to the environment and, more specifically, to the introduction of the European Water Framework Directive (European Commission, 2000), the availability of reliable recharge estimates is regarded as essential to the proper management of the country's water resources.

Under the EU Water Framework Directive, recharge estimates are required for the integrated management of surface and groundwater resources within River Basin Districts (RBDs). Article 4, for example, states that Member States shall "*prevent deterioration of groundwater status and ensure a balance between abstraction and recharge of groundwat*er". Again, under Annex II, Member States (as part of the initial characterisation of groundwater bodies) shall identify "*land use in the catchment or catchments from which the groundwater body receives its recharge..*".

The main focus for hydrogeological work in Ireland in the last decade has been the preparation of groundwater protection schemes. These schemes are being prepared on a county-by-county basis, and include groundwater vulnerability mapping at a scale of 1:50,000. There are close links between the characteristics used to assess vulnerability and the factors that influence the rate of recharge (thickness and permeability of subsoil, surface drainage density, etc.). This Recharge and Vulnerability project provided an opportunity to investigate this relationship further.

1.2 Objectives

The overall aim of the research project was to develop a quantified link between groundwater vulnerability, as mapped using Geological Survey of Ireland (GSI) procedures, and groundwater recharge. The project objectives were to:

1. Review and evaluate current methods for the estimation of groundwater recharge at sub-catchment level

2. Review current data availability and identify suitable sub-catchments which form the basis of experimental studies (these would preferably comprise areas where vulnerability mapping and relevant, long-term, monitoring data already exist)

3. Examine relationships between information from detailed instrumented sites with sub-catchment-scale maps of groundwater vulnerability and aquifer potential

4. Develop a preliminary Geographical Information System (GIS)-based assessment tool for the estimation of groundwater recharge (recharge acceptance).

Regarding Objective 4, this project did not require the development of a **new** GIS tool; rather, the additional data requirements and maps proposed for estimating recharge would be such that they could be incorporated by the GSI within its existing GIS system.

1.3 Project Reports

This Synthesis Report provides a short summary of the project outcomes, including the results of four case studies where the relationship between recharge and vulnerability was quantified, and the development of a preliminary GIS-based tool for estimating recharge. For the full project results the reader is referred to the End of Project Report, available for download on http://www.epa.ie/downloads/pubs/research/water. The End of Project Report is divided into three parts: Part A: Literature Review (Chapters 2 to 4); Part B: Case Studies (Chapters 5 to 7); and Part C: Project Outcomes (Chapters 8 and 9).

2 Background on Groundwater Vulnerability and Recharge

2.1 Groundwater Vulnerability

The vulnerability of an aquifer to contamination is influenced by many factors including the leaching characteristics of the topsoil, the permeability and thickness of the subsoil, the presence of an unsaturated zone, the type of aquifer, and the amount and form of recharge. In Ireland, the groundwater vulnerability is determined mainly according to the thickness and permeability of the subsoil that underlies the topsoil, as these properties strongly influence the travel times and attenuation processes of contaminants that may be released into the subsurface from below the topsoil (as in the case of contaminants from landfills, septic tank systems and underground storage tanks). The type of recharge is also considered in karstic areas, where indirect recharge (termed 'point recharge' in Ireland) may occur through swallow holes or sinking streams. The vulnerability mapping guidelines are summarised in Table 2.1.

There are four vulnerability categories: Extreme, High, Moderate and Low. On the most recent vulnerability maps, the Extreme category includes a subcategory 'X', representing rock outcrop and subsoil less than 1 m thick. Understanding the properties of the subsoil is essential for classifying the vulnerability and hence for establishing the link with recharge. The classification of the groundwater vulnerability relies partly on a qualitative assessment as to whether the subsoil permeability is High, Moderate or Low. A standard methodology is used to describe the subsoils, based on the standard engineering code contained in the British Standard (BS) 5930 (British Standards Institution, 1999; Swartz *et al.*, 2003). Indirect indicators of subsoil permeability include drainage density and vegetation characteristics (Misstear and Daly, 2000; Fitzsimons *et al.*, 2003).

2.2 The Link between Groundwater Recharge and Vulnerability

Most recharge in temperate regions, including Ireland, occurs as direct recharge, i.e. recharge takes place via vertical infiltration of precipitation where it falls on the ground. Indirect recharge can also be important in some areas, notably in karst regions in the west of Ireland, but this indirect recharge was not considered in this study. Rather, the focus of the research project was on the link between groundwater vulnerability and direct recharge.

The factors that influence the amount and type of recharge include precipitation (volume, intensity, duration), topography, vegetation (cropping pattern, rooting depth), evapotranspiration, soil and subsoil types, flow mechanisms in the unsaturated zone, bedrock geology, and available groundwater storage (Misstear *et al.* 2006). Several of these factors also have a strong influence on groundwater vulnerability, especially the subsoil characteristics. The influence of subsoils on recharge has also been considered in the UK (Rushton *et al.*, 1988; Rushton 2005). In his 2005 paper, Rushton proposes three approaches for quantifying recharge through glacial tills (or 'drift

Table 2.1. Vulnerability classes (adapted from DoELG *et al.*, 1999).

Vulnerability rating	Hydrogeological conditions				
	Subsoil permeability (type) and thickness			Unsaturated zone	Karst features
	High permeability (sand/gravel)	Moderate permeability (e.g. sandy till)	low permeability (e.g. clayey till, clay, peat)	(sand/gravel aquifers only)	(<30 m radius)
Extreme	0–3.0 m	0–3.0 m	0–3.0 m	0–3.0 m	–
High	>3.0 m	3.0–10.0 m	3.0–5.0 m	>3.0 m	N/A
Moderate	N/A	>10.0 m	5.0–10.0 m	N/A	N/A
Low	N/A	N/A	>10.0 m	N/A	N/A

Note: N/A, not applicable.

deposits' as they are termed in the UK), the choice depending on the heterogeneity and permeability of the deposit. In the first approach, a constant, low recharge rate through the till is assumed. In the second, the vertical infiltration rate through the till is calculated using Darcy's equation. For the third approach, the potential recharge (the effective rainfall) is multiplied by a 'recharge factor', the factor depending on the thickness and permeability of the till, and also the vertical hydraulic gradient. The approach followed in Ireland is similar to the latter: firstly, the effective rainfall is calculated using a soil moisture budget approach such as the Penman–Grindley method, the FAO Penman–Monteith method (Allen *et al*., 1998) or the Aslyng scale (Misstear, 2000). The effective rainfall is then multiplied by a recharge coefficient to determine the recharge. The vertical hydraulic gradient is assumed to be equal to unity. The recharge coefficient is expressed as a percentage, ranging from less than 30% for a low permeability subsoil to as much as 90% for a high permeability subsoil (Fitzsimons and Misstear, 2006). The proportion of effective rainfall that does not give rise to recharge is assumed to give rise to overland flow or interflow.

Using a simple one-dimensional numerical model, Fitzsimons and Misstear (2006) demonstrated that the key linkage is that between recharge and subsoil permeability, since this has more influence over the recharge coefficient than either subsoil thickness or vertical hydraulic gradient. Moreover, variations in subsoil properties have a far greater influence on recharge than variations in the soil moisture budgeting parameters used to calculate actual evapo-transpiration and hence effective rainfall.

3 Case Studies

3.1 Selection of Study Areas

The main criteria in the selection of study areas were:

- the aquifer class
- the vulnerability category
- the availability of data, including vulnerability maps, aquifer property data, and river flow data.

The main focus of the study was on regionally important aquifers since these are, by definition, the most important aquifers. The following vulnerability categories were investigated: High, Moderate and Low. It was not attempted to try and investigate recharge in areas where vulnerability is categorised as Extreme, since indirect (point) recharge is likely to be significant in many such areas. Nevertheless, the proposed GIS-based tool does take into account direct (diffuse) recharge in Extreme vulnerability areas (see Section 4.4).

As noted in Section 2.2, it was recognised at the outset that the key link for this project to investigate was that between recharge and subsoil permeability. It was also recognised that the Moderate vulnerability category can encompass a wide range of subsoil permeability, and so it was decided to investigate two such areas.

Four areas were selected for detailed study:

1. the Curragh gravel aquifer in County Kildare (an area of high permeability subsoils)
2. the Callan–Bennettsbridge lowlands in County Kilkenny (moderate permeability subsoils)
3. the Galmoy area of County Kilkenny (moderate permeability subsoils)
4. and the Knockatallon aquifer in County Monaghan (low permeability subsoils).

The field investigations were carried out between August 2003 and July 2006, and included groundwater-level monitoring (Knockatallon aquifer), water sampling and isotope analyses (Knockatallon aquifer, Curragh aquifer and Galmoy).

3.2 High Permeability Subsoil Area: The Curragh Gravel Aquifer

The area with high permeability subsoils selected for this study contains the largest gravel aquifer in Ireland. The Curragh gravel aquifer is located in County Kildare, about 40 km west of Dublin. A substantial groundwater monitoring programme was initiated across the aquifer in 1997 in response to the construction of a road bypass for the main town in the area, the Kildare town bypass (shown by the green line in Fig. 3.1). Road construction began in 2001 and included 2 years of significant dewatering to complete a 3.5-km long section of cutting below the water table. The monitoring programme covers groundwater levels within the gravel aquifer as well as discharges from the aquifer. These discharges include major springs to a fenland about 5 km north-east of the road cutting. This fenland, Pollardstown Fen, is one of the most important ecological sites of its type in Ireland.

The Curragh aquifer consists of glacio–fluvial subsoil deposits overlying Carboniferous limestone bedrock. These deposits vary between 20 m and 60 m in thickness (Hayes *et al.*, 2001). Although variable, the stratigraphic sequence generally comprises a lower unit of fine sands, followed by a middle layer of gravel and a thin upper layer of till (this till was described along the cutting exposure as e.g. sandy gravelly CLAY or very clayey, very sandy GRAVEL).

Several approaches were applied in the estimation of recharge to the Curragh aquifer, including soil moisture budgeting, well hydrograph analyses and a catchment water balance (see Section 5.6 of the End of Project Report). The soil moisture budgeting was carried out using the Penman–Grindley and the FAO Penman–Monteith methods (see Allen *et al.*, 1998) for a 30-year series (1971–2000) of daily rainfall and evapotranspiration data. The results, in terms of annual averages, were similar, with effective rainfall

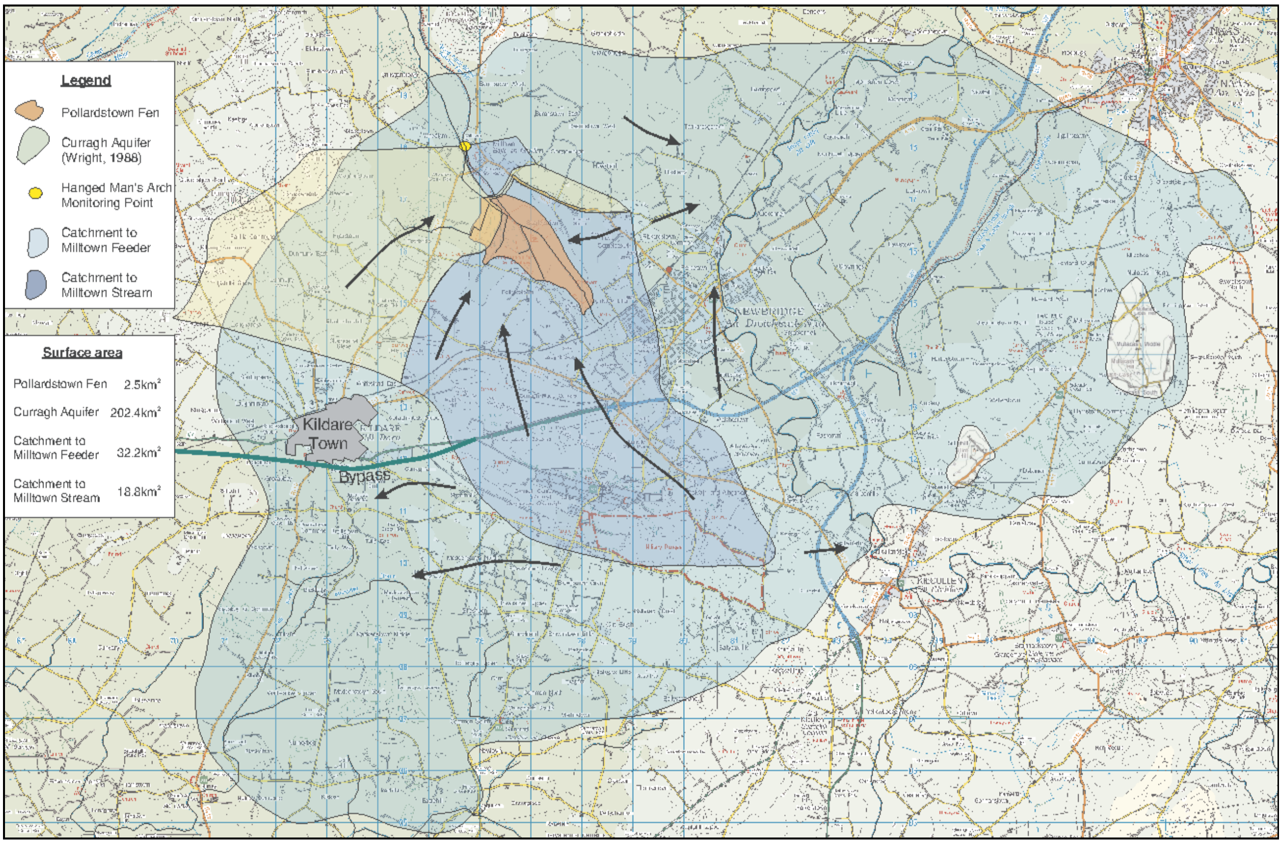

Figure 3.1. Location map showing Kildare town and Pollardstown Fen (catchments shown are based on work by A. Kuczyńska, personal communication, 2006).

values of 334 mm/year and 321 mm/year for the Penman–Grindley and FAO Penman–Monteith methods, respectively. These figures represent the likely ‘potential recharge’ values, before any account is taken of ‘losses’ to surface run-off or interflow. As the subsoils in this area have high permeabilities, it was expected that these ‘losses’ would be small, and that the recharge coefficient values would be high.

Recharge can be estimated from water-level fluctuations using a relationship of the following form:

$$R = (\Delta h \times S_y) + Q_a + (Q_{out} - Q_{in})$$

In this water balance equation, R is the recharge, Δh the change in water table elevation, S_y the specific yield, Q_a the groundwater abstraction during the period under consideration, and Q_{out} and Q_{in} are any other lateral subsurface outflows and inflows during the same period. Taking a water-level hydrograph for a well close to the groundwater divide (approximately midway between Kildare town and the fen), where there is a relatively rapid response to recharge (as shown by the steep rising limb on the sample hydrograph in Fig. 3.2), and applying the simplifying assumptions that Q_a is very small and can be ignored, and that Q_{out} equals Q_{in}, then the recharge can be estimated from the hydrograph rise Δh and the specific yield S_y. The difficulty in applying this type of analysis is in determining accurate values for specific yield. The value of 0.13 adopted in an earlier numerical groundwater modelling exercise in the area would give recharge coefficient values in the range 50–80%, which are considered too low for this area. (The absence of observed surface run-off in the central parts of the Curragh aquifer suggests higher recharge coefficient values.) On the other hand, applying a value of 19% as an average specific yield for coarse gravel in this area (which is not unreasonable given that, e.g., Healy and Cook (2002) suggest a value of 22% for the specific yield of a gravel aquifer) produced a range of recharge coefficients between 72% and 100%.

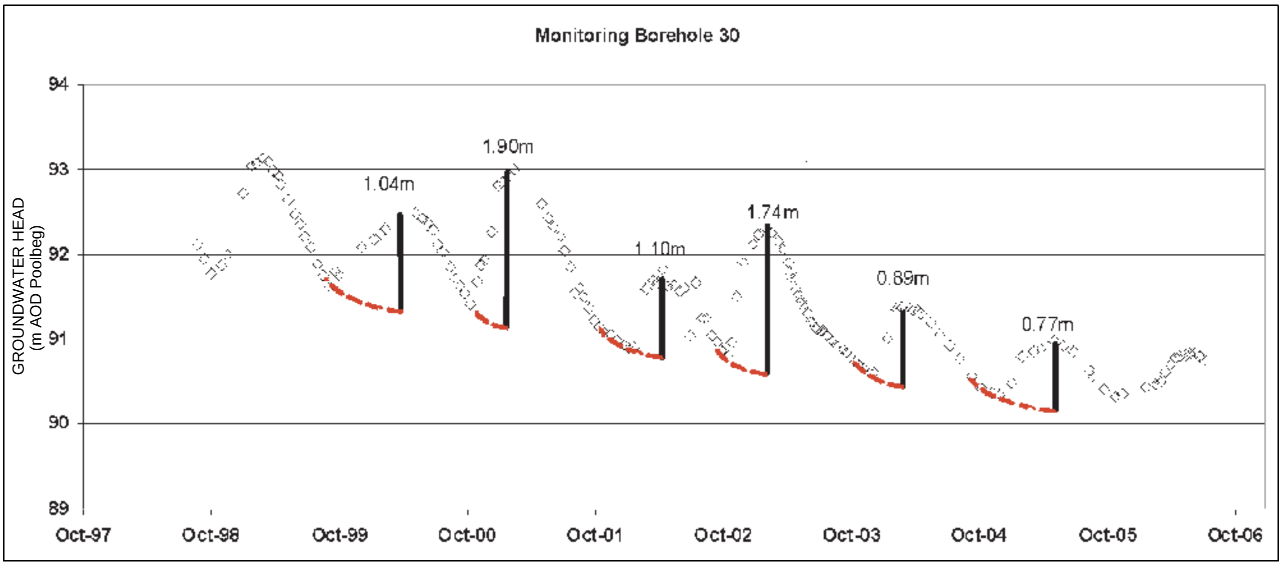

Figure 3.2. Example of well hydrograph analysis, Curragh aquifer.

Recharge quantities in the Curragh aquifer have also been determined by undertaking a water balance of the catchment draining to springs in Pollardstown Fen. Discharges to Pollardstown Fen occur as several large springs but also numerous seepage zones, which drain an area that is defined by topography as 32 km^2 (see Fig. 3.1 for details of catchment area). The total discharge from all springs and seepages was measured at 9.14×10^6 m^3/year (A. Kuczyńska, personal communication, 2006). Based upon these discharges and the catchment size, recharge is calculated to be 285 mm. With estimated effective rainfall values of between 335 mm/year and 351 mm/year for the period in question (March 2002 to May 2005), the recharge coefficient is thus calculated at between 81% and 85%, which is considered to be a realistic range for a high permeability, high vulnerability gravel aquifer such as the Curragh.

3.3 Moderate Permeability Subsoil Areas

Moderate vulnerability includes a wide range of permeability values (1×10^{-4} m/s down to about 1×10^{-8} m/s) and, as such, two areas were selected for investigation in this research: the Callan–Bennettsbridge area and the Galmoy area, both located in County Kilkenny.

3.3.1 The Callan–Bennettsbridge area

The Callan–Bennettsbridge area lies in the River Nore catchment in County Kilkenny. The subsoils in this area are typically silty clays and probably have a permeability towards the lower end of the moderate permeability range. The study area comprises two catchments: a sub-catchment of the River Nore between the gauging stations at St John's Bridge in Kilkenny city and Mount Juliet downstream (referred to here as the Bennettsbridge sub-catchment), and the catchment of the King's River, a tributary of the Nore which joins the right bank of the main river at Annamult, just upstream of Mount Juliet (Fig. 3.3).

Recharge in these sub-catchments was estimated using soil moisture budgeting and river baseflow separation techniques. The two sub-catchments were selected because they contain greater uniformity of hydrogeological conditions, including a higher proportion of moderate permeability subsoils, than is the case for the Nore catchment as a whole (which has an area of approximately 2,400 km^2). The Bennettsbridge sub-catchment is part of the main river catchment (as opposed to a catchment of a tributary river, as in the case of the King's River). Misstear and Fitzsimons (2007) also isolated this section of the Nore for the purposes of river baseflow analysis. In that study, the analysis procedure involved the subtraction of the daily flow values from the Kilkenny city (St John's

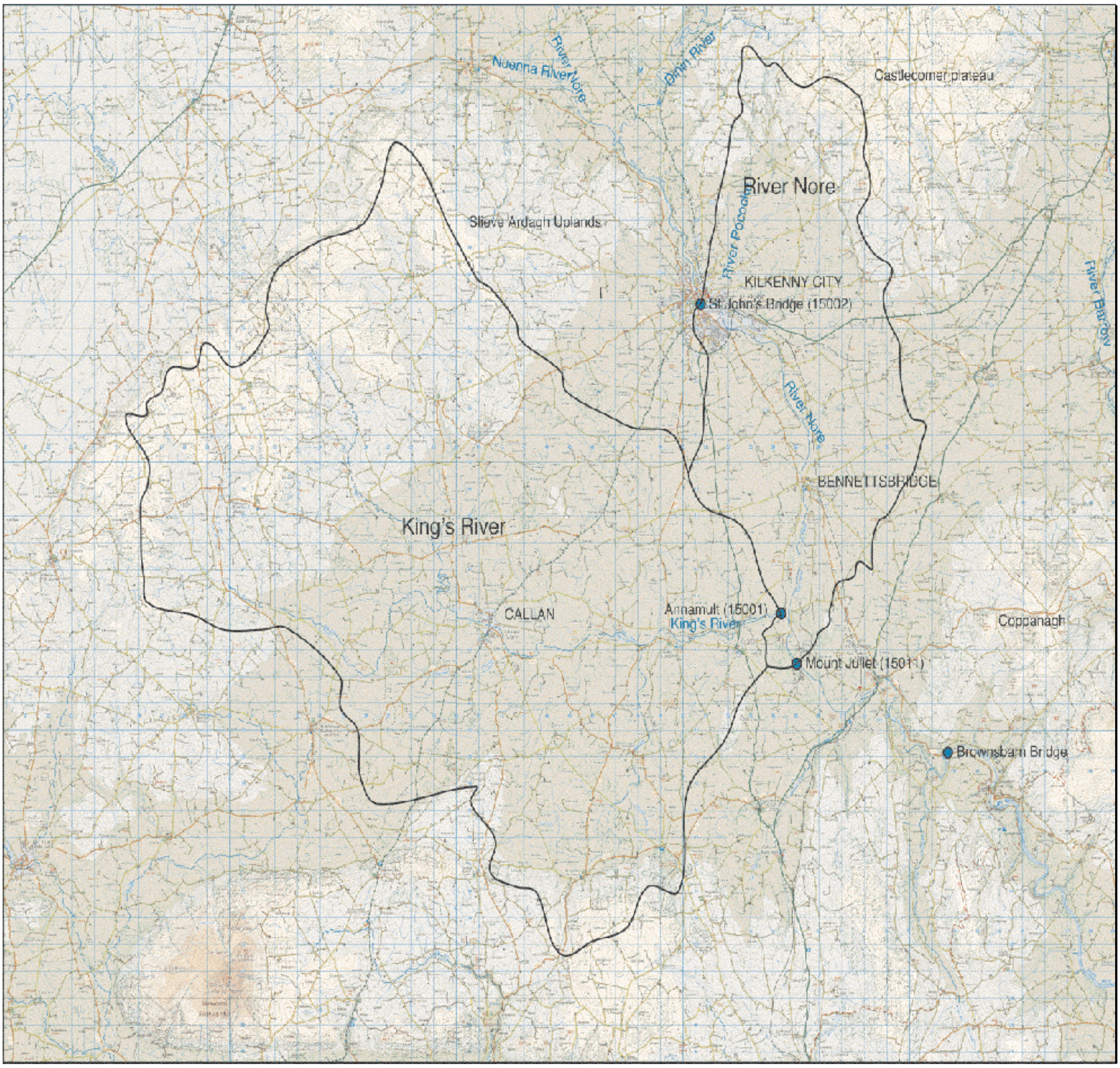

Figure 3.3. Location of study catchments, Callan–Bennettsbridge area.

Bridge) and King's River (Annamult) upstream gauges from the flows downstream at Mount Juliet, resulting in a 'hybrid hydrograph' for the sub-catchment of interest. The Institute of Hydrology method (1989) was then applied to the hydrograph analysis.

In the Recharge and Vulnerability study, the Boughton baseflow algorithm (Boughton, 1993, 1995; Chapman, 1999) was applied directly to the data from the two upstream gauging stations (St John's Bridge and Annamult) and the downstream station (Mount Juliet), and average values of baseflow and total flow were calculated for each gauge. The average baseflow and total flow values of the upstream gauges were then subtracted from the downstream values, thereby providing estimates of the baseflow and total flow for the Bennettsbridge sub-catchment.

The Boughton algorithm was applied to each of the data sets to provide a range of baseflow values. Examples of higher and lower estimates of baseflow analysis are presented in Fig. 3.4 for the King's River at Annamult. Higher and lower estimates are given, in view of the inherent uncertainties involved in identifying the groundwater component of a stream hydrograph.

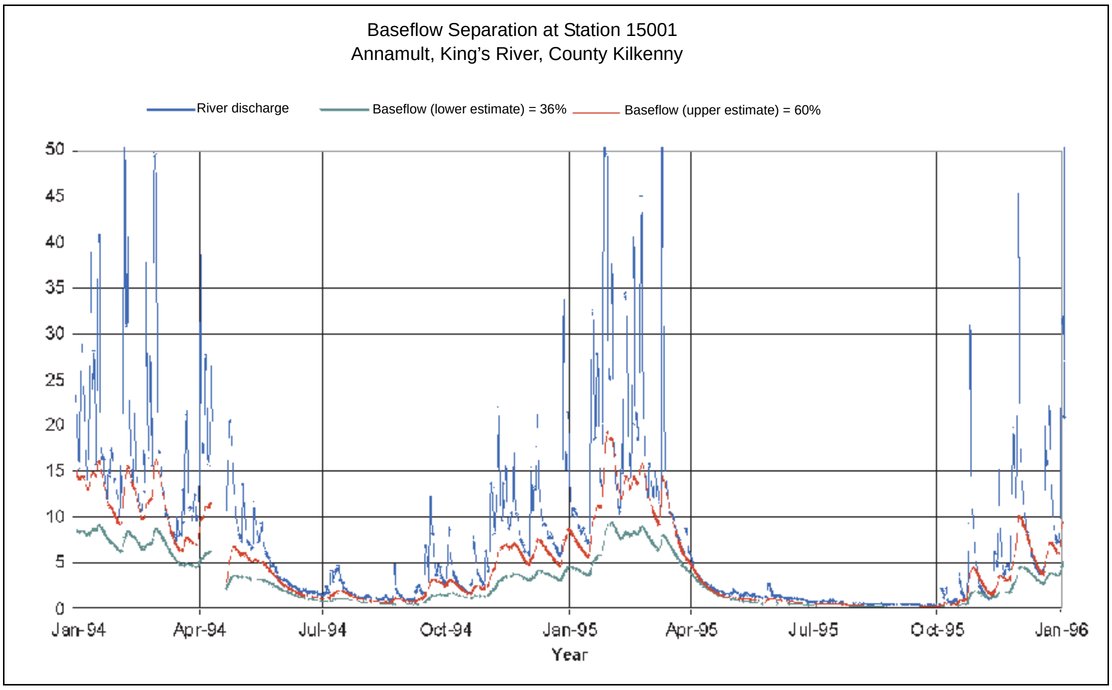

Figure 3.4. Baseflow analysis on the King's River, using the Boughton (1995) two-parameter algorithm.

With an average effective rainfall of 407– 428 mm/year – calculated using the FAO Penman–Monteith method (for a 30-year data set from Kilkenny city) – the estimated recharge coefficients for the two sub-catchments ranged between 36% and 60%. By calculating the areas of sub-catchment covered by low or high permeability subsoils, and assigning likely recharge coefficient values to these subsoils, then the range of recharge coefficients for the moderate permeability subsoils within the sub-catchments could be narrowed to 41–54% (see Section 6.1.6.2 of the End of Project Report).

3.3.2 *The Galmoy area*

The second area of moderate permeability subsoils studied was around Galmoy mine in County Kilkenny. Here the subsoil is largely sandy SILT, between 1 and 12 m thick, and has a permeability probably towards the upper end of the moderate permeability range. The subsoil overlies fractured dolomite and limestone bedrock.

At Galmoy, zinc and lead minerals are mined from depths of up to 150 m *via* a series of inclined roadways. In order to extract the ore, several large-diameter wells were initially installed to dewater the bedrock; since the onset of mining operations, all dewatering has been undertaken by drains and pipework along the underground roadways. The dewatering has created a large cone of depression focused around the mine workings. A water balance calculation based on the volume of groundwater abstracted from the estimated zone of contribution to the mine area (equivalent to 264 mm/year) *versus* the effective rainfall for the area (407–428 mm/year) would suggest a recharge coefficient of around 62–65%. However, the groundwater system is not in steady state with respect to dewatering, as groundwater levels in the immediate vicinity of the mine are continuing to drop, and thus the above calculation is likely to be an overestimate of the amount of recharge, i.e. some of the abstraction volume is being drawn from aquifer storage. The chlorofluorocarbon (CFC) analyses of mine water samples at Galmoy also indicated that the water being abstracted comprises a mixture of modern recharge and older groundwater from aquifer storage. Assuming about 10–20% of the dewatering represents depletion of aquifer storage, then the recharge coefficient is estimated (very approximately) at around 55% (see Section 6.2.6 of the End of Project Report).

3.4 Low Permeability Subsoil Area: The Knockatallon Aquifer

The Knockatallon aquifer is a fractured bedrock aquifer near the village of Tydavnet in north County Monaghan. The Knockatallon aquifer consists of two formations of limestone and other Carboniferous rocks: the Dartry Limestone Formation and the Meenymore Formation. Geophysical logging carried out during this project indicated that the Dartry Limestone is the main aquifer unit. Reinterpretation of original pumping test data for the most productive well in the Tydavnet Group Water Scheme (TGWS) showed that this well is abstracting from a relatively isolated block of aquifer (see Section 7.6.3 of the End of Project Report). The aquifer was originally delineated as a ‘regionally important fissured aquifer’ by the GSI, although its status has since been downgraded to ‘locally important’. Groundwater pumping by the TGWS over the last 20 years has caused groundwater levels in the aquifer to fall substantially. The well field consists of five production wells up to 125 m deep. For the years 2000 to 2005, an average of 1,000 m^3/day was abstracted. Groundwater levels are locally depressed by up to 40 m below pre-pumping water levels (Misstear *et al.*, 2005). Kelly (2001) attributed the falling water levels to low recharge as the aquifer is covered by substantial thicknesses (up to 53 m) of low permeability subsoils (Fig. 3.5).

The lowering of groundwater levels in the vicinity of the well field is shown clearly by the piezometric map in Fig. 3.6. Since the steep declines in water levels during the early years of pumping, groundwater levels in several wells within the monitoring network were relatively stable, or showed only a slight lowering, in the period 2000–2005, suggesting that the abstraction rate of 1000 m^3/day by the TGWS was in near-equilibrium with recharge to the aquifer. In September 2005, a treated surface water source was brought into supply, and groundwater abstractions were cut back, with a consequent recovery in water levels in some boreholes.

Owing to the presence of the thick, low permeability subsoil (of which the lower 20 m have a high clay content), direct recharge to the Knockatallon aquifer in the vicinity of the well field would be expected to be low. A simple calculation illustrates this point. Assuming:

- the effective rainfall, calculated using the Penman–Monteith method, is between 502 mm and 514 mm for a weather station south-west of the study area (the effective rainfall in the higher ground around the Tydavnet area would be somewhat higher),

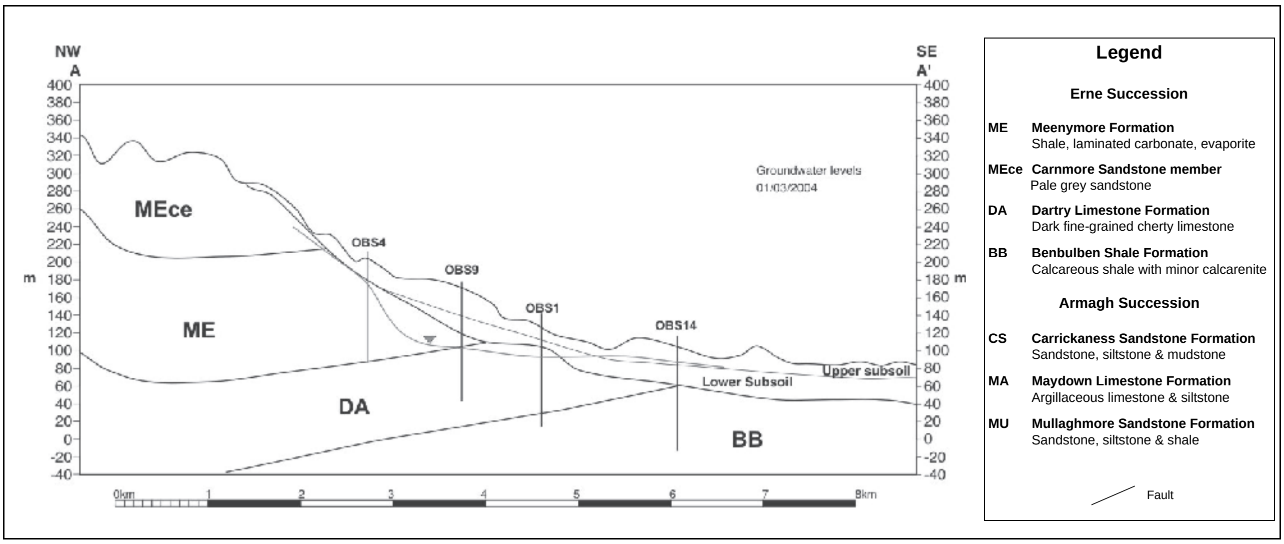

Figure 3.5. Cross-section of the Tydavnet area showing subsoil geology, bedrock geology and potentiometric surface in March 2004 (Misstear *et al.*, 2005).

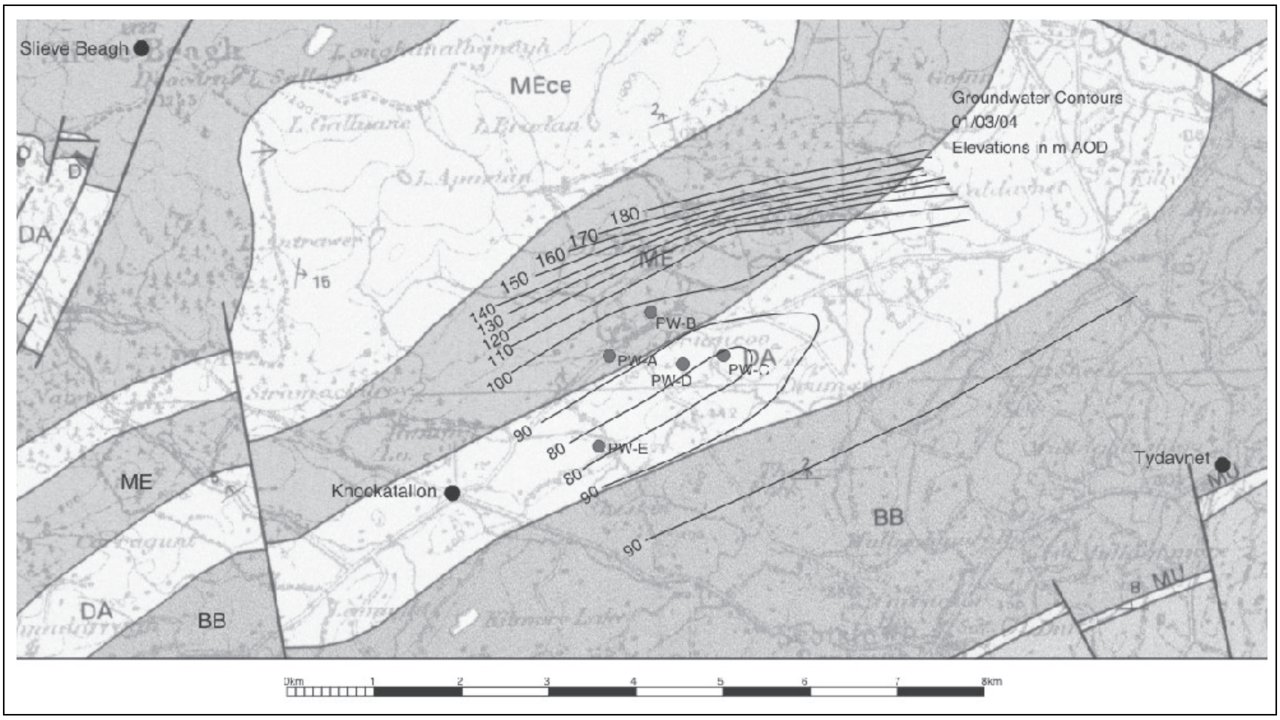

Figure 3.6. Piezometric levels (m above datum) in the Knockatallon aquifer (01/03/2004). (Geology from Geraghty *et al*., 1997; refer to Fig. 3.5 for the geological legend).

- the area of subsoil within the zone of contribution (ZOC) to the well field is approximately 14 km^2 (estimated from Fig. 3.6), and

- that the average withdrawal from the aquifer of around 1000 m^3/day in the period 2000–2005 was approximately in balance with recharge,

then the average annual recharge through the subsoil would be 26 mm, or 5% of the effective rainfall. This represents an upper limit for the recharge through the subsoil. When the low permeability and large thickness of the subsoil in the well-field area are taken into account – together with the fact that some of the abstraction was derived from aquifer storage, as groundwater levels had not stabilised fully – then the recharge coefficient is likely to be less than 5%.

A simple calculation can be made to estimate the travel time for any recharge water entering the bedrock aquifer via the overlying subsoil. Assuming:

- an average hydraulic conductivity for the lower, more clayey subsoil of 1×10^{-9} m/s

- that this low permeability subsoil is about 20 m thick, and

- has a porosity of 40%

then a Darcy flux calculation (with saturated flow conditions) indicates a travel time through this layer of about 250 years. If the subsoil is the major pathway for recharge, the groundwater therefore would be expected to be 'old'. It was decided to investigate the age of the groundwater further by sampling for CFCs. Samples taken from two of the production wells both indicated the age of the groundwater to be 1979. As shown by the calculation above, this relatively young recharge age cannot be explained by direct recharge through the subsoil; as such, the CFC analyses indicate that the main recharge is not via the subsoil, but from another source.

Subsoil mapping by the GSI shows that the subsoils thin rapidly north of the Knockatallon aquifer and that the Carnmore Sandstone Member of the Meenymore outcrops on the higher ground (Fig. 3.5). It is therefore considered likely that the main mechanism for recharge to the Knockatallon aquifer is via the

Carnmore Sandstone Member, with the water moving down gradient in fractures mainly located along the extensively weathered rock head of the Meenymore and Dartry formations. In terms of protecting the well field, it is therefore potential contamination hazards in the Carnmore Sandstone outcrop area that are of more relevance than hazards closer to the well field, where the thick subsoils offer protection to the groundwater.

River baseflow separation (again using the Boughton technique) on data from two gauging stations located several kilometres downstream of the main aquifer area suggested recharge coefficients of 12–17%. These are likely to be overestimates, in that the 'slow flow' component interpreted as groundwater baseflow is likely to include releases from peat deposits and other subsoils. Application of the Institute of Hydrology method (1989) produced even higher baseflow estimates (Section 7.7.5 in the End of Project Report).

4 Development of a GIS-Based Assessment Tool

4.1 Introduction

The fourth objective of this study was to develop a preliminary GIS-based assessment tool for the estimation of groundwater recharge (recharge acceptance). It is important for readers to appreciate that this GIS tool is only intended to provide an initial estimation of recharge as part of a project desk study and should not replace the detailed hydrogeological characterisation of any site.

The hydrogeological properties and estimated recharge coefficients for the four sites studied in this project are summarised in Table 4.1. Together with the coefficients derived in previous studies, these data can be used to develop guidelines on how recharge can be estimated for any site where the aquifer properties, subsoil cover properties and climate data are known or can be inferred. This can be achieved by using the existing data available in the GSI GIS.

4.2 Project Results in Relation to Previous Irish Recharge Studies

Previous investigations into recharge in Ireland include the studies by Scanlon (1985), Daly (1994), MacCarthaigh (1994), Aslibekian (1999) and Fitzsimons and Misstear (2006). These earlier recharge findings have been used in the document *Guidance on the Assessment of the Impact of Groundwater Abstractions*, which was published in 2005 by the Working Group on Groundwater. The Working Group document includes a table linking groundwater vulnerability to a range of hydrogeological settings, and presents likely ranges of recharge coefficient for each setting (Table 4.2). As described in Section 2.1, vulnerability categories are determined mainly by subsoil thickness and permeability, but the hydrogeological settings also take account of main soil type (well drained, poorly drained and peat). The case study areas are shown (in bold) in the table under the relevant hydrogeological settings, and it can be seen that the recharge coefficient results (Table 4.1) are consistent with the values from this earlier assessment.

Table 4.2 is based to a significant extent on the work published by Fitzsimons and Misstear (2006). That study also investigated, with the aid of a one-dimensional numerical model, the sensitivity of the recharge coefficient (termed infiltration coefficient in the paper) to variations in subsoil permeability, till thickness and vertical hydraulic gradient. It was found that, for cases where the subsoil is more than a few

Table 4.1. Summary table of the main project results.

Study area	Main aquifer, subsoil and topographic setting	Methodology	Recharge coefficient
Curragh Aquifer County Kildare	Regionally important gravel aquifer. Thin (<3 m), moderate to low permeability till cover; high vulnerability. Lowland setting	Soil moisture budget (SMB), hydrograph analysis, numerical modelling, natural tracers and catchment water balance	81–85%
Bennettsbridge lowlands	Two sub-catchments studied. Mixed aquifer, including regionally important limestone. Variable thickness of moderate permeability till and high permeability gravel cover. Mainly lowland topography	SMB, baseflow analysis	41–54% (for moderate permeability subsoils) (36–60% for entire sub-catchments)
Galmoy Mine, County Kilkenny	Regionally important limestone aquifer. Till cover generally 5–10 m thick and of moderate permeability. Lowland setting	SMB, natural tracers and water balance using dewatering discharges	55–65%
Knockatallon Aquifer County Monaghan	Locally important aquifer. Thick, low permeability till cover. Upland and lowland topography	SMB, dewatering discharges, baseflow analysis and natural tracers	<17% (and probably <5%)

Table 4.2. Recharge estimations (based on Working Group on Groundwater, 2005).

Vulnerability category	Hydrogeological setting	Recharge coefficient (rc)		
		Min. (%)	Inner range	Max. (%)
Extreme				
1.i	Areas where rock is at ground surface	60	80–90	100
1.ii	Sand/gravel overlain by well-drained soil	60	80–90	100
	Sand/gravel overlain by poorly drained (gley) soil			
1.iii	Till overlain by well-drained soil	45	50–70	80
1.iv	Till overlain by poorly drained (gley) soil	15	25–40	50
1.v	Sand/ gravel aquifer where the water table is ≤3 m below surface	70	80–90	100
1.vi	Peat	15	25–40	50
High				
2.i	Sand/gravel aquifer, overlain by well-drained soil **(Curragh aquifer, Kildare)**	60	80–90	100
2.ii	High permeability subsoil (sand/gravel) overlain by well-drained soil	60	80–90	100
2.iii	High permeability subsoil (sand/gravel) overlain by poorly drained soil			
2.iv	Moderate permeability subsoil overlain by well-drained soil	35	50–70	80
2.v	Moderate permeability subsoil overlain by poorly drained (gley) soil	15	25–40	50
2.vi	Low permeability subsoil	10	23–30	40
2.vii	Peat	0	5–15	20
Moderate				
3.i	Moderate permeability subsoil and overlain by well-drained soil	25	30–40	60
3.ii	Moderate permeability subsoil and overlain by poorly drained (gley) soil	10	20–40	50
3.iii	Low permeability subsoil	5	10–20	30
3. iv	Basin peat	0	3–5	10
Low				
4.i	Low permeability subsoil **(Knockatallon aquifer, Monaghan)**	2	5–15	20
4.ii	Basin peat	0	3–5	10
High to Low				
5.i	High permeability subsoil (sand and gravel)	60	85	100
5.ii	Moderate permeability subsoil overlain by well-drained soils **(Callan–Bennettsbridge lowlands and Galmoy)**	25	50	80
5.iii	Moderate permeability subsoil overlain by poorly drained soils	10	30	50
5.iv	Low permeability subsoil	2	20	40
5.v	Peat	0	5	20

metres thick, the main factor influencing the recharge coefficient is the subsoil permeability. Moreover, as shown in Fig. 4.1, the sensitivity is greatest in the permeability range 1×10^{-7} m/s to 1×10^{-8} m/s (or approximately 0.001–0.01 m/day). This permeability band corresponds to the lower end of the moderate permeability range (1×10^{-4} m/s to 1×10^{-8} m/s) used in the GSI's groundwater vulnerability mapping guidelines (Fitzsimons *et al*., 2003).

The results from the case studies in this Recharge and Vulnerability project are plotted in Fig. 4.2 to illustrate the relationship between subsoil permeability and recharge coefficient. This diagram is clearly approximate, as the subsoil permeability values in each study area are not known with a great deal of accuracy, and in any case would be expected to vary locally. Nevertheless, the diagram shows that there is a large variation in recharge coefficient across the span of moderate permeability subsoil values (from about 30% to 80%). The diagram also helps to highlight the boundaries between the low and moderate, and between the moderate and high, subsoil permeability categories. The value of 1×10^{-8} m/s used for the low/moderate boundary, which was based largely on the work published by Swartz *et al.* (2003), seems reasonable for distinguishing between the subsoils encountered in the study areas. The value of 1×10^{-4} m/s for the moderate/high boundary, which was based mainly on work by Ó Súilleabháin (2000), may need further reflection. The value of 1×10^{-3} m/s subsoil permeability for the Curragh gravel aquifer shown on Fig. 4.2 represents the **horizontal** permeability. The estimated **vertical** subsoil permeability is 4 m/day, or about 5×10^{-5} m/s (see Table 5.3 in the End of Project Report). Given that the Curragh aquifer is the most extensive and productive of its kind in Ireland, there may therefore be a case for lowering the moderate/high boundary permeability value to say 1×10^{-5} m/s or 5×10^{-5} m/s, to reflect the

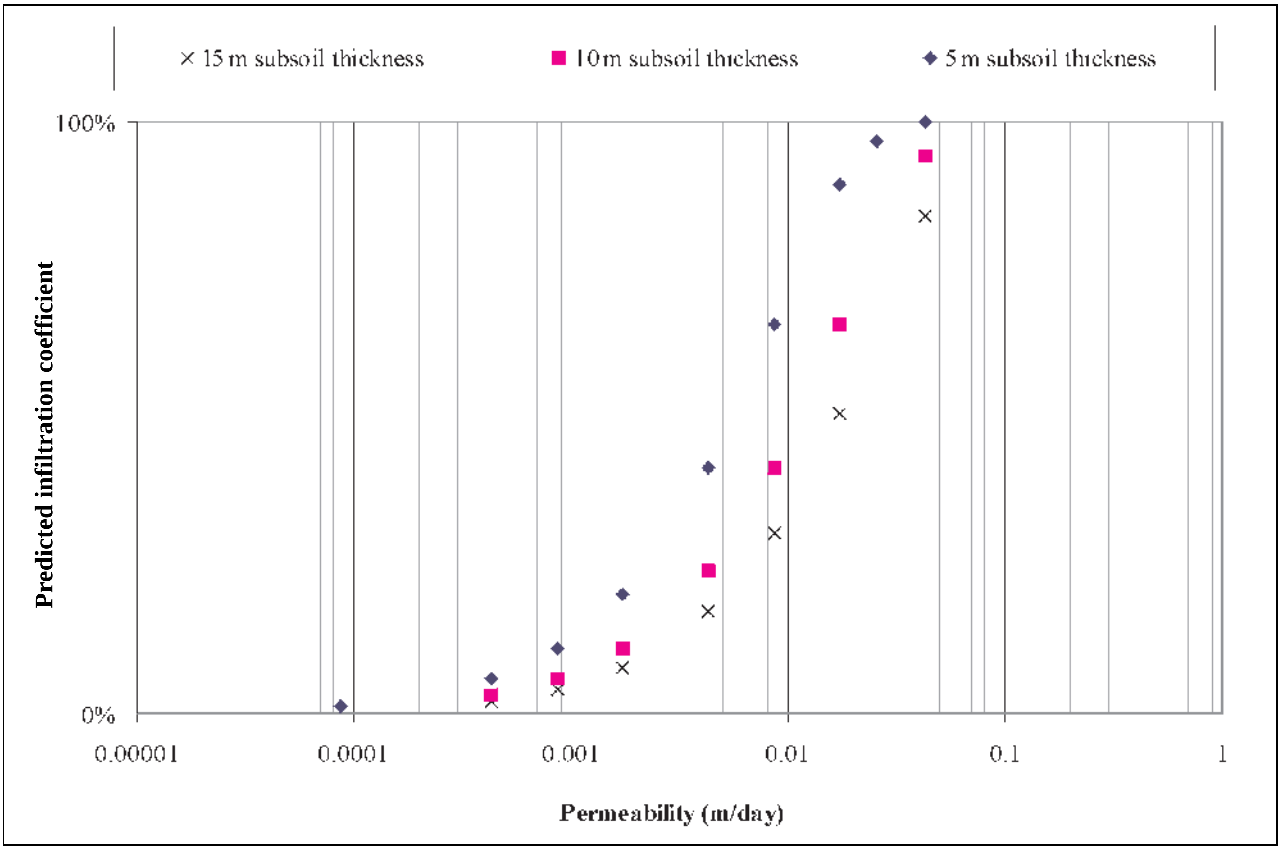

Figure 4.1. Theoretical relationship between subsoil permeability and recharge (infiltration) coefficient (on vertical axis) (from Fitzsimons and Misstear, 2006).

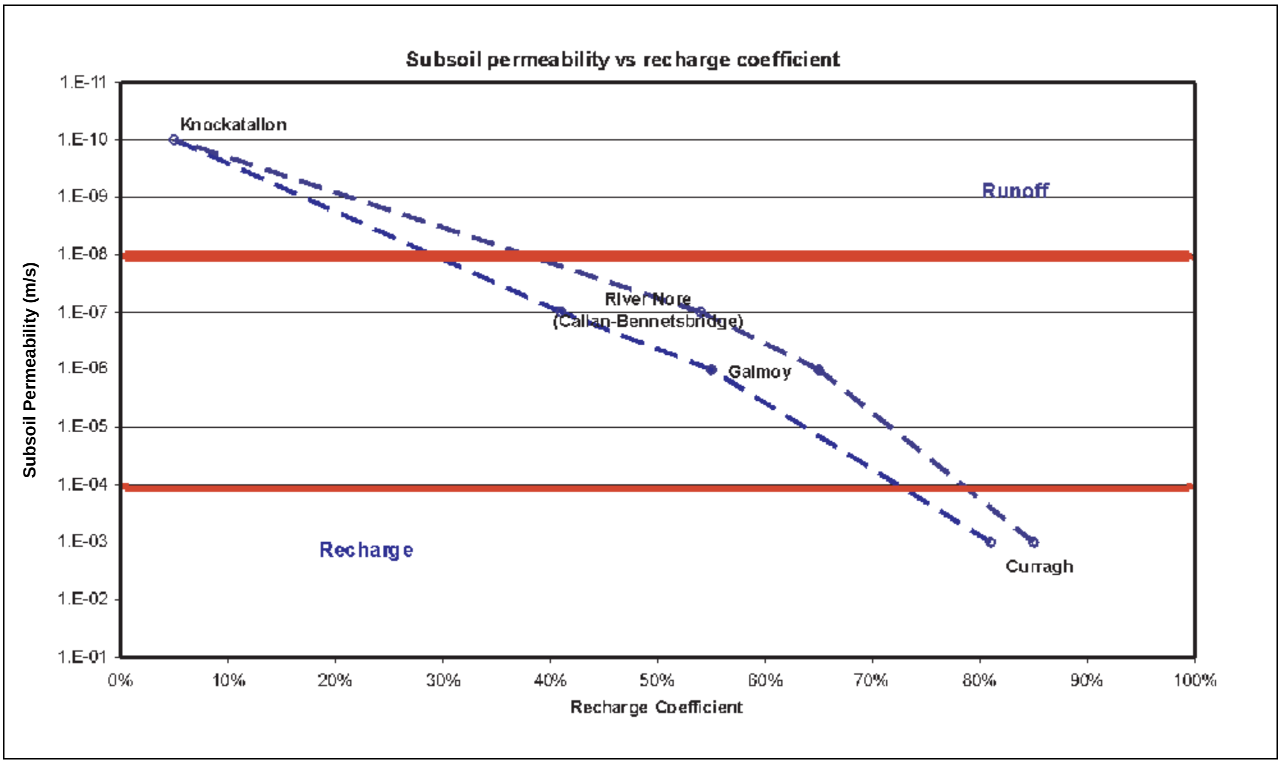

Figure 4.2. Plot of subsoil permeability (m/s) versus recharge coefficient using data from this project.

fact that we are considering vertical permeabilities in this classification.

For the proposed recharge estimation tool, it is not intended to include soil category, since this was outside the project scope and was not considered in detail in the case study areas – and so cannot be validated using the project results. However, it is proposed to make one exception to this general statement, and that is to take account of peat soils, since even a thin layer of peat, especially non-cutover lowland peat, can have a significant influence in reducing potential recharge. It should also be added that, at the time of writing, there are two other relevant projects being undertaken in relation to the Water Framework Directive implementation which may provide further insights into the use of soils data in assessing run-off and recharge – namely, the groundwater–surface water interactions project and the flow duration curves in ungauged catchments project (see Section 3.4 of the End of Project Report).

Finally, it is necessary to consider the ability of the aquifer to accept the potential recharge that is estimated from the effective rainfall values and recharge coefficients. Again, the Recharge and Vulnerability project was asked to consider only **regionally important** aquifers (although the Knockatallon aquifer, originally classified as regionally important, was downgraded to locally important during the course of the project, and partly as a consequence of the project findings). Regionally important aquifers comprise less than one-third of the aquifers in Ireland, and any national assessment of recharge must therefore also consider those aquifers classed as either poor aquifers or locally important. These aquifers will have a limit to the amount of recharge that they can accept, and when that cap is achieved all subsequent recharge will be rejected. Although these limits have not been investigated as part of this project, the Working Group on Groundwater (2005) report suggests that recharge caps of 100 mm/year and 150–200 mm/year should be applied to poor and locally important aquifers, respectively. When these recharge caps are exceeded then rejected recharge occurs and this adds to surface run-off (or interflow).

4.3 Proposed Linkages between Subsoil Permeability, Aquifer Vulnerability and Recharge

Based on the above discussion of the project findings and how they tie in with previous studies, it is proposed that the recharge coefficients for subsoils should be classed into three groupings:

1. High recharge coefficient: 70–90%
2. Intermediate recharge coefficient: 30–70%
3. Low recharge coefficient: 5–30%.

For the High category, the upper value of recharge coefficient is proposed as 90% rather than 100%, since it is considered that some of the effective rainfall will almost always be lost to run-off and/or interflow, even where subsoils are thin, absent or of high permeability. This 90% upper limit therefore makes some allowance for run-off due to factors such as topography and high intensity rainfall events. Again, a minimum value of 5% is proposed for the Low category, since it is likely that some recharge will generally occur, even where the subsoils are thick and have a low permeability.

As indicated previously the main subsoil characteristic that influences recharge potential is the subsoil permeability. The proposed linkages in Table 4.3 are therefore driven by this characteristic. The table shows the recharge category (High, Intermediate or Low) for the different permeability categories, but also takes account of subsoil thickness. By so doing, the table provides a quantified link between recharge and vulnerability class. The Extreme vulnerability class is defined by a thickness of 1–3 m; the 'X' category (rock outcrop and subsoil less than 1 m thick) delineated on current vulnerability maps is not included in the table, as its properties relate to the topsoil rather than the subsoil, but it is taken into account in the proposed GIS tool described in Section 4.4.

Table 4.3 also shows possible run-off (including interflow) categories, where these are related directly to the recharge class: High recharge = Low run-off; Intermediate recharge = Intermediate run-off; and Low recharge = High run-off. Thus, for example, the High run-off category would correspond to between 70% and 95% of effective rainfall.

In Section 4.2, the issue of recharge acceptance was discussed in the context of how much water could be taken in by the aquifer. It is also important to consider whether the recharge coefficient categories are consistent with likely rainfall intensities and infiltration rates. This may be a particular issue with the Intermediate recharge category when subsoil permeabilities are as low as 1×10^{-8} m/s (the boundary between moderate and low permeability subsoil). A permeability of 1×10^{-8} m/s would imply a maximum infiltration rate of around 0.9 mm/day. Assuming a recharge season of 6 months, this in turn would imply a maximum infiltration capacity of 150 mm. Therefore, this would suggest that the lower value of the Intermediate recharge coefficient range (i.e.

Table 4.3. The link between subsoil permeability, recharge, run-off and aquifer vulnerability.

Subsoil			Recharge	Run-off	Aquifer vulnerability
Permeability		Thickness (m)			
High	>1 x 10^{-4} m/s	1–3	High	Low	Extreme
		3–10	High	Low	High
		>10	High	Low	High
Moderate	1 x 10^{-4} to 1 x 10^{-8} m/s	1–3	High	Low	Extreme
		3–10	Intermediate	Intermediate	High
		>10	Intermediate	Intermediate	Moderate
Low	<1 x 10^{-8} m/s	1–3	Intermediate	Intermediate	Extreme
		3–5	Low	High	High
		5–10	Low	High	Moderate
		>10	Low	High	Low

30%) should be applied when the subsoil permeability is near the boundary between the moderate and low permeability categories.

In Section 4.2, it was stated that it is not proposed to take soil type into account in the methodology, other than in the case of peat. However, it may be worthwhile considering refining the recharge tool in the future to take account of 'wet' and 'dry' soil categories where the subsoil is less than 3 m in thickness.

4.4 Methodology for Adapting the Current GIS-Based Tool to Include Recharge

The proposed GIS tool is shown schematically in Fig. 4.3. This shows the linkages between the existing GIS layers or databases, and new databases. The new databases will enable the determination of:

- effective rainfall
- subsoil recharge coefficient
- recharge acceptance (for poor and locally important aquifers).

The output will consist of estimates of the recharge (as a range of values) and run-off (again as a range of values).

4.4.1 Available data sets

The GSI, Teagasc, the Ordnance Survey of Ireland (OSI) and Met Éireann maintain databases of geological, hydrogeological, geographical and climatological data within their GISs. Several of these national databases are available to the public via the Internet; others are only accessible in-house.

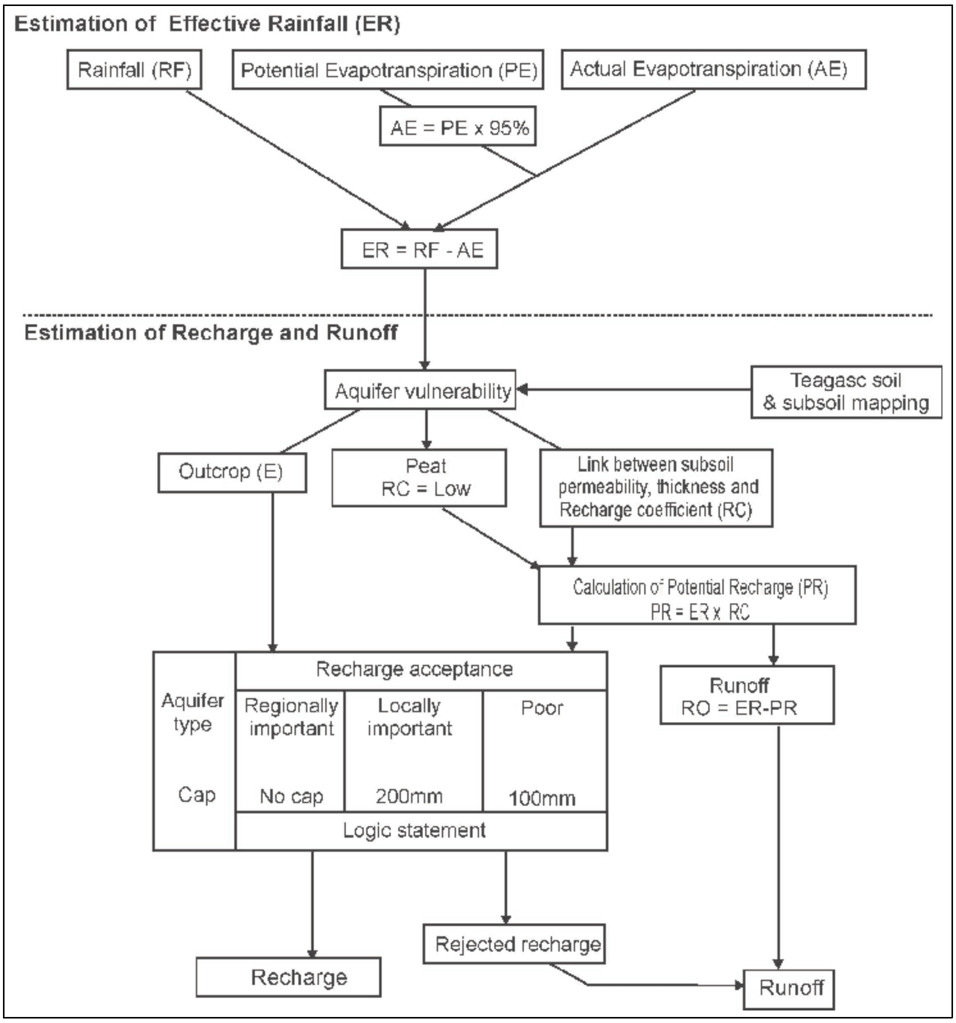

Figure 4.3. Structure and methodology of GIS-based tool for estimating recharge.

Climate data (Met Éireann)

- 30-year rainfall
- 30-year actual evapotranspiration (Penman–Monteith)

Climate data have been provided by Met Éireann to the GSI as two data sets, rainfall and actual evapotranspiration (AE). The data are available as both monthly and annual averages for the 30-year periods 1961–1990 and 1971–2000. The 1961–1990 data set is being used by both the groundwater–surface water interaction project and the flow duration curve project, because this period is considered more representative; for consistency, this climate period presumably would also be used in the recharge tool. The rainfall and evapotranspiration data sets are available nationally and are presented in the GIS as a series of contours, which are derived from monitoring locations maintained by Met Éireann. Rainfall data are based on a combination of the 750 manual (storage) rain gauges and 13 synoptic stations. However, the AE data set is based upon the 13 synoptic stations only. The AE values are calculated from PE (Penman–Monteith) for grassland, using a 10% reduction to account for a stress during the summer period.

Topography (OSI)

- 1:50,000 (Discovery Series) raster maps
- Topographic contours

The OSI maintains a national topographic database. These data are presented in the GIS as a series of contours (with user-defined spacing).

Geology (GSI)

- National bedrock
- National bedrock aquifers
- National sand and gravel aquifers
- Karst landforms
- Rock outcrop
- Aquifer vulnerability
- River Basin Districts

The GSI has compiled data sets for both bedrock type and aquifer (bedrock and sand and gravel) classification. The maps are available on the GSI website, and show the RBD boundaries.

As part of the GSI groundwater protection schemes, subsoil thicknesses were determined on a county-by-county basis to develop a county database for depth to bedrock. These data were collected using a rotary auger-drilling rig to probe subsoil depth. Samples were described according to BS 5930:1999, and these descriptions, together with information on drainage density and vegetation characteristics, were used to estimate permeability; for the more recent county groundwater protection schemes, samples were taken for particle size distribution analysis. The programme of groundwater protection schemes has not been completed for all counties: at present (2007) the data are available for approximately half of the country.

Soils and subsoils (Teagasc)

- National subsoil survey
- National soil survey

Teagasc completed a national programme of subsoil mapping in 2006. These data, which were mapped using aerial photographs, identify the parent materials for the subsoils. The subsoils map is available on a county-by-county basis. Where GSI vulnerability data are not available for a county, then the Teagasc data may be used to estimate the vulnerability category. Only an interim vulnerability map can be produced, since the subsoil thickness is unknown. The interim vulnerability maps consist of three vulnerability classes: ‘X’ (rock near surface or karst), Extreme and undifferentiated High to Low.

4.4.2 New databases

The new databases that will be required to determine recharge are:

(a) Effective rainfall presented as a contour map of mm/year based upon rainfall and AE

(b) Recharge coefficient for the subsoil that covers the aquifer

(c) Recharge acceptance of the aquifer.

The Teagasc subsoils map will also be required to identify areas of peat, which will be assigned a Low recharge coefficient (5–30%).

Effective rainfall

As both rainfall and actual evapotranspiration are available as data sets, the calculation of effective rainfall is simply the net balance of the two. Effective rainfall can be calculated as annual values but also as monthly averages, using 30-year averages. Given the availability of these data then it would be preferable to calculate effective rainfall as both monthly and annual averages, so that seasonality of recharge can be taken into account.

Subsoil recharge coefficient

During this project, ranges of recharge coefficient values were derived for each of the study areas, and compared with ranges obtained previously for similar hydrogeological settings (Table 4.2). As explained in Section 4.3, this is also the proposed approach for the GIS tool, where the subsoil will be categorised as having a High, Intermediate or Low recharge coefficient. The hydrogeologist would then decide as to whether the upper, middle or lower end of each range was the most appropriate for the particular conditions encountered. For example, a 5-m thick moderate permeability subsoil would have a recharge coefficient in the Intermediate category (30–70%) according to Table 4.3; then, if the estimated subsoil permeability value was close to the moderate/high boundary (1×10^{-4} m/s), the higher end of the recharge coefficient band (i.e. 70%) would be chosen as being more likely to be applicable.

Aquifer recharge acceptance

As explained in Section 4.2, and illustrated in Fig. 4.3, caps on recharge acceptance are imposed on poor and locally important aquifers, where the caps are 100 mm/year and 150–200 mm/year, respectively. Here it is proposed to adopt the upper value of 200 mm/year for the cap on recharge to locally important aquifers (the lower value being considered too similar to the cap for the poor aquifer).

An example calculation is given in Section 8.4.3 of the End of Project Report.

4.5 Estimating Recharge Where Vulnerability Maps Are Not Available

The scope of this project was to consider only those areas for which vulnerability maps are available. In areas where full vulnerability maps are not available, recharge can be estimated by using the Teagasc soils and subsoils maps (which form the basis of the interim vulnerability maps showing ‘X’ (rock near surface), Extreme (1–3 m subsoil) and undifferentiated High to Low). The GSI, in conjunction with RBD consultants, has recently assigned tentative permeability classes to the main subsoil mapping categories on the Teagasc maps. These data, together with the recharge coefficient values for the different hydrogeological settings in Table 4.2, can then be used to make preliminary estimates of recharge as described in Moe *et al.* (2007). A useful exercise would be to test these GIS-based recharge estimates against the recharge data collected for the study areas in this project.

5 Conclusions and Recommendations

5.1 Conclusions

The recharge coefficient values obtained were:

- 81–85% for the high permeability subsoils of the Curragh gravel aquifer
- 41–54% for the moderate permeability subsoils within the Callan–Bennettsbridge lowlands (or 36–60% for the full sub-catchment areas, which include high and low permeability subsoils as well as moderate permeability subsoil)
- 55–65% for the moderate permeability subsoils of the Galmoy mine area
- less than 17% (and probably less than 5%) for the low permeability subsoils of the Knockatallon aquifer.

These results are consistent with the values proposed by Fitzsimons and Misstear (2006) and by the Working Group on Groundwater (2005; see Table 4.2).

The results of the case studies were used to develop a quantified link between subsoil permeability, aquifer vulnerability, recharge and run-off (Table 4.3). Recharge and run-off coefficients are each classed into three groupings: High (70–90%), Intermediate (30–70%) and Low (5–30%). A High recharge coefficient equates to a Low run-off coefficient, and *vice versa*. For the High category, the upper value of recharge coefficient is proposed as 90% rather than 100%, since it is considered that some of the effective rainfall will almost always be lost to run-off (and/or interflow), even where subsoils are thin, absent or of high permeability. This 90% upper limit therefore makes some allowance for run-off due to factors such as topography and high intensity rainfall events. Again, a minimum value of 5% is proposed for the Low category, since it is considered likely that some recharge will generally occur, even where the subsoils are thick and have a low permeability.

A GIS-based tool is proposed that will enable the estimation of recharge using recharge coefficient values (Section 4.4). Potential recharge is calculated as the product of effective rainfall and recharge coefficient. The actual recharge is then calculated taking account of the ability of the aquifer to accept the available recharge. Recharge caps (existing values) are applied to poor and locally important aquifers. Run-off (including interflow) is calculated from the effective rainfall that does not become potential recharge, plus any rejected recharge.

It is not proposed to incorporate the characteristics of the topsoil within the recharge assessment tool, except in the case of peat deposits, which are assigned to the Low recharge coefficient grouping. However, it is recognised that topsoil characteristics may influence recharge, especially where the subsoils are thin (i.e. in ‘X’ and Extreme vulnerability areas), and so the tool could be refined to include the main soil groupings of ‘wet’ or ‘dry’ where subsoils are less than 3 m thick.

The project provided some useful insights into the methods used for estimating recharge:

- The river baseflow analyses illustrated the difficulties involved in applying these techniques to areas where the catchments covered by the stream gauge network involve a significant degree of heterogeneity in aquifer and subsoil types. Following earlier work described in Misstear and Fitzsimons (2007), some of these difficulties were partially addressed in the Callan–Bennettsbridge lowlands by applying the analysis to a hybrid sub-catchment containing more uniform characteristics than the larger river catchment, though even here the moderate permeability subsoil covers only 28% of the area. As indicated in Section 3.3.1, the baseflow percentages for this hybrid sub-catchment, and for the King’s River sub-catchment (48% moderate permeability subsoil), were adjusted to give the possible ranges of recharge coefficient for the proportions of the sub-catchments comprising moderate permeability subsoil.

- The Boughton method was the preferred method for the baseflow separation exercises because this method allows the hydrogeologist considerable flexibility in carrying out the analyses. Moreover, the Boughton method was used to give likely ranges of baseflow, rather than single values. It was also evident that other methods can result in unrealistically high estimates of baseflow, even for rivers such as those draining the Tydavnet/ Knockatallon area, where the aquifer is covered by thick, low permeability subsoils and where groundwater discharge would be expected to be very small. It should be noted, however, that the choice of parameters when applying the Boughton method is somewhat subjective and, therefore, as with other baseflow separation techniques, this method should be used with caution.

- The CFC analyses were useful for providing possible ages for the groundwater samples. In the Knockatallon aquifer, the relatively young groundwater ages helped to demonstrate that the majority of groundwater at the well field was unlikely to derive from direct (diffuse) recharge through the overlying thick low permeability subsoils.

The project also provided useful insights into the hydrogeology of the study areas, including:

- The well hydrograph analysis in the Curragh area indicated that the specific yield of this gravel aquifer is higher than previously assumed. Applying the single value of specific yield (13%) incorporated in the existing groundwater model of the aquifer gave unrealistically low values of recharge coefficient (50–80%). A higher value of 19% gave more reasonable estimates of between 72% and 100%. This finding may be useful when considering the specific yield values of other sand and gravel aquifers in Ireland.

- The CFC analyses in the Galmoy area indicated that the water being abstracted for the mine dewatering comprises a mixture of modern recharge and older groundwater from aquifer storage.

- Being one of only five groundwater bodies in Ireland considered to be at risk in terms of quantitative status, the trends in groundwater levels in the Knockatallon aquifer were of considerable interest. The monitoring showed that the groundwater levels in the vicinity of the well field had nearly (but not completely) stabilised by 2005, with an average abstraction of around 1,000 m^3/day. Abstractions have recently reduced (owing to the introduction of an additional, surface water component to the group water scheme), and continued monitoring will be needed to establish the sustainable abstraction rate.

- Geophysical logging was found to be very useful for providing additional data on the Knockatallon boreholes. The main aquifer unit was confirmed to be the Dartry Limestone.

- Reinterpretation of pumping test data from 1992 showed that the most productive well in the Knockatallon aquifer appears to take its water from a relatively isolated, fault-bounded, block of aquifer.

5.2 Recommendations for Further Work

1. The enhancements proposed for the existing GIS system, to achieve the quantified link between recharge and vulnerability, should be implemented initially on a pilot basis, in one of the counties for which good quality vulnerability mapping is available. This should be done when the results of the other ongoing projects relating to recharge and run-off are available, notably the groundwater–surface water interactions project and the flow duration curve/catchment descriptors project. The methodologies proposed in all three projects should be tested in the same area, the results compared, and then the methodologies should be refined as appropriate.

2. The Knockatallon aquifer case study highlighted the influence of recharge on the aquifer potential: the thick low permeability subsoils covering the aquifer inhibit recharge and hence limit the available resource. Consequently, despite relatively high aquifer transmissivities, the sustainable well yields are not as high as was

originally envisaged and the aquifer was downgraded from regionally important to locally important during this project. Consideration should therefore be given to incorporating recharge potential as a factor when classifying an aquifer.

3. Groundwater-level monitoring should continue in the Knockatallon aquifer, with a view to further refining the estimates of sustainable resource of this aquifer.

4. Appropriate recharge caps should be investigated for locally important and poor aquifers. This could involve a study of groundwater-level hydrographs and specific yield as part of the proposed monitoring programme for poorly productive aquifers.

5. The subsoil permeability value used for the boundary between the moderate and high permeability categories (1×10^{-4} m/s) should be reviewed in the light of the study of the Curragh gravel aquifer during this project. On the basis that this boundary value should reflect a **vertical** permeability, there may be a case for lowering the boundary permeability value to say 1×10^{-5} m/s or 5×10^{-5} m/s.

References

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. Food and Agriculture Organisation Irrigation and Drainage Paper 56. FAO, Rome, Italy.

Aslibekian, O., 1999. Regional assessment of groundwater recharge. *The GSI Groundwater Newsletter*, No. 35. Geological Survey of Ireland, Dublin, Ireland.

Boughton, W.C., 1993. *A Hydrograph-Based Model for Estimating Water Yield of Ungauged Catchments*. Institute of Engineers Australia National Conference. Publ. 93/14, 317–324.

Boughton, W.C., 1995. Baseflow recessions. *Australian Civil Engineering Transactions* **CE37(1):** 9–13.

British Standards Institution, 1999. BS 5930:1999 *Code of Practice for Site Investigations*. BSI, London, UK.

Chapman, T., 1999. A comparison of algorithms for stream flow recession and baseflow separation. *Hydrological Processes* **13:** 710–714.

Daly, E.P., 1994. *Groundwater Resources of the Nore River Basin*. GSI Report 94/1. The Geological Survey of Ireland, Dublin, Ireland

DoELG, EPA and GSI, 1999. *Groundwater Protection Schemes*. Department of Environment and Local Government, Environmental Protection Agency and Geological Survey of Ireland, Dublin, Ireland.

European Commission, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water resources. *Official Journal of the EC* **L327:** 1–73.

Fitzsimons, V.P. and Misstear, B.D.R., 2006. Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland. *Hydrogeology Journal* **14:** 548–561.

Fitzsimons, V., Daly, D. and Deakin, J., 2003. *GSI Guidelines for Assessment and Mapping of Groundwater Vulnerability to Contamination.* Draft, June 2003, The Geological Survey of Ireland, Dublin, Ireland.

Geraghty M., Farrelly, I., Claringbold, K., Jordan, C., Meehan, R. and Hudson, M.,1997. *The Geology of Monaghan–Carlingford (Sheet 8/9).* The Geological Survey of Ireland, Dublin, Ireland.

Hayes, T., Sutton, S., Cullen, K. and Faherty, J., 2001. The Curragh Aquifer – Current conceptual understanding and numerical modelling. *In: Gravel Aquifers: Investigation, Development and Protection*. Proceedings of the 21st Annual IAH (Irish Group) Groundwater Seminar, Tullamore, Ireland.

Healy, R.W. and Cook, P.G., 2002. Using groundwater levels to estimate recharge. *Hydrogeology Journal* **10(1):** 91–109.

Institute of Hydrology, 1989. *Flow Regimes from Experimental and Network Data (FREND)*. NERC, Wallingford, UK.

Kelly, R., 2001. *An Investigation into Groundwater Resources in the Knockatallon Area Northwest of Monaghan*. Unpublished MSc thesis, Civil Engineering Department, Queen's University Belfast. Belfast, Northern Ireland.

MacCarthaigh, M., 1994. *Summary Details of Water Balances in Glyde, Dee, Finn and Blackwater (Monaghan) Catchments for the Period December 1975 – November 1977*. Environmental Protection Agency, Dublin, Ireland.

Misstear, B.D.R., 2000. Groundwater recharge assessment: a key component of river basin management. *In: River Basin Management*. Tullamore National Hydrology Seminar 2000, Proceedings pp. 52–59.

Misstear, B.D.R. and Daly, D., 2000. Groundwater protection in a Celtic region: the Irish example *In:* Robins, N.S. and Misstear B.D.R. (eds) *Groundwater in the Celtic regions: Studies in Hard Rock and Quaternary Hydrogeology*. Geological Society, London, Special Publications **182:** 53–65.

Misstear, B.D.R. and Fitzsimons, V., 2007. Estimating groundwater recharge in fractured bedrock aquifers in Ireland. Chapter 16 in *Groundwater in Fractured Rocks*. Special Publication 9 of the International Association of Hydrogeologists, J. Krasny & J. Sharp (eds), Taylor and Francis, 2007, pp. 243–257.

Misstear, B.D.R., Brown L. and Hunter-Williams, T., 2005. The Knockatallon aquifer in County Monaghan: A bedrock aquifer under significant stress from pumping. In *Proc. 25th annual groundwater seminar on 'Groundwater in Ireland'*, International Association of Hydrogeologists (Irish Group), Tullamore, 19–20 April 2005, pp. 41–48.

Misstear, B.D.R., Banks, D. and Clark, L., 2006. *Water Wells and Boreholes*. J. Wiley & Sons, UK.

Moe, H., Daly, D., Hunter-Williams, T., Mills, P. and Gaston, L., 2007. A national assessment of groundwater abstraction pressures. *In: Proc. 27th annual groundwater seminar on 'Groundwater Pressures and Opportunities'*. International Association of Hydrogeologists (Irish Group), Tullamore, 24–25 April 2007, 5-25–5-32.

Ó Súilleabháin, C., 2000. *Assessing the Boundary between High and Moderate Permeability Subsoils*. Unpublished MSc thesis, Department of Civil, Structural and Environmental Engineering, Trinity College Dublin, Dublin, Ireland.

Rushton, K.R., 2005. Estimating recharge for British aquifers. *Water and Environment Journal* **19:** 115–124.

Rushton, K.R., Kawecki, M.W. and Brassington, F.C., 1988. Groundwater model of conditions in the Liverpool Sandstone Aquifer. *Journal of the Institution of Water and Environmental Management* **2:** 67–84.

Scanlon, B.R., 1985. *A groundwater Study of the Maine River Basin, County Kerry*. Geological Survey of Ireland report series SR 85/1. The Geological Survey of Ireland, Dublin, Ireland. 35 pp.

Swartz, M., Misstear, B.D.R., Daly, D. and Farrell, E.R. 2003. Assessing subsoil permeability for groundwater vulnerability.

Quarterly Journal of Engineering Geology and Hydrogeology **36(2):** 173–184.

Working Group on Groundwater, 2005. *The characterisation and analysis of Ireland's River Basin Districts in accordance with Section 7 (2 & 3) of the European Communities (Water Policy) Regulations 2003 (SI 722 of 2003).* National Summary Report, Ireland. Available on www.wfdireland.ie

Wright, G., 1988. *The Mid-Kildare Gravel Aquifer. In:* Proceedings of the 8th Annual IAH (Irish Group) Groundwater Seminar, Portlaoise, Ireland.

National Development Plan 2007 - 2013

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.

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