Ireland at risk – Possible implications for groundwater resources of climate change

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1 Introduction

The aim of this paper is to highlight potential impacts on groundwater resources in Ireland due to forecasted climate change. The current situation and future predictions for groundwater resources are indicated, knowledge gaps highlighted, and potential future courses of action suggested, in terms of both infrastructural development strategy and research areas.

This document is intended to be read as an accompaniment to papers produced for the IAE Workshop held in May 2007, to address some of the groundwater aspects already raised in the other papers, and highlight other issues relating to groundwater resources in the context of climate change. Qualitative assessments of the risks from climate change to the subsurface part of the hydrological cycle are given from the perspective of groundwater conditions particular to Ireland. It is neither an exhaustive literature survey nor a comprehensive overview of the subject.

2 Groundwater resources in Ireland

2.1 Overview

Groundwater resources in Ireland, in terms of both quantity and quality, can be classed as generally good. Risk assessment of abstraction pressures on groundwater indicate that less than 1% of groundwater bodies (GWBs) in Ireland are currently known to be at risk of over-abstraction (EPA/RBD Co-ordinating Authorities, 2005; Moe *et al.*, 2007). Overall, groundwater quality is generally good. There are, however, widespread issues of poor microbiological quality (Page *et al.*, 2006). In certain areas, particularly the southeast, elevated nitrate concentrations occur.

2.2 Groundwater occurrence

Groundwater is water located beneath the ground surface in pore spaces and fractures of geologic formations. If the subsurface deposit can yield water in useful quantities, then the term aquifer is often used.

Groundwater is an integral part of the hydrological cycle – rain falling on the ground surface can either run off to surface waters, or percolate into the subsurface. Water that reaches the groundwater system flows underground until it discharges in rivers, at springs, or at groundwater-supported ecosystems such as fens and turloughs. Whilst there are seasonal variations in groundwater levels and flows to the surface, there is an overall long-term balance between recharge and outflows.

2.2.1 Aquifers in Ireland

In most Irish bedrock aquifers, groundwater flows through fissures, fractures and faults. The amount of groundwater that can flow through fractured bedrock depends on the number, size and connectivity of fissures. More groundwater can flow through a highly-fissured rock in which the fracture aperture is large, and the fissures are well-connected. Conversely, less groundwater is able to flow through a rock in which there are few fractures, and those that exist are poorly connected and very small. The aquifer map of Ireland is shown in Figure 1.

The development of fissures through which groundwater can flow depends principally on the rock type (e.g., limestone, sandstone, granite, etc.), its original structures (e.g., bedded, unbedded, cooling joints, etc.), and the type and amount of deformation that the rock has been subjected to (e.g., folding and faulting). Limestone purity influences a rock's susceptibility to dissolution (karstification); bedding presence or absence influences the prevalence of jointing. Undeformed rocks generally have little fissuring in them; rocks subjected to moderate stresses and strains display a range of fracturing from moderate to intense; very highly deformed rocks can be so strongly altered that fracture size and connectivity decreases.

Groundwater is also found in useable amounts in unconsolidated deposits of sand and gravel. If sufficiently large, these deposits may form the groundwater resource in their own right and be classed as aquifers; smaller deposits may act as a high-porosity "reservoir" of groundwater over a fractured bedrock aquifer.

The aquifer classification system used in Ireland, which was developed by the GSI, is defined in the Groundwater Protection Schemes publication (DELG/EPA/GSI, 1999). It is intended to (i) reflect the groundwater flow type (flow through fissures, flow through karst systems, intergranular flow through gravels) and (ii) describe the resource potential (e.g., Regionally important, Locally important, Poor). Differences in aquifer properties and groundwater flow regimes are incorporated into aquifer categories and are described by their associated conceptual models (Box 1).

2.2.2 Groundwater recharge

Groundwater recharge depends broadly on three main factors: effective rainfall, subsoil properties and aquifer properties. The amount of water available to potentially become groundwater recharge depends ultimately on rainfall. Key meteorological parameters are rainfall amount, effective rainfall and rainfall timing. Effective rainfall is the component of rainfall available to run off to surface or recharge to groundwater once the demands of plants (transpiration) or evaporation has been taken into account. Evapotranspiration depends on temperature and vegetation type, since different plants have different growing seasons and different water demands. Prolonged rainfall is more effective at recharging groundwater; shorter, more intense periods of precipitation often cannot percolate through the soils and subsoils, but instead runoff to surface water bodies.

Subsoil permeability is the principal subsoil factor controlling recharge, with subsoil thickness being a secondary factor. Subsoil permeability influences how quickly effective rainfall can percolate into the subsurface to become groundwater recharge. Work done by the GSI (Daly, pers. comm.; Fitzsimons and Misstear, 2006) demonstrates that the velocity at which water can flow vertically downwards through the subsoil layer reduces dramatically in low permeability subsoils, with the consequence that much of the effective rainfall runs off to surface water bodies, even under low intensity rainfall conditions. An EPA-funded ERTDI study (Misstear *et al.*, 2006) quantifying recharge proportions for different hydrogeological scenarios indicates less than 5% of annual effective rainfall becomes groundwater recharge where subsoils are thick clay, whereas recharge to gravel aquifers is in excess of 80% of effective rainfall. The Irish Working Group on Groundwater (GWWG) has produced guidelines on recharge coefficients for many different subsoil permeabilities and hydrogeological settings (GWWG, 2004).

Box 1. Description of GSI's aquifer classes

Regionally Important Bedrock Aquifers: Bedrock aquifer unit is capable of supplying regionally important abstractions (e.g. large public water supplies), or 'excellent' yields (>400 m^3/d). The continuous aquifer unit generally has an area of >25 km^2. Groundwater flow predominantly occurs through fractures, fissures and joints.

Rf Regionally Important Fissured Bedrock Aquifer: Aquifer in which the network of fractures, fissures and joints, through which groundwater flows, is well connected and widely dispersed, resulting in a relatively even distribution of highly permeable zones. There is relatively good aquifer storage, and groundwater flow paths can be up to several kilometres in length. Substantial groundwater discharge to surface waters likely ('baseflow') and large (>2000 m^3/d), dependable springs may be associated with these aquifers.

Rk Regionally Important Karstified Bedrock Aquifer: 'Karstification' is the process whereby limestone is slowly dissolved away by percolating waters. It most often occurs in the upper bedrock layers and along certain fractures, fissures and joints, at the expense of others. Karstification frequently results in the uneven distribution of permeability through the rock, and the development of distinctive karst landforms at the surface (e.g. swallow holes, caves, dry valleys), some of which provide direct access for recharge/surface water to enter the aquifer. The landscape is characterised by largely underground drainage, with most flow occurring through the solutionally-enlarged, interconnected fissure/conduit zones, which may be several kilometres long. Groundwater velocities through fissures/conduits may be high and aquifer storage is frequently low. Groundwater often discharges as large springs (>2000 m^3/d), which range from regular and dependable to highly variable ('flashy'). There is strong interconnection between surface water and groundwater. The degree of karstification ranges from slight to intense. GSI recognises two types of karst aquifer: those dominated by diffuse flow (Rkd) and those dominated by conduit flow (Rkc).

Rg Regionally Important Sand/Gravel Aquifer: A sand/gravel aquifer is classed as regionally important if it can sustain regionally important abstractions (e.g. large public water supplies), or 'excellent' yields (>400 m^3/d). It is highly permeable, more than 10 m thick or has a saturated thickness of at least 5 m, and normally extends over at least 10 km^2. Groundwater flows through the pore spaces between sand/gravel grains, and permeability is mainly determined by the grain size (larger grains give larger pore spaces), and the 'sorting' of the material (more uniform grain sizes give higher permeability). There is a relatively uniform distribution of groundwater, good aquifer storage and long groundwater flow paths, typically limited by the aquifer's extent. Groundwater gradients are typically low ('flat' water tables), giving relatively low groundwater velocities. There is generally a strong interaction between surface water and groundwater, with groundwater discharging into streams if the water table is high, or conversely, the surface water moving into the aquifer, if the surface water level is high. Large, dependable springs (>2000 m^3/d) are often associated with sand/gravel aquifers, especially in low-lying areas or at the periphery of the aquifer.

Locally Important Bedrock Aquifers: Bedrock aquifer unit capable of supplying locally important abstractions (e.g. smaller public water supplies, group schemes), or 'good' yields (100-400 m^3/d). Groundwater flow occurs predominantly through fractures, fissures and joints.

Lm Locally Important Bedrock Aquifer, Generally Moderately Productive: Aquifer in which the network of fractures, fissures and joints, through which groundwater flows, is reasonably well connected and dispersed throughout the rock, giving a moderate permeability and groundwater throughput. Aquifer storage is moderate and groundwater flow paths can be up to several kilometres in length. There is likely to be a substantial groundwater contribution to surface waters ('baseflow') and large (>2000 m^3/d), dependable springs may be associated with these aquifers. This classification also includes aquifers similar to the Regionally Important Fractured Bedrock Aquifer (Rf), but with a smaller continuous area (<c.25 km^2). Although the aquifer may supply 'excellent' yields, the small size limits the amount of recharge available to meet abstractions.

Ll Locally Important Bedrock Aquifer, Moderately Productive only in Local Zones: Aquifer with a limited and relatively poorly connected network of fractures, fissures and joints, giving a low fissure permeability which tends to decrease further with depth. A shallow zone of higher permeability may exist within the top few metres of more fractured/weathered rock, and higher permeability may also occur along fault zones. These zones may be able to provide larger 'locally important' supplies of water. In general, the lack of connection between the limited fissures results in relatively poor aquifer storage and flow paths that may only extend a few hundred metres. Due to the low permeability and poor storage capacity, the aquifer has a low 'recharge acceptance'. Some recharge in the upper, more fractured/weathered zone is likely to flow along the relatively short flow paths and rapidly discharge to streams, small springs and seeps. Groundwater discharge to streams ('baseflow') can significantly decrease in the drier summer months.

Lk Locally Important Karstified Bedrock Aquifer: Essentially similar to the Regionally Important Karstified Bedrock Aquifer (Rk), but with a smaller continuous area (<c.25 km^2). Although the properties imply that this aquifer can supply 'excellent' yields, the smaller size limits the amount of recharge available to meet abstractions.

Lg Locally Important Sand/Gravel Aquifer: Similar to a Regionally Important Sand/Gravel Aquifer (Rg), but with a smaller continuous area (c.1-10 km^2) and/or less consistent permeability. Although the aquifer may supply 'excellent' yields, the smaller size limits the amount of recharge available to meet abstractions.

Poor Bedrock Aquifers: Bedrock aquifer capable of supplying small abstractions (e.g. domestic supplies, small group schemes), or 'moderate' to 'low' yields (<100 m^3/d). Groundwater flow occurs predominantly through a limited and poorly-connected network of fractures, fissures and joints.

Pl Poor Bedrock Aquifer, Moderately Productive only in Local Zones: Similar to a Locally Important Bedrock Aquifer, Moderately Productive only in Local Zones (Ll), but with fewer and more poorly-connected fractures, fissures and joints, and with less permeable and/or more limited zones of higher permeability. Overall permeability, storage capacity, recharge acceptance, length of flow path and baseflow are likely to be less than in Ll aquifers.

Pu Poor Bedrock Aquifer, Generally Unproductive: Aquifer with generally few and poorly connected fractures, fissures and joints. This low fissure permeability tends to decrease further with depth. A shallow zone of slightly higher permeability may exist within the top few metres of more fractured/weathered rock, and higher permeability may rarely occur along large fault zones. In general, the poor fissure network results in poor aquifer storage, short flow paths (tens of metres) and low 'recharge acceptance'. Groundwater discharge to streams ('baseflow') is very limited.

An aquifer may be covered by subsoils that permit a significant proportion of effective recharge to pass through them. However, the nature of the bedrock or sand and gravel aquifer largely determines the 'recharge acceptance' of the aquifer (Box 2). Highly fissured aquifers can, in general, accept more recharge than can poorly fissured aquifers. Sand and gravel aquifers typically accept the most recharge, as they have significantly higher porosity than fissured bedrock aquifers. In areas where the water table is close to the ground surface, high groundwater levels may be the limiting factor on recharge.

Box 2. Aquifer classification and relationship with recharge.

Poorly productive aquifers. The poorly productive aquifers (**Pu, Pl, Ll**) generally have significant fracturing only in a thin zone at the top of the rock. The fractures are the features that allow groundwater to be stored[1] and transmitted in the subsurface. However, the transmissive and storage zone is thin, and therefore limited in its ability to (a) accept recharge to the groundwater; (b) transmit the recharge laterally, thereby creating space to accept more recharge.

Productive aquifers. In the more productive aquifers (**Rf, Lm**), the depth and extent of interconnected fracturing is greater, so they have higher transmissivities. Storage capacities are still low (1-2%). The aquifers are more able to transmit recharge laterally, and create space to accept more recharge.

Karstified aquifers. Diffusely karstified (**Rkd**) aquifers behave in a hydrogeologically similar way to the productive (Rf, Lm) aquifers. They occur mainly in the SE of the country. Karst in which groundwater is transmitted through conduits (**Rkc** aquifers) can generally accept a significant quantity of recharge, because transmissivities are very high. They are mainly found in the west and NW of the country. However, storage is low in Rkc aquifers, since the flow is concentrated into only 0.5-1% of the void space of the rock (the voids, i.e. conduits, just happen to be very large). The low storage translates into very large water level changes when water enters (recharges) or leaves (discharges) the karst system. Small karstified areas are classed as Locally important karstified aquifers (**Lk**).

Sand and Gravel aquifers. Sand and gravel aquifers (**Rg, Lg**) are transmissive and have high storage.

In areas where the groundwater table is high (e.g., in low-lying areas, or near rivers or lakes), the potential for recharge is limited in all types of aquifers.

The combination of the climatic and geologic factors outlined above determines the amount of recharge to groundwater, and therefore the amount that the groundwater system can supply to surface waters or ecosystems, and also the amount potentially available for sustainable abstraction. An interim recharge map for Ireland is shown in Figure 2 (ERBD, 2007).

It is important to note that 70% of Ireland is underlain by 'poorly productive' bedrock aquifers. Many of these aquifers underlie the high ground across Ireland, in areas where rainfall is typically high. The low storage capacity and low transmissivity of these aquifers means that much of the effective rainfall cannot be accepted by the aquifer, but instead runs off to surface water bodies. In contrast, recharge that high transmissivity aquifers (e.g. karst, gravel, productive fissured aquifers) could otherwise accept will be limited where low permeability subsoils overlie these aquifers. This occurs in, for example, east County Galway and south County Wexford.

[1] Because, in all Irish bedrock aquifers, the effective porosity is low - on the order of 1-2% - the storage capacity is low. Therefore, for a small change in volume of groundwater, the water level change is large. When recharge commences at the end of summer, the water table quickly rises, and further recharge cannot be accepted by the aquifer. Note also that when groundwater levels drop in summer, the water table falls below the thin transmissive zone and into the less fractured and less permeable part of the aquifer.

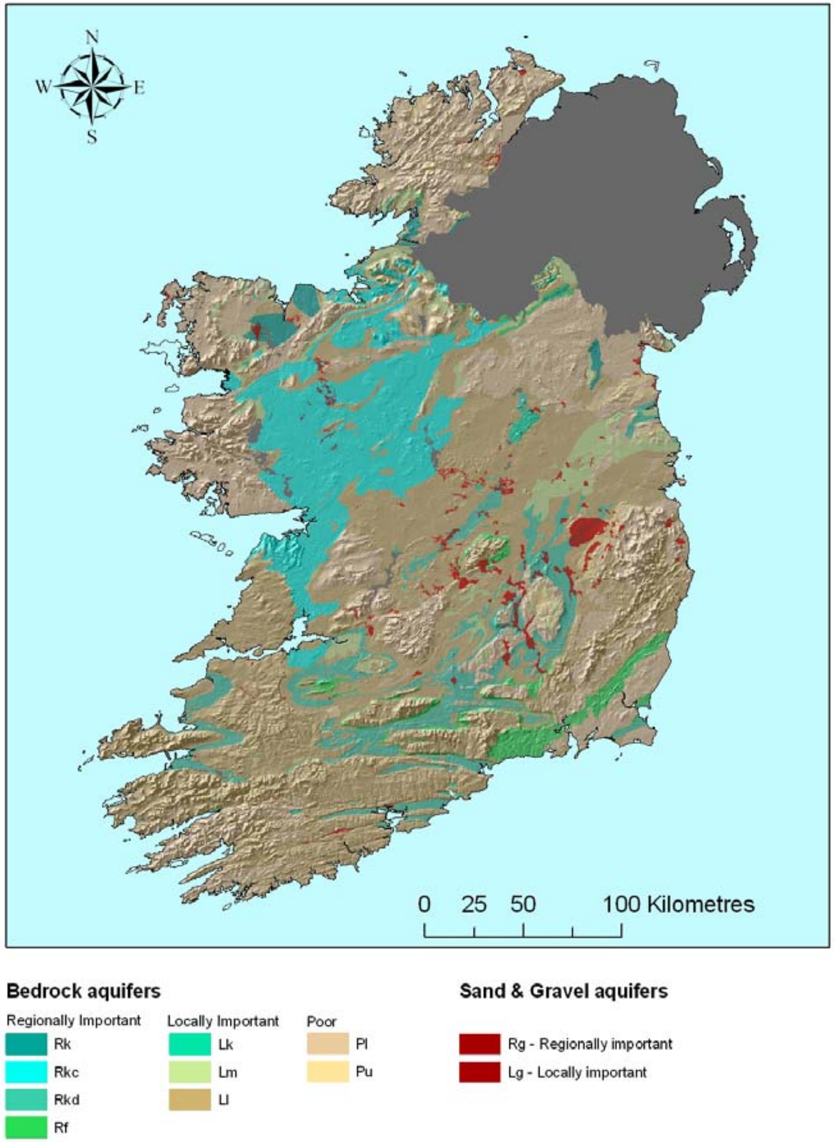

Figure 1: Bedrock and Gravel aquifers in Ireland, GSI.

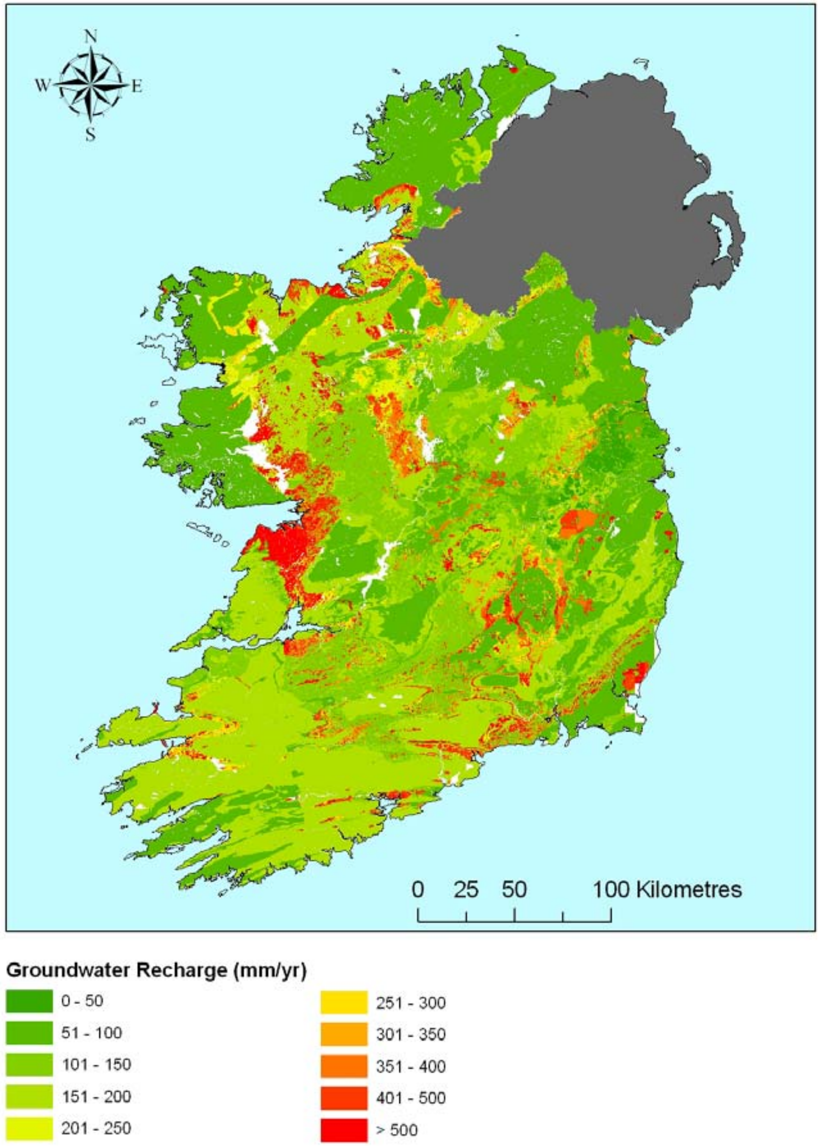

Figure 2: Interim groundwater recharge map (ERBD, 2007).

2.3 Current groundwater use

This paper focuses mainly on groundwater for human use. However, it should be borne in mind at all times that many natural systems (e.g. rivers, fens) are partially or wholly dependent on groundwater to sustain them.

2.3.1 National groundwater usage

Recent values compiled for groundwater abstraction show that total annual groundwater abstraction for public, group and industrial water supplies is almost 200 million m^3 (Moe *et al.*, 2007). Nationally, almost 30% of water supplies are obtained from groundwater (ERBD, in preparation). For public water supplies, this value rises to more than 50% in some counties (e.g. Roscommon, Offaly). Groundwater is usually abstracted by pumping from wells or boreholes, although springwater is also exploited. Well depths in bedrock aquifers typically range from 30-100m below ground. It is estimated that at least 100,000 wells and springs are in use nationally.

As part of the Water Framework Directive (WFD) initial characterisation phase a register of national abstraction data for all known groundwater abstractions greater than 10 m^3/d was compiled. The initial register of abstractions was based on EPA and GSI data, and these were added to by the different River Basin District (RBD) project consultants. The register has been further updated by the Eastern RBD project (ERBD, in prep.; Moe *et al.*, 2007). The table below summarises all groundwater abstractions included in the national register. The table incorporates supply wells and springs that serve public supply and industrial purposes. The register does not include domestic wells, as these are too numerous. Additionally, most of the domestic abstraction is returned to ground via septic systems. Whilst this affects groundwater quality, it has a negligible impact on quantities.

Summary of Groundwater Abstractions for Supply Purposes
(from Moe *et al.*, 2007)

River Basin District	Total No. Wells *	Public	Private/GWS/ Industrial	Total Estimated Abstraction (m^3/day)
Northwest	64	29	35	34,003
Neagh-Bann	41	34	7	23,820
Shannon	843	172	671	144,117
West	182	22	160	42,779
East	249	86	163	39,590
Southeast	180	116	64	153,387
Southwest	315	163	152	96,053

** It is believed that most, if not all, public and group water schemes have been identified and included, but it is unlikely that all industrial and small private abstractions (e.g., schools, hospitals) are captured in the new register. Other scenarios yet to be fully verified include mine dewatering and quarry abstractions.*

Approximately 530,000 m^3/day is presently being abstracted from almost 1,900 identified supply wells or springs. Approximately 100 abstraction points nationally supply more than 1,000 m^3/day, while a further 500 abstraction points produce greater than 100 m^3/day. The majority of supply wells and springs produce between 10-100 m^3/day.

Assessment of abstraction pressures on groundwater undertaken to satisfy Article 5 of the WFD indicates that, of more than 700 groundwater bodies in Ireland, only six (<1%) are at risk of over-abstraction, with a further 36 (<5%) potentially at risk (EPA/RBD Co-ordinating Authorities, 2005; Moe *et al.*, 2007). It is indicated, therefore, that there is sufficient groundwater to satisfy the current usage sustainably (i.e., without impacting on ecological receptors) over most of the country.

2.3.2 Environmental groundwater needs

Groundwater – the underground component of the hydrological cycle – is often poorly understood. It plays a critical role in the natural environment. Aquifers discharge groundwater on land and at sea as springs and seeps, providing baseflow to wetlands and rivers, and maintaining surface-water ecosystems during dry months.

Rivers, lakes and estuaries receive a proportion of their flow from groundwater. Groundwater provides baseflow and solutes to streams, thereby influencing the flow regime and the water quality.

Some wetlands, such as turloughs, fens, and petrifying springs are virtually completely dependent on groundwater, while others, such as raised bogs and lakes, are dependent to some degree. Where the water table is relatively close to the surface, trees tap groundwater directly.

Groundwater dependent ecosystems are often critical in supporting sustainable livelihoods and biodiversity. Sustainable use of groundwater should account for the vital role that groundwater plays in maintaining the natural environment (EPA, 2007).

2.3.3 Factors influencing the use of groundwater

The use of groundwater as a source of drinking water or for industrial processes depends on a variety of factors. One primary control on larger sustainable sources of groundwater is geology, through the influence of aquifer type and subsoil.

The aquifer classification scheme used in Ireland reflects the natural variations in rock type and their capacity to support abstractions (DELG/EPA/GSI, 1999). Regionally important aquifers, by definition, should be able to supply larger demands. For all aquifer classes, the exact location of an abstraction borehole relative to local fault/fissure systems can influence the yield significantly. In counties where subsoils have high permeability (e.g. Offaly), surface water bodies are less readily available as drinking water sources than in counties that have a high density of surface water bodies due to low permeability subsoils (e.g. Leitrim).

The use by Local Authorities of groundwater for supply sources is variable, notwithstanding geographical variations in aquifer type. The historical use of groundwater as a source of drinking water within a Local Authority can influence current and future use of groundwater within a county. Availability of suitable land on which to develop well head protection and pump control housing may also be an issue – potential constraints within the protection zone of the source (SPZ) has made some landowners hesitant about the development of groundwater resources close to or within their land (Church, 2007). Development of groundwater supplies abstracting >5,500 m^3/d requires an Environmental Impact Statement (EIS, S.I. No. 600/2001).

In rural Ireland, domestic water needs are commonly provided for by individual private wells where there is no Public or Group Water Scheme. A renewed interest in groundwater as a source of public drinking water is reported as being driven by large increases in urban population, with consequent increased water demands, coupled with recent planning legislation, particularly Strategic Environmental Assessments (SEAs, 2001/42/EC, S.I. No. 435/2004, S.I. No. 436/2004) (Skehan, 2004). Public health issues associated primarily with surface water sources may also be motivating increased groundwater use, since the subsurface environment provides natural subsoil and bedrock ‘filters’ through which groundwater passes slowly.

2.3.4 Assessment of groundwater resources

The Geological Survey of Ireland (GSI) provides much of the large-scale mapping of groundwater resources and groundwater vulnerability in Ireland. The resource and vulnerability maps are combined and, together with source protection zones, produce land surface zoning maps. These maps can be used in conjunction with responses for potentially polluting activities. The maps and responses together comprise a Groundwater Protection Scheme (GWPS, DELG/EPA/GSI, 1999). The overall aim of the GWPS is to preserve the quality of groundwater, particularly for drinking water purposes, for the benefit of present and future generations.

The Schemes are county-based projects that are undertaken jointly between the GSI and the respective Local Authority. The maps provide a framework for decision-making and guidelines for the Local Authorities in carrying out their functions. Since 2003, the Department of Environment, Heritage and Local Government has recommended that groundwater protection schemes are incorporated into County Development Plans (Circular Letter SP 5/03 – Groundwater Protection and the Planning System). The maps and data are also made available to other end users, who include the groundwater community, engineers, planners and private individuals.

In recent years, national- and regional-scale mapping of relevance to the groundwater environment has also been produced by Teagasc and consultants as part of the Water Framework Directive (WFD) Requirements. This work has been partly or entirely funded by the DEHLG and the EPA. The main National mapping outputs include:

- Aquifer map, Rock Unit Group map, Groundwater body (GWB) map and descriptions (GSI);
- Subsoil map and Soil map (Teagasc);
- Interim Vulnerability map, Interim Recharge map (RBD consultants/GSI/Compass);
- Estimations of Natural Background Levels of key groundwater chemical constituents (RBD consultants);
- Groundwater-dependent terrestrial ecosystems (GWDTEs) within conservation areas (National Parks and Wildlife Service).

2.3.5 Groundwater monitoring

Groundwater monitoring in the Republic of Ireland historically has focused on the protection of drinking water supplies, and investigating the impacts of point source pollution. However, the WFD and the Groundwater Directive adopt a more holistic view of water resources, establishing links between groundwater and associated surface water and ecological receptors. Therefore, national groundwater monitoring networks have been developed to improve knowledge of, and quantify the links between, groundwater and the ecological health of associated receptors.

The new monitoring networks – for groundwater quality and groundwater levels/flows – incorporates much of the original EPA monitoring network, some of the GSI's long-term water level monitoring boreholes, and existing drinking water supplies and industrial abstractions. In addition, development of the groundwater monitoring network requires the drilling of additional monitoring wells in specific poorly productive aquifers. The sites and the boreholes will be very well characterised, and monitoring will be detailed. These monitoring locations will greatly enhance our understanding of groundwater flow in poorly productive aquifers.

The National WFD Groundwater Monitoring Programme is implemented by the EPA. The monitoring is used to: (i) assess the general state of groundwater quality and groundwater levels/ flows in the Republic of Ireland; (ii) determine the status of groundwater in the

Republic of Ireland; (iii) help protect groundwater used for public and private drinking water supplies, and also protect surface water and ecological receptors connected to the groundwater system.

2.4 Information needs for groundwater assessment

2.4.1 Groundwater-related mapping

Currently, approximately 50% of the country has digital GWPS map coverage. As the Schemes are integral components of the planning process, it is important that resources are devoted to their completion. Progress towards this is being made as, over the next seven years, the national subsoil permeability map and national depth to rock map will be completed with funding from the National Development Plan (NDP). Groundwater vulnerability (a measure of the degree of protection of the underlying aquifer), one of the major components of the GWPSs described above, is a function of both subsoil thickness and permeability.

A recharge map has been produced by the ERBD as part of the WFD Abstraction Pressures study (ERBD, 2007). This is based on GSI subsoil permeability mapping, as well as GSI aquifer maps, MetÉireann meteorological data, and Groundwater Working Group guidance on geologically-based recharge coefficients (GWWG, 2004). In counties where subsoil permeability has not yet been mapped, a predicted permeability is assigned to the subsoils mapped by Teagasc (Meehan, 2004-2006). The NDP-funded completion of the subsoil permeability mapping will allow the compilation of a national recharge map, and go a long way towards enabling the completion of the GWPSs.

2.4.2 Improvements in conceptual understanding

While much progress has been made in the last 15 years, our conceptual understanding of groundwater flow is still incomplete. Information on aquifer parameters, in particular hydraulic conductivity and effective porosity, and recharge is relatively poor.

The current recharge map is based on the predicted bulk behaviour of the percolation of effective recharge through subsoils, and on current conceptual models of groundwater flow in different bedrock aquifers. More physically-based research into recharge mechanisms to verify and improve current mapping and understanding is required.

The complex and variable nature of the interaction between groundwater and surface water is still not understood sufficiently. This lack of knowledge and understanding can be particularly significant in areas where groundwater is a major contributor to surface flows and ecosystems, and where groundwater acts as a pathway for contaminants to surface water.

Funded research is both planned and underway to address these issues to some degree. In the period 2000-2006, the EPA has funded groundwater research through its ERTDI programme. From 2007-2013, further significant funding is being provided through the STRIVE programme. The recently-announced Griffiths Geoscience Research Awards will fund research into several groundwater-related areas. Significant ERTDI/STRIVE/Griffiths-funded research areas include:

- Groundwater-surface water interactions, prediction of water and contaminant movement in the hydrological cycle;
- Improving the understanding of complex ecosystems;
- Recharge and Groundwater Vulnerability;
- Assessment of highway drainage on water quality;
- Wastewater treatment efficiency of subsoils, filters and constructed wetlands;

- Effects of agricultural practices on nitrate and phosphate migration;
- Characterisation of unpolluted groundwater;
- Water resources assessments under future climate scenarios

2.4.3 Groundwater monitoring

Long-term monitoring is essential to assess the impact of climate change on groundwater systems, and also to assess the impacts of human activities on groundwater levels and quality. Records for some of the boreholes monitored by the GSI extend back to 1974. As such, they provide the only long-term water level monitoring data for Ireland. The EPA has monitored groundwater levels in a larger network for the last 11 years, typically on a monthly basis.

The new EPA groundwater monitoring programme, which will monitor water levels continuously and water quality quarterly, makes great progress in establishing a national monitoring network. The network has been established on the basis of current hydrogeological conditions, land use and abstraction pressures.

There is potentially a need to enhance the monitoring network by adding new monitoring locations where impacts on groundwater are anticipated, for example near groundwater-dependent ecosystems and regionally important coastal aquifers, so that monitoring can begin before impacts are experienced. This will give both context to the data, and may assist in the early detection of climate change impacts on groundwaters.

3 Potential consequences of changes in climate and development pattern for groundwater resources in Ireland

Changes in climate are likely to have a significant impact on water resources – both surface and groundwaters. Such impacts have the potential to alter each hydrological element within the catchment water balance.

Overall, it is thought that there will be less impact on groundwater as compared to surface water due to the greater storage in aquifers, even taking into consideration the predominance of fracture flow in Irish bedrock aquifers. Consequently, additional groundwater sources are likely to be sought for drinking water. It is possible that irrigation will be required to maintain food supplies and that groundwater will be targeted as the supply source.

The direct (decreased recharge) and indirect (increased use) impacts of climate change on groundwater, coupled with projected population growth and increased water demands overall, will result in groundwater becoming increasingly at risk of over-abstraction. This will potentially have consequences for rivers and other ecosystems that are dependent on groundwater, and also on future human water consumption and settlement patterns.

Due to the often complex interactions between subsoil properties, aquifer properties, effective rainfall amount and rainfall timing, there is not just one type of predicted impact on groundwater systems. The sections below discuss qualitatively the likely impacts on groundwater and consequences of these changes.

3.1 Summary of predicted climate changes in Ireland

Sweeny *et al.* (2003, 2007) derive downscaled estimates of temperature and rainfall changes based on mean ensembles, produced from the weighted averaging of Global Climate Change (GCM) outputs. For rainfall, their predictions are as follows:

2020’s: Winter precipitation likely to increase by 0.7-3.7%. Greatest seasonal changes predicted for summer, with 8.5% rainfall reduction. Reductions of between 10-16% are predicted for regions along the southern and eastern coasts.
2050’s: 10% increases in winter, reductions of between 12-17% in summer. Increases during winter along the east coast and midlands, reductions of between 20-28% projected to occur along the southern and eastern coast during the summer season.
2080’s: Seasonal and spatial changes in precipitation are further exacerbated, with winter increases of 11-17% and summer reductions of between 14-25%.

The largest percentage increases in winter precipitation are projected to occur in the midlands, of up to 20%, while the largest reductions during the summer months are again projected to occur along the southern and eastern coast, which are likely to experience decreases of between 30-40% during these months.

For average temperature changes, they predict an increase of 0.75-1.0^{o}C by 2020’s. By the 2050s, Irish temperatures will have increased by 1.4-1.8^{o}C, with most of the increases predicted to occur in the autumn. The mean temperature in all seasons is suggested to increase by 2^{o}C or more by the 2080’s. Summer increases in the order of 2.5-3.0^{o}C are forecast.

3.2 Possible impacts on groundwater resources

3.2.1 Impacts of different rainfall patterns on groundwater recharge

The Intergovernmental Panel on Climate Change (IPCC, 2001) suggest that increased winter rainfall – as projected under most scenarios for mid-latitudes – is likely to result in increased groundwater recharge. This statement may hold true in many countries but, although winter rainfall is likely to increase, groundwater recharge volumes will not necessarily increase over much of Ireland. This is due to the nature of Irish bedrock aquifers: the increased recharge cannot be accepted by the poorly productive aquifers that underlie approximately 70% of Ireland (Figure 1). In other areas, low permeability subsoils may be the limiting factor in increased effective rainfall becoming groundwater recharge.

Prolonged rainfall is more effective at recharging groundwater levels. However, climate change is likely to result in shorter, more intense periods of precipitation becoming more frequent, thus decreasing the amount of water that is infiltrated to storage (Arnell and Reynard, 1996). The growing season is also likely to change as a consequence of different temperatures and rainfall amount/timing availabilities. Such changes are capable of altering the timing and duration of the recharge period.

Potential consequences to groundwater recharge as a function of changing climate, aquifer type and subsoil cover are indicated in Boxes 3 and 4.

Box 3. Aquifer classification and potential consequences of climate change on recharge

Poorly productive aquifers. The poorly productive aquifers (**Pu, Pl, Ll**) generally have limited ability to (a) accept recharge to the groundwater; (b) transmit the recharge laterally, thereby creating space to accept more recharge. Therefore, greater rainfall amounts in winter will not contribute to greater recharge, since it cannot be accepted by the aquifers. Even current annual rainfall amounts in the west (up to 2000mm) mainly run off, rather than recharge poorly productive aquifers. Recharge amounts in poorly productive aquifers are in the range 100-250 mm/year. 'Poorly productive' aquifers underlie 70% of the country. The increased amount of run-off will lead to greater winter river flows and possibly more flooding.

Productive aquifers. In the more productive aquifers (**Rf, Lm**), the depth and extent of interconnected fracturing is greater, so they have higher transmissivities. Storage capacities are still low (1-2%). The aquifers are more able to transmit recharge laterally, and create space to accept more recharge. Greater effective rainfall may lead to greater recharge amounts in these aquifers (if subsoil permeability is not a limiting factor, see below). However, the Rf, Lm aquifer types are mainly located in the south and east of the country, where rainfall is expected to decrease.

Karstified aquifers. Diffusely karstified (**Rkd**) aquifers behave in a hydrogeologically similar way to the productive (Rf, Lm) aquifers. Karst in which groundwater is transmitted through conduits (**Rkc** aquifers) can generally accept a significant quantity of recharge, because transmissivities are very high. However, storage is low in Rkc aquifers, which translates into very large water level changes when water enters (recharges) or leaves (discharges) the karst system. Greater effective rainfall is likely to lead to greater recharge amounts in these aquifers. However, the very low storage combined with the high transmissivities means that much of the recharge will not be 'retained' by the karst system, but will flow out (to springs, rivers, lakes, sea) rapidly. The large water level responses to rainfall combined with ability of the karst system to transmit groundwater quickly will increase flooding in low-lying karst areas.

Sand and Gravel aquifers. Sand and gravel aquifers (**Rg, Lg**) are transmissive and have high storage. Under conditions of increased effective rainfall, recharge volumes are likely to also increase. Where effective rainfall decreases, recharge volumes will also decrease. However, where groundwater levels are already high (near rivers, fens, coast), there is little space for recharge acceptance at present or in the future.

Box 4. Subsoil permeability and potential consequences of climate change on recharge

Subsoil permeability influences how quickly effective rainfall can percolate into the subsurface to become groundwater recharge. Therefore, where low permeability subsoils overlie productive (Rf, Lm), gravel (Rg, Lg) or karst (Rk, Lk) aquifers, recharge may be inhibited, even with higher rainfall amounts.

In areas overlain by low or moderate permeability subsoils, different rainfall intensity patterns may not result in higher recharge, since the vertical permeability cannot transmit high rainfall down into the subsurface quickly enough. Flooding will increase in areas already susceptible to flooding from surface run-off, and may become a problem in areas which do not currently suffer from floods.

In areas overlain by high permeability subsoils, acceptance of high-intensity rainfall is not likely to be an issue. However, where these deposits overlie a bedrock aquifer that cannot accept the recharge (due to low storage/transmissivity and/or high water table), this will be the limiting factor on the rainfall becoming recharge.

In general, catchments that have higher storage capacity (soil, subsoil, aquifers) are thought to be less vulnerable to climate change impacts than those with lower storage capacity (Murphy and Charlton, 2006). The storage acts as a 'buffer' against the extreme events i.e. increased storage to offset summer droughts and higher infiltration capacities to reduce the risk of winter flooding.

3.2.2 Impacts of changes in groundwater recharge on groundwater levels, volumes and quality

The interactions between meteorological and geological parameters is complex, therefore outcomes of these interactions are diverse. In many cases, recharge is likely to decrease, especially in the south and east of the country. This has consequences for groundwater levels, volumes and quality, which translate into impacted drinking water resources, rivers and ecosystems.

Reduced groundwater levels in all types of aquifers will have generally detrimental consequences for supply. In areas where recharge decreases, the zones of contribution (ZOCs, or catchment areas) to borehole or spring supplies will increase in order to meet the same demand - i.e. they will take water from a wider area to compensate for the reduced water input per unit area. This will result in (a) the demand possibly not being met if the connected flow systems within the aquifers are limited, and (b) the exposure of the source to more potentially polluting activities that maybe occurring within these additional areas.

Spring flows, which are often fed by shallow groundwater and therefore more susceptible to changes in the water table elevation, are likely to decrease. Well-developed conduit karst systems are more likely to be affected than diffuse karst systems or regionally important, well-connected fissure flow aquifers, as they tend to have less storage capacity. Some of the numerous small springs and seeps flowing from poorly productive aquifers are likely to dry up. Springs often provide a significant quantity of water to streams and rivers or particular ecosystems; springs of all sizes are often tapped for public or private drinking water supplies or for farm animals. Diminution or cessation of flow will affect ecosystems, humans and husbandry practises. Groundwater-dependent ecosystems that are reliant on a certain quantity and quality of groundwater can be extremely sensitive to small changes in groundwater level or chemistry.

Due to their low storage capacity, and predominance of flow in the upper part of the aquifer, the summer resource potential of poorly productive aquifers is also likely to be reduced by a lowering of the water table. This is already seen in dry years at existing sources, for example Banagher PWS, in Co. Offaly. As Sweeny *et al.* (2007) point out, under current conditions the late autumn and winter recharge period is critical to sustaining groundwater levels throughout the year. By mid to late century, significant reductions in storage during this time of the year will increase the risk of severe drought, as the failure of winter or spring precipitation may result in prolonged drought periods where the groundwater system is unable to recover from previous dry spells.

Groundwater flow to rivers (baseflow) is likely to be reduced. Since this provides a high proportion of the summer river flow, lower baseflows may result in deteriorations in river water quality because of lower dilution rates. Some rivers may dry up entirely along parts of their reach, if the water table falls below the river bed.

In certain circumstances, increases in higher rainfall and rainfall intensity may have adverse effects on the groundwater quality. We already see that in some karst spring supplies the first autumn/winter precipitation is flushing sediment from the aquifer system into the water supply. This is likely to be exacerbated. Pulses of other contaminants, such as nitrates or pesticides, may pose a problem to groundwater at the beginning of the recharge period, since summers are predicted to have longer dry spells. Due to decreased recharge, even if contaminant loading remains the same as present, concentrations in groundwater will increase.

At present, saline intrusion is not common in Ireland. The best-known example is the low-lying, karst limestone area east and south of Galway city. Sea level rises will result in regionally important coastal aquifers becoming inundated with saline waters, which affects their water quality. This not only impacts on the resource potential (abstractions for drinking water), but also on the quality of rivers and ecosystems that are supported by such aquifers.

3.2.3 Potential increase in flood likelihood

Generally, increased winter rainfall should increase the recharge into the aquifers over this period. In lower lying areas, aquifers are likely to become saturated with further rainfall, which then becomes ‘rejected recharge’ or runoff.

Flooding becomes more of risk when an area is underlain by low permeability subsoil and/or poorly productive aquifers (see Boxes), especially along the lower reaches of rivers. Groundwater recharge coefficients have been derived for different aquifer type, vulnerability and subsoil settings (GWWG, 2004; Fitzsimons and Misstear, 2006). From this, runoff risk rankings – High, Intermediate, Low – were estimated that take account of the soil type, subsoil permeability and aquifer type (Kelly and Daly, 2006). They do not include rainfall or slope parameters.

The amount of rainfall that can infiltrate and recharge the aquifer will also depend on the intensity of the rainfall – higher intensities are more likely to lead to runoff rather than infiltration.

3.3 Impact of changes in development patterns on groundwater

While available groundwater resources vary across the country, groundwater is increasingly being explored for public and private supplies (Moe *et al*., 2007). Some rivers and lakes are reaching their capacity as primary sources of water supply. Surface water sources, in contrast to groundwater systems with their in-built filtering systems and longer residence times, generally have higher risk of microbiological contamination than groundwater sources. Further, questions are being raised over the health and status of freshwater aquatic ecosystems.

Industrial growth is adding new abstractions, although not on the same scale as local authority efforts to meet the growing domestic water demands. There are several large-scale groundwater exploration schemes currently underway in counties such as Meath, Kildare, Wexford, and Louth. These are partly driven by Environmental Impact Assessment regulations, and partly by concerns over local ecological impacts. Even counties with limited groundwater resources such as Wicklow are exploring groundwater options to augment present supplies. The housing boom in commuter belt and rural areas are adding to overall abstractions but this is regarded less as a quantity and more as a quality issue, on account of the return of water through septic systems in unsewered areas.

The introduction of Strategic Environmental Assessment legislation in 2004 has spurred interest in use of groundwater for supply purposes, as it can be difficult to obtain permission to abstract from surface water. The increasing use of groundwater as a primary source of water supply implies that new schemes will also require increased regulatory attention in the context of WFD-required water resources management (Moe *et al.*, 2007). The various national WFD studies led by individual river basin district (RBD) projects are drawing attention to a variety of water management issues which, combined, will broaden the understanding of groundwater and surface water interactions, and impact how groundwater is monitored and managed.

Whilst the NDP has undoubtedly brought, and will continue to bring, significant benefits to Ireland, the undertaking of the NDP also has the potential to impact significantly on groundwater. For example, major infrastructural works also have the potential to disrupt groundwater flow patterns and levels, with potential deleterious consequences for groundwater-dependent ecosystems.

The large-scale expansion in road building and upgrades is likely to have consequences for groundwater quality, as road run-off, which carries pollutants such as hydrocarbons and chromium, is sometimes discharged to ground. A currently-favoured approach to urban drainage is 'SUDS' (sustainable urban drainage systems), which aims to attenuate storm flows in urbanised environment drainage systems by ponding water, then discharging to ground. This has the potential to allow contaminants to enter the groundwater system.

4 Mitigating impacts of change on groundwater resources

It is clear that climate change will impact significantly on water supplies in the future, whether fresh surface waters, or groundwaters. A key challenge for the future will be adapting to meet those changes, whilst maintaining a supply for an increasing population that is becoming more urbanised *and* whilst maintaining the ecological requirements for water quantity and quality of river systems, lakes and groundwater-dependent ecosystems. In some areas, groundwater will become an increasingly important part of the water supply equation. In other areas, possibly those not hydrogeologically suitable for providing supplies sufficient to meet demand, surface water preservation/storage solutions will be used. It is likely that both surface and groundwaters will be used conjunctively.

In terms of provision of groundwater, there is currently underutilisation of this resource for abstraction purposes, and therefore 'slack' in the system that can be taken up. Currently, large sources of water supply are sought. Church (2007) suggests that, to be economic (in terms of infrastructure costs), the development of abstraction boreholes for public supply require sustainable yields in excess of 500-1000 m^3/d. However, due to the generally low transmissivities and storativities of the poorly productive aquifers, most (70%) of the aquifers in Ireland are not capable of producing these yields sustainably. Therefore, there may be a case for developing more numerous, smaller schemes, with abstractions on the order of 100-300 m^3/d. This is actually the situation that has naturally evolved in many rural counties, where groundwater has been used for small public supplies for some time.

Hydrogeological consultants and Local Authorities report difficulties in obtaining land for the purposes of developing groundwater supplies, since landowners are concerned that they will subsequently be restricted in what activities will be permissible on that land. In reality, for many hydrogeological settings, there are very few restrictions as long as generally good practice is followed in any activities on the land. However, it may be desirable to explore options for compensating landowners for any restrictions placed upon them, or for changing the use to which their land is put.

Other papers from the IAE "Ireland at Risk" Workshop mention water metering for the purpose of reducing demand per person/improving efficiency of use (Philips, 2007; IAE Draft position paper, 2007). Water metering has commenced in Northern Ireland, and has been in use in parts of England for at least a decade. As part of the WFD Abstractions Pressures study being undertaken by the ERBD, water metering is being assessed.

Inferences drawn from predicted climate changes in Ireland indicate that groundwater recharge will decrease. As Phillips (2007) suggests, artificial recharge may be a solution for offsetting lower natural recharge rates in some areas, particularly in areas underlain by regionally important aquifers.

In areas where declining groundwater levels and/or fluxes are impacting upon important ecosystems due to decreased recharge, engineering solutions may be required to ameliorate these impacts, if it is considered economically feasible or sufficiently important from a national or international perspective to do so. Artificial recharge upstream of the receptor could be used to augment natural recharge. Another possibility would be to 'dam' the groundwater, if hydrogeological conditions were amenable – this is currently done in South America to trap groundwater in river alluvium so that it can be used for dry season irrigation.

All future developments will have to be undertaken within the environmental legislative framework of the Water Framework (WFD), Groundwater (GWD) and Strategic Environmental Assessment (SEA) Directives, and within the resource management framework of the WFD River Basin Districts. The existing legislation places high priority on the environment, and uses the health of aquatic or water-dependent ecosystems to measure impacts on both water quantity and quality of existing human activities. The WFD stipulates that there may be no deterioration in water quantity or quality in the future due to human impacts, but that existing water bodies that have less than good status must be improved.

5 Areas of research to help reduce uncertainty

Current indications are that groundwater resources are 'plentiful', with very few areas at risk of over-abstraction. At present, it is difficult to put a volumetric estimate on groundwater resources due to (i) the dynamic nature of the hydrological system, (ii) the multiple 'demands' on groundwater (e.g., rivers, ecosystems, humans), and (iii) insufficient hydrogeological data to assist quantification.

Due to the complex relationship of the variables involved, there are many uncertainties and large margins of error associated with estimates of climate change, and of their impacts on hydrological systems. These uncertainties highlight the need for extensive research into all of the specific areas outlined above e.g. impact on regional resources, ecosystems, etc.

To address these areas, work in the following areas is needed to improve current knowledge of:

- *recharge amounts, timing and location*. More physically-based research into recharge mechanisms is required to verify and improve current mapping and understanding of the influence of subsoil/unsaturated zone on groundwater quality, protection and recharge.
- *groundwater-surface water interactions at both the small scale and the large scale*. This is particularly significant in areas where groundwater is a major contributor to surface flows and ecosystems, and where groundwater acts as a pathway for contaminants to surface water.
- *groundwater-dependent ecosystems*. The dynamics of these ecosystems and their sensitivities to changes in water quantity and/or quality are insufficiently understood.
- *aquifer characteristics*. There are limited data on aquifer parameters such as transmissivity and storativity, fracture characteristics and frequency, effective aquifer thickness, and groundwater flow systems at all scales.
- *sustainable yield of aquifers and groundwater sources*, which will allow better water resources assessments under future climate scenarios.
- *groundwater abstractions*. The recent compilation of groundwater abstractions by the RBD projects has improved massively the abstractions database, and should be maintained and improved.
- *predicted climatic conditions*, such as return periods of extreme events, rainfall timing, impact on soil moisture and growing seasons.
- *loading and leaching of contaminants on groundwater quality*. The migration of contaminants may be different under changed climate conditions.
- *natural groundwater quality changes* that may occur as a function of different throughputs and changed groundwater levels.

Research is underway to address some of the aspects highlighted above, whilst others remain to be tackled. Areas of work that could be undertaken in the short term include:

- a preliminary assessment of the impact on recharge of future climate change scenarios by applying predicted effective rainfall to the current recharge coefficient map;
- establishing new monitoring locations where impacts on groundwater are anticipated so that monitoring can begin before impacts are experienced. This will give both context to the data, and may act as an early warning system.

6 References

Arnell, N.W. and N.S. Reynard (1996) The effects of climate change due to global warming on river flows in Great Britain. Journal of Hydrology, 183, 397-424, 1996.

Circular Letter SP 5/03 – Groundwater Protection and the Planning System

Church, R. (2007) Groundwater Resource Assessment for Public Water Supply Schemes in the Midlands of Ireland. *Proceedings of IAH (Irish group) 27th Annual Groundwater Conference, Groundwater: Pressures and Opportunities.* pp. 2-9 – 2-16.

EPA (2007) Science, Technology, Research & Innovation for the Environment (STRIVE) Programme 2007 – 2013. Technical Description, EPA Call for Research Proposals: Water Quality and the Aquatic Environment.

EPA/RBD Coordinating Authorities (2005) "Article 5 Risk Assessment" - 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). 156 pp.

ERBD (in preparation) National Abstraction Pressure Assessment Study, carried out by the ERBD project (www.erbd.ie).

ERBD (2007) Draft National Recharge Map. Produced by CDM Ireland and Compass Informatics.

EU Directive 2001/42/EC *On the Assessment of the Effects of Certain Plans and Programmes on the Environment*.

EU Directive 2000/60/EC *Establishing a framework for Community action in the field of water policy* ("Water Framework Directive.")

Daly, D. & Warren, W. P. 1998. Mapping groundwater vulnerability: the Irish perspective. In: Robins, N. S. (ed.) *Groundwater pollution, aquifer recharge and vulnerability*, Geological Society, London, Special Publications, 130, 179–190.

DELG/EPA/GSI (1999) *Groundwater Protection Schemes.* Joint Department of the Environment and Local Government, Environmental Protection Agency and Geological Survey of Ireland Report, 24 pp.

Fitzsimons, V. and Misstear, B. (2006) Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland. *Hydrogeology Journal*, Volume 14, Number 4, pp. 548-561.

IAE (2007) Ireland at Risk - Recommended Actions from Workshop. Draft position paper (Draft 1).

IPCC (2001) Climate Change 2001: *Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K. S. (Eds.). Cambridge University Press, UK. 1042 pp.

Kelly, C. and Daly, D. (2006) Runoff risk rankings, GSI internal document.

Meehan, R.T. (2004, 2005, 2006) Maps produced as part of EPA Soils and subsoils Mapping Project. Teagasc, Kinsealy, Dublin.

Misstear, B., Brown, L. and Wijnen, J. 2002-W-MS/16: Recharge and Groundwater Vulnerability. ERTDI Programme 2000 – 2006, Phase 3: Water Framework Directive (WFD).

Moe, H., Daly, D., Hunter Williams, N., Mills, P. and Gaston, L. (2007) A National Assessment of Groundwater Abstraction Pressures. *Proceedings of IAH (Irish group) 27th Annual Groundwater Conference, Groundwater: Pressures and Opportunities.* pp. 5-25 - 5-32.

Murphy, C. and Charlton, R. (2006) The impact of climate change on catchment hydrology and water resources for selected catchments in Ireland. *Proceedings of the National Hydrology Seminar, Tullamore, 2006. Water Resources in Ireland and Climate Change.*

Murphy, C. Fealy, R., Charlton, R. and Sweeney, J. (2005) Changing precipitation scenarios: preliminary implications for groundwater flow systems and planning. *Proceedings of IAH (Irish group) 25th Annual Groundwater Conference, Groundwater in Ireland.* pp. 49-56.

Page, D., Wall. B. and Crowe, M. (2006) *The Quality of Drinking Water in Ireland: A Report for the Year 2005*. EPA, 105 pp.

Phillips, M. (2007) Ireland at Risk – Water Supply. Paper prepared for IAE Workshop on "Ireland at Risk – Impact of Climate Change on the Water Environment", 2nd May 2007, Dublin.

S.I. No. 600/2001 (2001) Planning and Development Regulations. Stationery Office, Office of the Attorney General.

S.I. No. 435/2004 (2004) European Communities (Environmental Assessment of Certain Plans and Programmes) Regulations 2004 .

S.I. No. 722/2003 (2003) European Communities (Water Policy) Regulations 2003.

S.I. No. 436/2004 (2004) Planning and Development (Strategic Environmental Assessment) Regulations 2004.

Skehan, C. (2004) Hydrogeology and the Future of Irish Planning. Session I, *Proceedings of IAH (Irish group) 24th Annual Groundwater Seminar, Groundwater Challenges of the National Development Plan.*

Sweeney, J., Murphy, C., Fealy, R. and Charlton, R. (2007) Climate Change Scenarios and Challenges for the Water Environment. Paper prepared for IAE Workshop on "Ireland at Risk – Impact of Climate Change on the Water Environment", 2nd May 2007, Dublin.

Sweeney, J. and Fealy, R. (2003) Establishing Reference Climate Scenarios, in, Sweeney, J. *et al* (ed.) *Climate Change: Scenarios and Impacts for Ireland,* Environmental Protection Agency, Johnstown Castle, Wexford, 229 pp.

Teagasc http://www.teagasc.ie/research/environment.htm

Irish Working Group on Groundwater (2004) *Guidance on the assessment of the impact of groundwater abstractions (GW5)*, 23 pp.