GROUNDWATER VULNERABILITY MAPPING

Lee, M., Hunter-Williams, N. (Geological Survey of Ireland)
Meehan, R. (Consultant Geologist)
Kelly, C., Kabza, M., Murphy, O. and Spillane, M. (Tobin Consulting Engineers)

Abstract

Groundwater Protection Schemes (GWPSs) have been undertaken by the Geological Survey of Ireland (GSI) in partnership with Local Authorities as an effective means of protecting groundwater, by informing planning and licensing processes. Since 2003, it has been recommended that GWPSs are incorporated into County Development Plans (DoELG, 2003). The spatial datasets underpinning the GWPSs provided key basic information for the characterisation and risk assessment phases of the implementation of the Water Framework Directive (WFD). Requirements of the WFD have accelerated the need for completing the datasets nationally.

The main components of the land surface zoning element of GWPSs are Groundwater Vulnerability and Aquifer maps. Significant progress has been made toward a national groundwater vulnerability dataset (GSI and River Basin District consultants). This dataset contributed to the preparation of groundwater recharge maps, runoff potential maps (GSI), and risk maps for diffuse and point pollution, and for groundwater over-abstraction. The data have also been used in a study to estimate low flows in ungauged catchments.

However, the Groundwater Vulnerability dataset is currently incomplete. The GSI has received National Development Plan funding that will allow the completion of a national subsoil permeability map and a depth to rock database. These data will allow groundwater vulnerability and groundwater protection zones coverage to be created nationally, thus assisting in the completion of a National Groundwater Protection Scheme programme.

The maps contribute to spatial planning by providing the basic framework for decision-making and future planning, and can be used to assist in the evaluation of:

- groundwater resource potential, and susceptibility to pollution;
- surface water risks, including flood risk;
- the suitability for a proposed activity;
- groundwater recharge estimates;
- climate change impacts on groundwater.

The GSI consider that completion of a National Groundwater Protection Scheme programme is necessary to assist with the data requirements of the WFD.

Introduction

Through the hydrological cycle, all waters are linked. This concept has become increasingly important with the introduction of more holistic catchment management and accordingly, for the Water Framework Directive (WFD).

The relevance of the Groundwater Protection Scheme maps extends beyond their sole use in groundwater protection. The properties of constituent map layers – aquifer resource and groundwater vulnerability (subsoil permeability and thickness) – can also be used for surface water quantity and quality assessments on the generalised premise that potential recharge that does not recharge the groundwater can reach the surface water network via direct runoff, interflow and as baseflow from aquifers. The purpose of this paper is to give the background to the Groundwater Protection Scheme datasets and outline some of the uses to date.

Groundwater Protection Schemes.

The Groundwater Protection Schemes employed in Ireland (DELG/GSI/EPA, 1999) are based on the concept of groundwater contamination risk assessment and risk management. The spatially related scheme allows a consistent protection policy approach across the Irish landmass, which is thorough, accurate and systematic, and employs the **hazard-pathway-target** model for environmental management to assess the vulnerability. Further information on the Groundwater Protection Schemes can be found on the Geological Survey of Ireland website (www.gsi.ie).

One key element of the risk assessment is the groundwater vulnerability dataset. Groundwater Vulnerability is defined as the intrinsic geological and hydrogeological characteristics that determine the ease with which groundwater may be contaminated by human activities (Daly & Warren, 1998).

The overall aim of the groundwater vulnerability assessment process is to provide relevant information for land-use planning decisions, so that potentially polluting developments can be controlled in an environmentally acceptable way.

Groundwater vulnerability: an element of the risk concept, and of risk management.

Risk can be defined as the likelihood or expected frequency of a specified adverse occurrence. When applied to groundwater, the risk expresses the likelihood of contamination arising in that groundwater from potentially polluting sources or activities. Within this framework, any development, group of developments or activities that pose a threat to groundwater are the **hazard**. The **pathway** is the material between the hazard and the target, and therefore generally relates to subsoil, as the point of release of contaminants is often below the land surface. The groundwater itself is the **target** that has to be protected.

In general, little attenuation of contaminants occurs in the bedrock in Ireland because flow is almost wholly *via* fissures, therefore, the subsoils (sands, gravels, glacial tills (or boulder clays), peat, lake and alluvial silts and clays) are the single most important natural feature influencing groundwater vulnerability and prevention of groundwater contamination. Groundwater is most at risk where the subsoils are absent or thin[1] and, in areas of karstified limestone where direct ('point') recharge occurs, *e.g.* where surface streams sink underground at swallow holes.

Attributes that determine groundwater vulnerability.

The vulnerability of groundwater depends on 1) the time of travel of infiltrating water (and contaminants); 2) the relative quantity of contaminants that can reach the groundwater and; 3) the contaminant attenuation capacity of the geological materials through which the water and contaminants infiltrate. All three of these factors (travel time, attenuation capacity and quantity of contaminants) are a function of:

- the permeability/porosity of the subsoils overlying the groundwater,
- the thickness of the unsaturated zone through which the contaminant moves, and,
- the type of recharge (either point or diffuse).

By taking account of these three elements the vulnerability of groundwater to pollution can be mapped.

In the majority of situations across the Irish landscape, recharge to the groundwater system takes place diffusely. The rates of infiltration and percolation will depend on how permeable the material is, combined with how thick it is *e.g.* rates will be slow if there is thick clay, as opposed to thin gravels. The result is that the groundwater deep below the surface is protected intrinsically by the recharge mechanism itself as

[1] Areas where the subsoils are absent or thin equates to areas of bedrock outcrop (at surface) or subcrop (within c.1m of the surface).

the soil and subsoil filter the recharging water, albeit at different rates and therefore to different degrees of purification.

Also considered is the 'type of recharge' *i.e.* diffuse verses point recharge. At locations of point recharge, there is rapid flow to the water table via a preferential flow pathway that *bypasses* the soil and subsoil filter. Mapped locations of point recharge comprise certain karst features such as swallow holes, cave entrances and collapse features.

The groundwater vulnerability map.

The subsoil permeability and depth, and localities of point recharge are mapped and combined to providing a groundwater vulnerability assessment for any area or site. Four groundwater vulnerability categories are defined: **extreme (E), high (H), moderate (M)** and **low (L)**. A subset of the 'extreme' category is termed the **'X – extreme'** category, and relates to areas of bedrock outcrop or subcrop, or within 30m of a location of point recharge. Vulnerability mapping guidelines are shown in Table 1 and an example of a vulnerability map is given in Figure 1.

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

i *N/A = not applicable.*
ii *Release point of contaminants is assumed to be 1–2 m below ground surface.*
iii *Permeability classifications relate to the engineering behaviour as described by BS5930.*
iv *Outcrop and shallow subsoil (i.e. generally <1.0 m) areas are shown as a sub-category of extreme vulnerability.*

(amended from Deakin and Daly (1999) and DELG/EPA/GSI (1999))

Table 1: Vulnerability Mapping Criteria.

In counties where Groundwater Protection Schemes have not been completed in detail, vulnerability is assigned an 'interim' classification, of **Extreme (E/X)** or **High-Low (H-L)**[2].

[2] In these counties, areas of 'Extreme' Vulnerability have also been delineated in an interim sense for the Water Framework Directive Initial Characterisation Report.

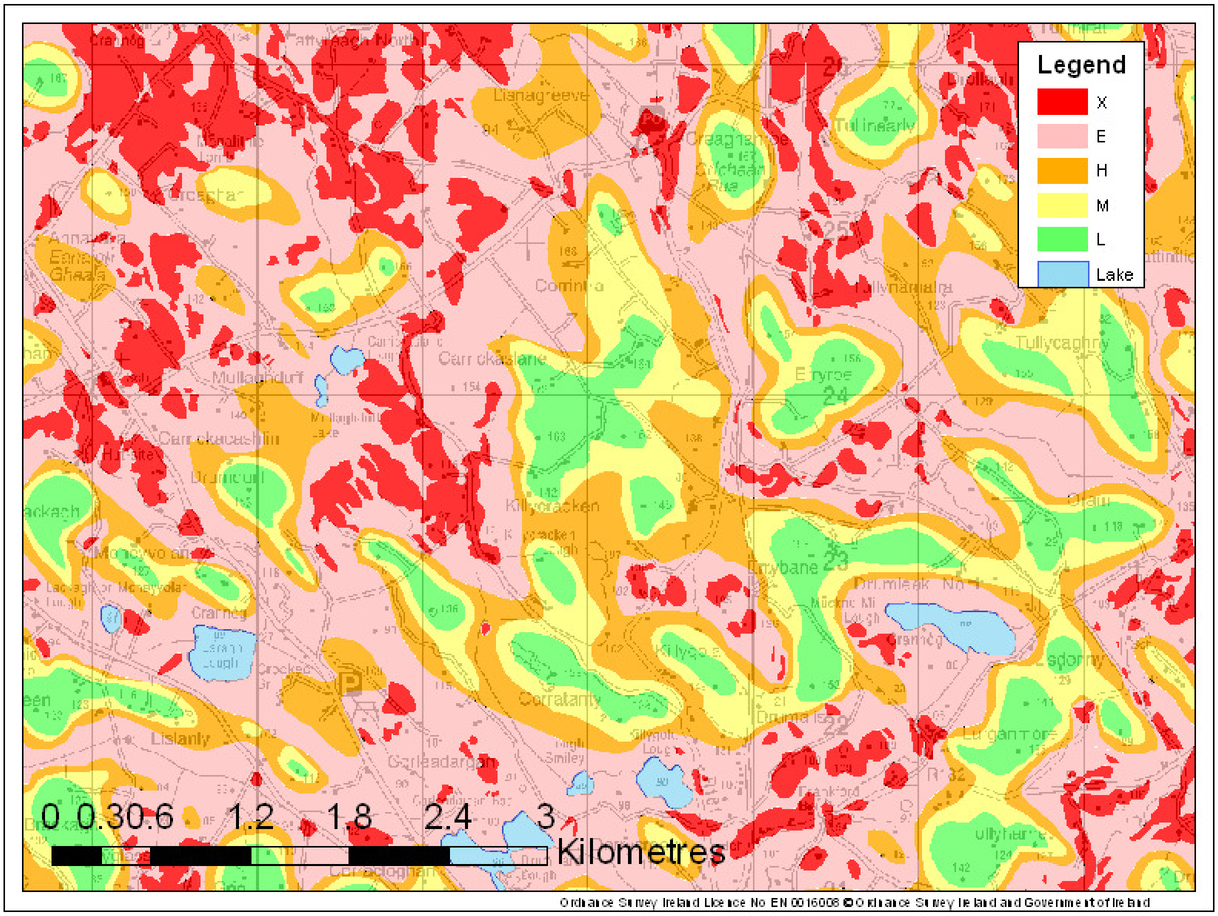

Figure 1: Sample Extract from Groundwater Vulnerability map.

The subsoil permeability map.

The subsoil permeability map is a critical component of the vulnerability map. Compiling information on permeability of subsoils involves assessing the infiltration capacity of these by direct and indirect means, which is based on the broad question '*can water and contaminants reach groundwater easily?*', and results in classifications of 'high', 'moderate' or 'low' subsoil permeability.

High permeability subsoil materials are generally sands and gravels. Moderate permeability subsoils are silty to sandy glacial tills that are generally quite free draining. Low permeability subsoil materials are clayey tills, peats and lake clays.

The GSI and Trinity College Dublin have completed a body of research in recent years on permeability assessment, developing proxies for assessing permeabilities at specific locations and to identify secondary indicators that provide an indication of recharge acceptance and vulnerability as a whole, across a particular area (*e.g*. Swartz, 1999; Lee, 1999).

The GSI Vulnerability Mapping Guidelines (Fitzsimons *et al*., 2003) outlines the approach taken in subsoil permeability mapping. This is a holistic method involving:

- field description/classification/analysis of texture using BS 5930;
- sampling and detailed grain size analysis at 'type' localities;
- examination of soil type, particularly presence or absence of mottling;
- presence of 'wet'/'dry' vegetation indicators in the areas examined;

- data on artificial and natural drainage density;
- parent bedrock characteristics and;
- topographic data.

Subsoil permeability mapping is not undertaken within areas where the depth to bedrock is interpreted as less than three metres. In these areas, subsoil matrix and permeability are considered to be unpredictable due to the presence of preferential flow paths, the influence of the underlying bedrock, and the influence of insitu weathered bedrock.

A provisional subsoil permeability map has been prepared by the Geological Survey of Ireland (Figure 2). Each subsoil permeability category has been expressed in terms of a 'confidence' to distinguish areas of 1) detailed mapping, 2) current mapping, 3) unmapped permeability and 4) expert and preliminary judgements.

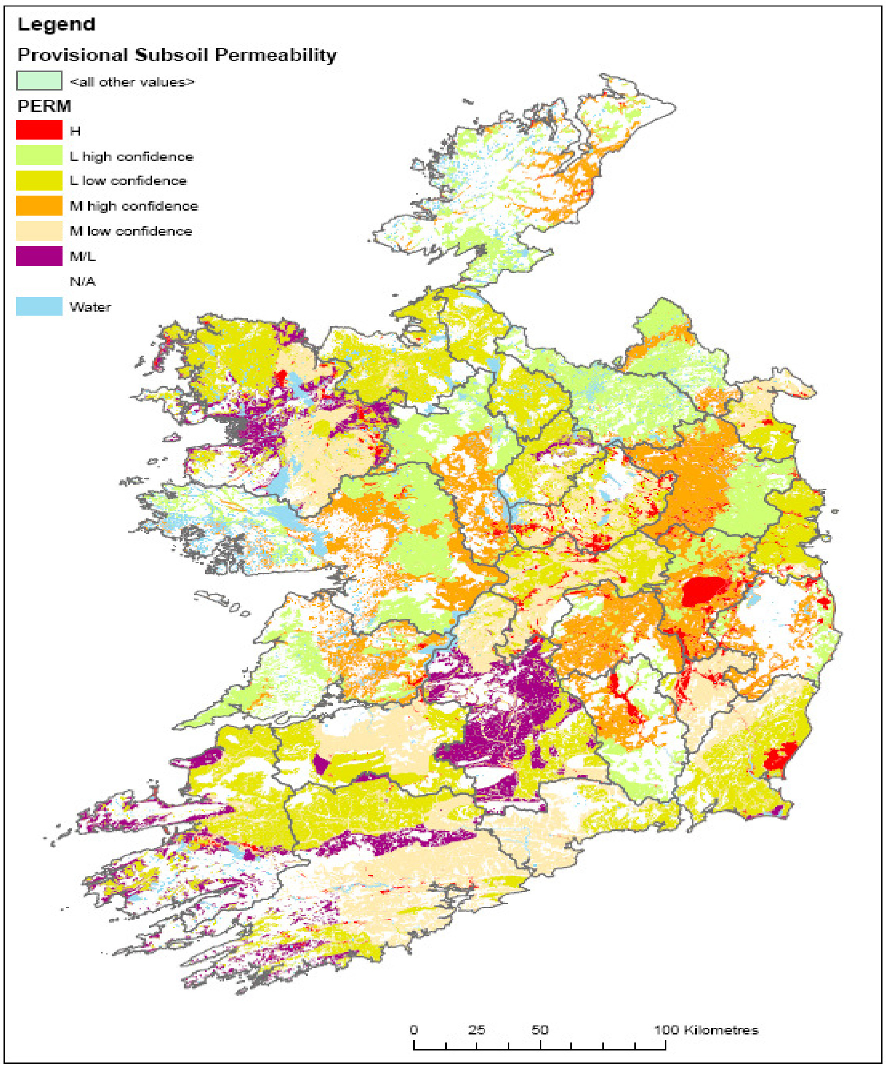

Figure 2. Provisional Subsoil Permeability Map, Geological Survey of Ireland, 2008.

The depth to bedrock map.

For regional scale vulnerability mapping, total subsoil thickness is assessed using contours at 3m, 5m and 10m. The contouring process uses a combination of data, expertise and experience. The data include:

- Outcrop and shallow rock locations from the GSI databases and the Teagasc Subsoil Mapping Project.
- Depth to bedrock from borehole databases[3].
- Karst data from GSI databases.
- Geophysical surveys.
- Elevation and slope of ground surface.
- Landscape morphology.

The contours provide general approximation of broad trends across an area at a regional scale.

Current status of groundwater vulnerability mapping.
GSI Groundwater Vulnerability Maps are presently available for the counties that have Groundwater Protection Schemes – Counties Cavan, Clare, Cork (South), Donegal, Galway, Kildare, Kilkenny, Laois, Meath, Monaghan, Offaly, Roscommon and Wicklow. Though Groundwater Protection Schemes have been completed for Limerick, Tipperary and Waterford, these early schemes did not use the more recent subsoil permeability mapping methodology. For these and the remaining counties, a national interim groundwater vulnerability map (GSI and River Basin District consultants) was produced to assist the work of the WFD.

The National Groundwater Protection Scheme, and thus National Groundwater Vulnerability map, will be completed over the next four years as part of the National Development Plan II. During 2008, subsoil permeability mapping has been completed for Sligo, Leitrim, Longford, Westmeath, Louth, and Dublin. This latest mapping has been incorporated into the provisional national subsoil permeability map given in Figure 2.

Uses of the groundwater maps.
The Groundwater Protection Scheme maps contribute to spatial planning by providing the basic framework for decision-making and future planning. They can be used to evaluate:

- groundwater resource potential, and susceptibility to pollution;
- surface water risks, including flood risk;
- the suitability for a proposed activity;
- groundwater recharge estimates;
- climate change impacts on groundwater.

Since 2003, it has been recommended that Groundwater Protection Schemes are incorporated into County Development Plans (DoELG, 2003), in order to promote sustainable development. In conjunction with the risk management element of Groundwater Protection Schemes, known as Groundwater Responses, the groundwater vulnerability and aquifer (bedrock and gravel) maps provide guidance to the acceptability of certain activities in the different hydrogeological settings. The activities for which groundwater responses are available, are single houses, landfills, licensed (IPPC) landspreading, earth-lined slurry stores and out-wintering pads.

Further to specific groundwater protection aspects, the national groundwater vulnerability and permeability datasets, along with national bedrock and gravel aquifer maps (GSI), and subsoil and soil maps (Teagasc, 2005) have been used to generate several other valuable datasets. These include groundwater recharge maps, runoff potential maps (GSI), and risk maps for diffuse and point pollution, and for groundwater over-abstraction. The data, which are in a GIS format, have also been used in a

---

[3] Includes well data from GSI Groundwater Section; borehole data from GSI Minerals and Geotechnical Sections; borehole records from road schemes, site investigations, academic studies, well surveys and other site data from consultants; Bord na Móna peat depth maps; Local Authority well grant records; and mineral exploration drilling.

further WFD study led by the Southwest River Basin District to quantify groundwater contributions to surface waters, and a joint ESB International (ESBI)/Environmental Protection Agency (EPA) study to estimate low flows in ungauged catchments (ESBI, *in prep.)*.

Examples of uses relating to both groundwater and surface water issues are briefly outlined below:

Susceptibility to Pollution

With regard to one-off housing, where it is assumed that the wastewater will be discharged mostly to ground, knowledge of the vulnerability assists a site assessor to evaluate the suitability of the ground to *accept* and *treat* the discharged effluent. For example, if a site is mapped as extreme groundwater vulnerability, the assessor knows that it is the groundwater that is likely to be at most risk. Consequently it is critical that adequate vertical and horizontal separation distances to relevant receptors exist. Conversely for a site mapped as low groundwater vulnerability, it is surface water that is likely to be at most risk as the assessor is likely to encounter low permeability subsoil that will not accept the hydraulic load. Such conditions frequently result in future break out and ponding of effluent, which may find its way to a neighbouring water course.

With regard to normal landspreading, knowledge of the vulnerability setting allows an evaluation to be made on appropriate setback distances from a known nearby receptor. A setback distance from a public supply borehole or a stream may be extended or reduced depending on the vulnerability. In a low vulnerability (and thus low permeability) setting, the setback distance should perhaps be extended for a stream (*i.e.* increased surface water risk) and reduced for a public supply borehole (*i.e.* low groundwater risk). Knowledge of the vulnerability is critical to understanding the risk to the receptor for a given activity.

Water Quality Assessments

An understanding of the groundwater vulnerability in an area can be an important aid to the evaluation of water quality both in groundwater and surface water. In Roscommon, concentrations of phosphates were observed in groundwater samples, which although were well beneath the drinking water guidelines (EU MAC of 2.2 mg/l), exceeded levels that could potentially result in eutrophication of surface waters (0.03 mg/l P for ortho-phosphates) (Lee, *et al*, 2002). These levels were observed in extremely vulnerable, highly karstified areas, where groundwater is likely to be making a considerable contribution to surface water due to the specific geology. In such instances, the groundwater may be providing a pathway for the phosphates to reach the surface water with potentially detrimental consequences.

Resource Potential

Groundwater vulnerability maps are useful in the targeting of productive aquifers that are well protected. Groundwater abstractions points are less susceptible to pollution in areas of low groundwater vulnerability. However, the irony is that recharge to the aquifers in areas covered by extensive, thick, low permeability tills is relatively low and over abstraction is a risk. Risk assessment guidance from abstraction was developed for the Water Framework Directive by the Groundwater Working Group (2004).

Assessment of Recharge

Misstear (2000) described groundwater recharge and its value and importance under the Water Framework Directive and suggested that research was required on the recharge mechanisms through Irish tills. 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. Misstear and Fitzsimons (2006) suggest that till permeability is the most sensitive parameter controlling groundwater recharge. Furthermore, the transition from moderate to low permeability till is where the greatest sensitivity occurs. The Irish Working Group on Groundwater (GWWG) has produced guidelines on recharge coefficients for many different subsoil permeabilities and hydrogeological settings (GWWG, 2004). As part of the Water Framework Directive, groundwater recharge maps using guidance on recharge coefficients developed by the Groundwater Working Group (2004), were produced (ERBD, 2006). A recent paper by Misstear et al, 2008, introduces a methodology for estimating groundwater recharge from groundwater vulnerability mapping.

Assessment of Runoff Potential

By using relevant geological layers (soils and subsoils, groundwater vulnerability, subsoil permeability and aquifer category), a runoff potential matrix was developed by the GSI, initially to assist Monaghan County Council to target higher priority streams, and to develop a greater understanding the different pathways to streams and rivers. It should be noted that soil moisture deficit, slope, intense rainfall and proximity from streams, which are all important considerations, were not taken into account. A GIS representation of the matrix is given in Figure 3.

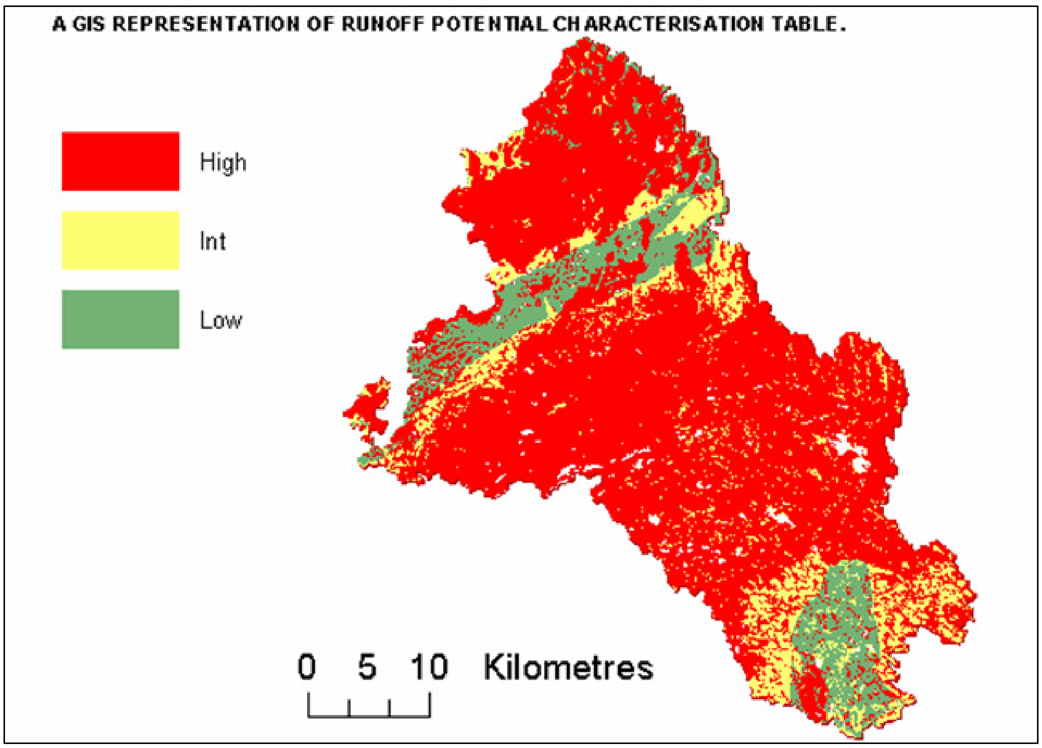

Figure 3. A GIS representation of runoff potential applied to Co. Monaghan.

Potential Impacts of Climate Change

The groundwater recharge maps, which are based on the groundwater vulnerability and permeability maps, the aquifer maps (GSI) and the soils maps (Teagasc), can be further utilised for the modelling of potential impacts of climate change on a) groundwater resources and b) surface water systems, especially with regard to potential flooding. Although the climate change modelling predicts increased winter rainfall (Sweeny *et al.* (2003, 2007), when combined with the recharge map, it can be seen that this rainfall is unlikely to recharge much of the groundwater across the country due to the low recharge acceptance of certain aquifers, and/or the presence of low permeability subsoils and/or low permeability soil (Hunter-

Williams and Lee, 2007). In such areas, surface runoff is more likely to occur and depending on the topography, flooding may be a risk. This is just one example of how these spatial data layers can provide more accurate predictions of impacts.

Conclusions

The ongoing vulnerability mapping will continue to improve the national groundwater vulnerability and groundwater protection scheme datasets. Apart from groundwater protection, the underpinning layers, in particular the subsoil permeability map, have been proven to be necessary components for other derived maps, such as the recharge maps. All of these maps are essential to make appropriate decisions in a spatial planning context, which is becoming increasing important with the continuation of the Water Framework Directive process, and to model the impacts of changing environmental parameters on future resources.

Acknowledgments

The authors would like to acknowledge the funding provided under the National Development Plan and to thank Donal Daly (EPA) for his comments during the preparation of this paper.

This paper is submitted with the permission of Dr. Peadar McArdle, Director, Geological Survey of Ireland.

References

Daly, D. and Warren, W., 1998. Mapping Groundwater Vulnerability: the Irish perspective. In: Robins, N.S., (ed) Groundwater Pollution, Aquifer Recharge, and Vulnerability, Geological Society, London, Spec. Publication. 130 pp 179-190.

Department of Environment and Local Government. (DoELG) 1999, Groundwater Protection Schemes. Department of Environment and Local Government, Environmental Protection Agency, Geological Survey of Ireland.

Department of Environment and Local Government, (DoELG), 2003 Circular Letter SP 5/03 – Groundwater Protection and the Planning System.

ESBI/EPA (in prep.). Flow Duration Curve and Low Flow Estimation for Ungauged Catchments. Joint ESB International/ Environmental Protection Agency study.

Fitzsimons, V.P., Daly, D. and Deakin, J., 2003. GSI Guidelines for Assessment and Mapping of Groundwater Vulnerability to Contamination. Geological Survey of Ireland, 75pp.

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.

Hunter-Williams, N. and Lee, M., 2007. Ireland at risk – Possible implications for groundwater resources of climate change. IGI Proceedings of IGI Conference 2007, Groundwater and Sustainable Developments.

Misstear, B.D.R., Brown, L. and Daly, D., 2008. A methodology for making initial estimates of groundwater recharge from groundwater vulnerability mapping. Hydrogeology Journal,

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

Lee, M. and D. Daly, 2002 . Roscommon Groundwater Protection Scheme. Geological Survey of Ireland.

Lee, M., 1999. Surface indicators and land use as secondary indicators of groundwater recharge and vulnerability. Unpublished (Research) MSc. Thesis. Department of Civil, Structural and Environmental Engineering, Trinity College Dublin.

Swartz, M., 1999. Assessing the permeability of Irish subsoils. Unpublished (Research) MSc. Thesis. Department of Civil, Structural and Environmental Engineering, Trinity College Dublin.

Swartz M, Misstear, B.D.R., Daly, D. and Farrell, E.R., 2003, Assessing subsoil permeability for groundwater vulnerability. Q J Eng Geol Hydrogeol 36(part 2):173–184.

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, 2005. National Subsoils Map produced under FIPS-IFS Project, 1998-2001; EPA Soil and Subsoil Mapping Project, 2002-2005.

Working Group on Groundwater, 2005. Water Framework Directive (WFD): Pressures and impacts assessment methodology: guidance on the assessment of the impact of groundwater abstractions. Geological Survey of Ireland, Environmental Protection Agency and River Basin Districts Coordinating Authorities, Dublin.

Working Group on Groundwater, 2008. National recharge map of Ireland. Geological Survey of Ireland, Environmental Protection Agency and River Basin Districts Coordinating Authorities, Dublin.