08 - A NATIONAL GROUNDWATER RECHARGE MAP FOR IRELAND

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Abstract

A national groundwater recharge map has been created to enable assessment of the impact of groundwater abstractions on the water balance of a groundwater body, which is required under the Water Framework Directive (WFD). In addition to its WFD applications, the map's utilities include groundwater resource sustainability assessments at regional, local and source scales – under both current and predicted future meteorological and climatic conditions. Since hydrologically effective rainfall that does not recharge the groundwater system comprises the surface runoff/interflow or 'quick flow' component, the map could also potentially form an independent dataset against which runoff estimated using other methodologies could be checked.

The groundwater recharge map is derived from existing hydrogeological and meteorological spatial datasets. The initial map was completed in 2005 by the Eastern RBD and CDM using original guidelines outlined by the Irish Working Group on Groundwater. The current version of the map includes: an improved algorithm, improved representation of wet soils over gravel aquifers, refined recharge coefficient estimates, and a greater coverage of full subsoil permeability and groundwater vulnerability mapping.

The main hydrogeological controls on groundwater recharge include: subsoil permeability, subsoil thickness, saturated soils, and the ability of the underlying aquifer to accept percolating waters. Combinations of these factors are assessed, and a 'recharge coefficient' established for 21 hydrogeological scenarios (a 'recharge coefficient' is the proportion of hydrologically effective rainfall that may become groundwater recharge). Where lower productivity aquifers underlie the land surface, a 'natural recharge capacity' limit is applied to allow for 'rejected recharge', even where subsoils are thin. This reflects the limited ability of these aquifers to accept, store and transmit recharging waters.

To produce the groundwater recharge map, the map of recharge coefficients is multiplied by the hydrologically effective rainfall. Met Éireann's 1971-2000 rainfall dataset is used, in tandem with an adapted Potential Evapotranspiration dataset. The recharge map is finally modified to take into account areas where the natural recharge capacity of the underlying aquifer is less than the estimated groundwater recharge potential,

The map depicts estimated recharge to the "deep" groundwater system, i.e. recharge that can be tapped as the sustainable groundwater resource. There are areas where effective rainfall infiltrates into the subsurface at higher volumes than indicated by the

estimated recharge, but flows laterally in either the subsoil or very shallow rock zone to streams or other groundwater discharge areas. As such, this subsurface water is not part of the abstractable groundwater resource (but is a subsurface flow pathway).

There are a number of assumptions made in creating the groundwater recharge map (e.g. natural recharge capacity of poorly productive bedrock aquifers; diffuse groundwater recharge through subsoils rather than point recharge; average recharge coefficients used; ground slope not directly incorporated), and precision limitations associated with the input datasets. For reasons of scale and generalisation to a national coverage, the map is useful for giving regional estimates of recharge but these, in many cases, will need to be refined using site-specific studies. However, the map is presented digitally with all steps of the calculation that underlie the final recharge estimates. Thus, the recharge estimation process is highly transparent, and values can be easily assessed and modified by the user if site-specific conditions suggest that this is warranted.

1. Introduction

Groundwater recharge is the process of water arriving to a body of groundwater to replenish it, usually by downwards percolation through the subsurface of some proportion of the rain that has fallen onto the land surface. In Ireland, much groundwater recharge occurs by waters percolating diffusely through the soil and subsoil cover (termed diffuse or direct recharge). In areas of karstified limestone, water also enters the groundwater system at discrete points via, for example, swallow holes (point or indirect 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. Approaches for estimating recharge can be grouped into the following categories (Misstear *et al.*, 2006): inflow estimation, aquifer response analysis, outflow estimation, and catchment water balance and modelling.

This paper describes a methodology for estimating the amount of diffuse recharge that enters the groundwater system using an inflow estimation technique in a Geographical Information System (GIS). The input layers, discussed further below, are: groundwater vulnerability, subsoil permeability, soil drainage, aquifer type, and hydrologically effective rainfall.

The national recharge map has been described previously (e.g. Moe *et al.*, 2007; Hunter Williams, 2009; Misstear *et al.* 2009; Dublin City Council, 2009). Since then, the map has been improved, by the inclusion of further coverage of the input datasets, and by improvements in the algorithm and recharge coefficient estimates (GSI, 2009, 2011).

The national interim groundwater recharge map was created to enable assessment of the impact of groundwater abstractions on the water balance of a groundwater body

(GWB) or on groundwater dependent terrestrial ecosystems (GWDTEs) (WGGW, 2005a; ERBD/CDM/Compass, 2005). As such, it depicts estimated recharge to the "deep" groundwater system, i.e. recharge that can be tapped as the sustainable groundwater resource, and is designed to be used at the scale of a GWB (e.g. 10's to several 100's km^2).

In addition to the original application, the groundwater recharge map is used extensively in groundwater source protection work. The overall size of the zone of contribution to a borehole is determined in a large part by the amount of recharge entering the groundwater system over a given area, which must balance out the amount of groundwater abstracted under sustainable usage. Where sufficient data exist, the methodology and datasets can be adapted to estimate recharge at local scales if conditions indicate that modifications are required to constrain better the recharge estimates.

Other applications for the recharge map include loading/dilution assessments for discharges to ground, making preliminary runoff estimates and cross-validating baseflow estimations, and improving predictions of climate change impacts on groundwater resources.

2. Background

Regional groundwater recharge assessments in Ireland date back to the 1980's, with assessments of groundwater resources in the north east and south east (An Foras Forbatha/Geological Survey Office, 1981a, b), and Wright *et al.*'s (1982) assessments of groundwater resources in Ireland. Scanlon's (1984) studies in Co. Kerry and Daly's (1994) work in the Nore River Basin made more detailed assessments of groundwater recharge, and these results have informed subsequent studies. Local groundwater recharge assessments are routinely undertaken in groundwater source protection zone studies, as part of the catchment delineation process (e.g. Deakin, 1995; Mannix, 2009; Kelly, 2010).

An EPA-funded STRIVE study (Misstear and Brown, 2008) examined in more detail the relationship between groundwater recharge and groundwater vulnerability, since both are concerned with the percolation of water through the soil and subsoil (if present) and down through the unsaturated zone to the water table. The interim results of this multi-annual study, together with results from other studies (e.g. UK TAG 2004), were used to develop the methodology for, and constrain values used in, the national recharge map.

The first two national groundwater recharge maps were created in 2005 and 2008 by consultants (CDM and Compass Informatics) working on behalf of the Eastern River Basin District, and using the Irish WGGW guidance documents (GW5 and GW8, WGGW 2005a, b). The map was used in the Water Framework Directive (WFD) 'Article 5' risk assessments (EPA, 2005), in order to examine whether or not groundwater bodies were at risk of overabstraction, or if groundwater dependent terrestrial ecosystems (GWDTEs) were at risk due to abstraction pressures.

The maps, although with improved coverage in the second version, were considered interim, as they relied on interim input mapping data (such as groundwater vulnerability, discussed further below). In 2009, the Geological Survey of Ireland created an updated map using the established algorithm (Dublin City Council, 2009) and an extended coverage of input data that were available due to the progress of the NDP-funded vulnerability mapping programme (Lee *et al.*, 2008).

Following the wider deployment of the maps and discussion within the hydrogeological community on their utility, a number of shortcomings were identified with the existing maps, including the way in which areas of peat influenced recharge, and the effective rainfall estimation. The algorithm used to combine the different input data layers was re-examined, additional hydrogeological scenarios were characterised, and additional data coverage was incorporated. Improved ranges for recharge coefficients are provided, based largely on the fuller findings of the EPA ERDTI funded study "Recharge and groundwater vulnerability" (Misstear and Brown, 2008; Misstear *et al.*, 2009). These improvements are incorporated in the current national groundwater recharge map (GSI, 2011), which now has full data coverage except for Co. Kerry and west and north Co. Cork, which will be completed in 2012.

3. Groundwater recharge

Groundwater is replenished by water percolating downwards under gravity through the subsurface to the groundwater table. The amount of water that is available to recharge the body of groundwater depends on the rainfall minus that taken up by plants (actual evapotranspiration). The proportion of hydrologically effective rainfall that becomes groundwater recharge depends on the hydraulic properties of the subsurface.

Recharge to an aquifer can be estimated by first calculating the effective rainfall using a soil moisture budgeting technique, and then by applying a recharge coefficient to indicate the proportion of this effective rainfall that contributes to groundwater recharge. The recharge coefficient is thus defined as the proportion of the effective rainfall that forms recharge, and is expressed as a percentage.

The main controls on groundwater recharge include subsoil permeability, subsoil thickness, soil saturation (e.g. gleying), and the ability of the underlying aquifer to accept waters percolating to the groundwater table. In Ireland, because groundwater flow in virtually all bedrock aquifers is exclusively or mainly through fracture pathways, the influence of the unsaturated zone in the bedrock is negligible.

Much of Ireland is overlain by tills and other sediments deposited during or just after the glaciations of the last c. 30,000 years. Glacial tills, glacio-fluvial sand and gravel deposits and peats are widespread, and percolation through these deposits and to areas of bare or sparsely covered rocks is diffuse. Point recharge occurs in karstified limestones where collapse features accept water from permanent or temporary streams (sinkholes) or collect and funnel recharging waters into the subsurface (dolines).

The recharge coefficient value is determined mainly by the permeability and thickness of the superficial deposits (subsoils) that overlie the country's aquifers. Estimated groundwater recharge is lowest in areas overlain by thick, low permeability clay (Misstear *et al.*, 2008). Even where soil is thin or absent, where lower productivity aquifers underlie the land surface, there is a limited ability to accept and transmit recharging waters, due to the poor development of permeable fracture pathways with depth. Potential groundwater recharge is frequently rejected in these scenarios, which is manifested as high drainage densities.

Previous investigations into recharge in Ireland include the studies by Scanlon (1985), Daly (1994), MacCarthaigh (1994), Aslibekian (1999), Fitzsimons and Misstear (2006) and Misstear and Fitzsimons (2007). Several of these studies, notably a draft of the Fitzsimons and Misstear (2006) paper, were used by the WGGW (2005a) in the preparation of a table linking groundwater vulnerability to a range of hydrogeological settings, with proposed ranges of recharge coefficient for each setting. Table 1 summarises the results of the EPA STRIVE recharge and groundwater vulnerability study that has established recharge coefficients in four study areas, and contrasts these with the 'infiltration coefficients' from Wright *et al.* (1982). The findings of the recharge and vulnerability study were used to inform the recharge coefficients in Table 2.

Table 1 Recharge coefficients from selected studies

Study area	**Main aquifer, subsoil and topographic setting**	**Recharge coefficient (Misstear *et al.* 2009)**	**Equivalent infiltration scenario and coefficient from Wright *et al.* 1982)**
Curragh aquifer, County Kildare	Regionally important gravel aquifer. Thin (generally <3 m), moderate to low permeability till cover; high vulnerability. Lowland setting	81–85%	Permeable 80%
Galmoy mine, County Kilkenny	Regionally important limestone aquifer. Till cover generally 5–10 m thick and of moderate permeability. Lowland setting	55–65%	Moderately permeable 50%
Callan-Bennettsbridge lowlands, County Kilkenny	Aquifer includes regionally important limestone and dolomite. Variable thickness of moderate permeability till and high permeability gravel cover. Mainly lowland topography	41–54% (for Mod perm. subsoils) (36–60% for entire subcatchments)	
Knockatallon aquifer, County Monaghan	Locally important limestone aquifer. Thick (up to 50 m) low permeability till cover. Upland and lowland topography	<17% (and probably <5%)	Poorly permeable 20% Virtually impermeable 0%

4. National groundwater recharge map

4.1 Methodology

The National groundwater recharge map is derived from existing hydrogeological and meteorological data layers, which were overlain and interpreted using the guidelines outlined by the Irish Working Group on Groundwater (WGGW) (which in turn, were informed by the UKTAG (2004) guidelines) and Dublin City Council (2009).

Considering the map in terms of the 'source-pathway-target' model that is used in risk assessments, the map describes the 'pathway' through which recharging waters percolate until they reach the groundwater table. The data layers create a hydrogeological scenario framework within which the recharge coefficients are established.

Table 2 summarises the hydrogeological scenarios, input hydrogeological data layers and groundwater recharge coefficients. It is an updated version of the table in guidance document GW8 (WGGW, 2005b).

4.2 Input layers

Examples of the input layers from counties Galway, Tipperary and Kildare are shown in Figures 1 to 5. These counties are selected as they cover a range of hydrogeological settings, including: higher effective rainfall in the west and lower in the east; extensive karst limestone aquifers in the west, fissured aquifers in the midlands and east, and extensive sand/gravel aquifers in the east; blanket peats in the west, basin peats in the midlands, and peats over extensive sand/gravel aquifers in the east. The layers are combined in a GIS as shown schematically in Figure 6.

Table 2 Recharge coefficients for different hydrogeological settings

Vulnerability category	Hydrogeological setting		Recharge coefficient (RC)		
			Min (%)	*Inner Range*	*Max (%)*
Extreme	1.i	Areas where rock is at ground surface	30	80-90	100
	1.ii	Sand/gravel overlain by 'well drained' soil	50	80-90	100
	1.iii	Sand/gravel overlain by 'poorly drained' (gley) soil	15	35-50	70
	1.iv	Till overlain by 'well drained' soil	45	50-70	80
	1.v	Till overlain by 'poorly drained' (gley) soil	5	15-30	50
	1.vi	Sand/ gravel aquifer where the water table is ≤ 3 m below surface	50	80-90	100
	1.vii	Peat	1	15-30	50
High	2.i	Sand/gravel aquifer, overlain by 'well drained' soil	50	80-90	100
	2.ii	High permeability subsoil (sand/gravel) overlain by 'well drained' soil	50	80-90	100
	2.iii	High permeability subsoil (sand/gravel) overlain by 'poorly drained' soil	15	35-50	70
	2.iv	Sand/gravel aquifer, overlain by 'poorly drained' soil	15	35-50	70
	2.v	Moderate permeability subsoil overlain by 'well drained' soil	35	50-70	80
	2.vi	Moderate permeability subsoil overlain by 'poorly drained' (gley) soil	10	15-30	50
	2.vii	Low permeability subsoil	1	20-30	40
	2.viii	Peat	1	5-15	20
Moderate	3.i	Moderate permeability subsoil and overlain by 'well drained' soil	35	50-70	80
	3.ii	Moderate permeability subsoil and overlain by 'poorly drained' (gley) soil	10	15-30	50
	3.iii	Low permeability subsoil	1	10-20	30
	3.iv	Peat	1	3-5	10
Low	4.i	Low permeability subsoil	1	5-10	20
	4.ii	Basin peat	1	3-5	10
High to Low	5.i	High predicted permeability subsoils (Sand/gravels)	30	80-90	100
	5.ii	Moderate permeability subsoil overlain by well drained soils	35	50-70	80
	5.iii	Moderate permeability subsoils overlain by poorly drained soils	10	15-30	50
	5.iv	Low permeability subsoil	1	5-10	20
	5.v	Peat	1	5	20

Note that, whatever groundwater recharge is indicated by the combination of soils and subsoils, a 'natural recharge capacity' limit is applied to poorly productive aquifers to simulate 'rejected recharge', even where subsoils are thin (Irish WGGW, 2005). This reflects the limited ability of these aquifers to accept and transmit recharging waters. The natural recharge capacity of locally important 'Ll' bedrock aquifers is taken as 200 mm/yr, and 100 mm/yr for poor 'Pl' and 'Pu' bedrock aquifers.

Areas of 'made ground' are assigned a recharge coefficient of 20%.

Groundwater vulnerability (Figure 1) in Ireland is determined mainly according to the thickness and permeability (hydraulic conductivity) of the subsoil that underlies the topsoil, since these properties have a major effect on the travel times and attenuation processes of any contaminants that are released into the ground from below the topsoil (e.g septic tanks, landfills, etc.). The type of recharge is also considered in karstic areas, where indirect recharge (termed 'point recharge' in Ireland) may occur through sinking streams, swallow holes or other solution features. There are five vulnerability categories: extreme (X, outcrop/shallow rock/karst), extreme (E), high (H), moderate (M) and low (L). Vulnerability mapping guidelines are summarised in DELG/EPA/GSI (1999) and Fitzsimons *et al.* (2003).

Groundwater vulnerability is used to frame the hydrogeological scenarios in Table 2. The dominant groundwater vulnerability category in terms of recharge is extreme, particularly the extreme (outcrop/rock close/karst) category.

Subsoil permeability (Figure 2) is classed by the GSI as high, moderate or low, using a standard methodology, 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 are also used, and include drainage density and vegetation characteristics (Misstear and Daly, 2000; Fitzsimons *et al.*, 2003).

Moderate permeability subsoils generally have less than 15% clay and low permeability subsoils have greater than 12% clay. Swartz *et al.* (2003) also noted that moderate permeability subsoils generally have less than 35% fines (i.e. clay and silt combined). Thus, confidence can be placed on permeability estimations based on the description and grain size distribution of lithological samples (when laboratory or borehole permeability measurements are unavailable). The boundary between the permeability bands is quantified only approximately: Swartz *et al.* (2003) suggested that the boundary between moderate and low permeability is in the region of 1×10^{-8} m/s.

Ó Súilleabháin (2000) proposed an upper limit for the moderate permeability category of around 1×10^{-4} m/s. In the sand and gravel Curragh aquifer in Co. Kildare (see Figure 5), Misstear and Brown (2008) estimate that vertical subsoil permeability is 4 m/day, or about 5×10^{-5} m/s. Misstear *et al.* (2009) suggest that the moderate/high boundary may need further reflection, since 1×10^{-4} m/s represents horizontal permeability, whilst it is vertical permeability that controls the downward percolation of recharging waters (or effluents).

Work by Fitzsimons and Misstear (2006) indicates that the primary geological control on diffuse groundwater recharge is the vertical permeability, which has more influence on recharge than subsoil thickness. Low permeability subsoils and peats significantly restrict recharge, and Fitzsimons and Misstear (2006) show that predicted recharge falls off rapidly in the permeability range 0.001 m/day and 0.01 m/day (1×10^{-7}–1×10^{-8} m/s) – i.e. near the boundary between moderate and low subsoil permeability.

Soil drainage (Figure 3) is distinguished on the Teagasc soil map (Fealy, 2006), with categories for poorly drained soils, well drained soils, peats and alluvium, as well as 'made ground'. The presence of 'poorly drained' soils, such as gleys and peats, will be the limiting factor as some runoff will occur irrespective of the ability of underlying layers to transmit percolating waters. This impact is captured in a reduction of the recharge coefficient where poorly drained soils are present (e.g. compare hydrogeological scenarios 1.iv and 1.v in Table 2).

The different types of peat (e.g. fen peat, blanket peat, cut peat, etc.) are not treated separately as there is insufficient detail at the map scale. (Site specific data could be applied to a study area if it is available.) However, where peats overlie sand and gravel aquifers, only significant extents of peat (>1 km^2) are included, because of the probability that runoff from these areas will enter the aquifer indirectly at another location.

In the GIS, areas of 'made ground' are derived from the soil drainage map. These areas are presumed to have restricted recharge due to paving, etc. and are assigned a recharge coefficient of 20%.

Aquifer categories (Figure 4) are assigned to different bedrock types and sufficiently extensive saturated sand and gravel deposits. There are nine aquifer categories, which describe both the groundwater resource value of the subsurface (Regionally Important, Locally Important and Poor), and also the predominant way in which water flows underground (through solutionally-enhanced fissures and conduits in karstified limestones, along fissures in bedrock, or between sand/gravel grains).

In poor and locally important bedrock aquifers (Ll, Pl and Pu), groundwater flow occurs in thin fracture zones (only a few metres in thickness) in the shallow bedrock; aquifer transmissivity is less than 50 m^2/day (and frequently less than 10 m^2/day); and specific yield is low (less than 0.5%). Regionally important fissured aquifers (Rf) and more productive locally important bedrock aquifers (Lm) can have an active zone of groundwater flow tens of metres in thickness. Transmissivity values usually exceed 100 m^2/day, and specific yield is typically 1–2%. Pure limestone aquifers are frequently characterised by secondary permeability that is often enhanced by the processes of karstification and/or dolomitisation. Effective aquifer thickesses are several tens of metres, and flow intervals may be discrete in conduits. Transmissivities are typically several 100's m^2/d. Where extensive, glacio-fluvial and fluvial sand and gravel deposits can form locally or regionally important aquifers, with transmissivity in excess of 500 m^2/day and specific yield between 10 and 20% (Misstear and Brown, 2008).

For aquifers classed as poor (Pu/Pl) or locally important (Ll), there will be an upper limit to the amount of recharge that they can accept. When that natural capacity is achieved all subsequent recharge will be rejected. The WGGW (2005b) suggests that recharge caps of 100 and 200 mm/year should be applied to poor and locally important aquifers, respectively. When these natural recharge capacities are exceeded then rejected recharge occurs and this adds to surface runoff (or interflow). These aquifers underlie approximately 65% of the country.

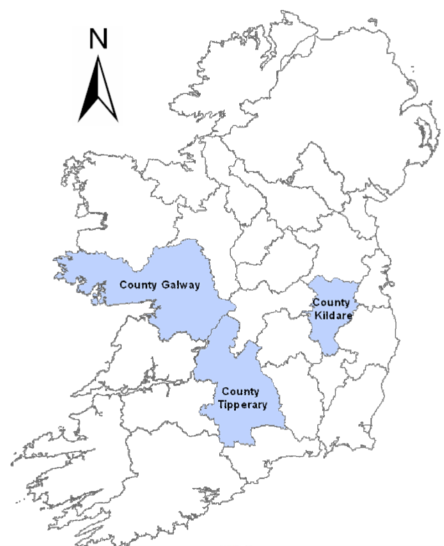
Effective rainfall (Figure 5). Rainfall reduces across the country from west to east, with annual means of more than 2,500 mm along the mountainous Atlantic seaboard reducing to 750 mm around Dublin. The majority of lowland Ireland receives between 800 and 1,000 mm annually, which is fairly evenly distributed throughout the year. Actual evapotranspiration in lower-lying areas is normally between 400 and 500 mm, and the typical range of effective rainfall is from 300 to 600 mm. As a consequence of the distribution of precipitation and evapotranspiration, most recharge occurs in the period from October to April.

Climate data are available from Met Éireann as three datasets: rainfall, potential evapotranspiration and actual evapotranspiration. For the current map, the 1971-2000 30 year annual average data are used. Met Éireann has generated a national map based on interpolation between monitoring locations maintained by Met Éireann. The rainfall data are on a 5 km x 5 km grid.

Previous studies (e.g. Daly, 1994) suggested that annual actual evapotranspiration (AE) for grassland in Ireland is typically about 95% of potential evapotranspiration, and AE is often estimated using this relationship (WGGW 2005). However, a multiplication factor of 0.82 to derive AE from the 1971-2000 PE dataset is indicated by more recent studies (Kennedy, 2010). That factor is used in the current map, in contrast to the 0.95 factor used previously.

Figure 1 Groundwater vulnerability maps and location index

The inset map shows the location of the study counties: County Galway, County Tipperary, and County Kildare. Effective rainfall is higher in the west and lower in the east; extensive karst limestone aquifers occur in the west, fissured aquifers in the midlands and east, and extensive sand/gravel aquifers in the east; blanket peats cover uplands in the west, basin peats occupy the midlands, and peats overlie extensive sand/gravel aquifers in the east



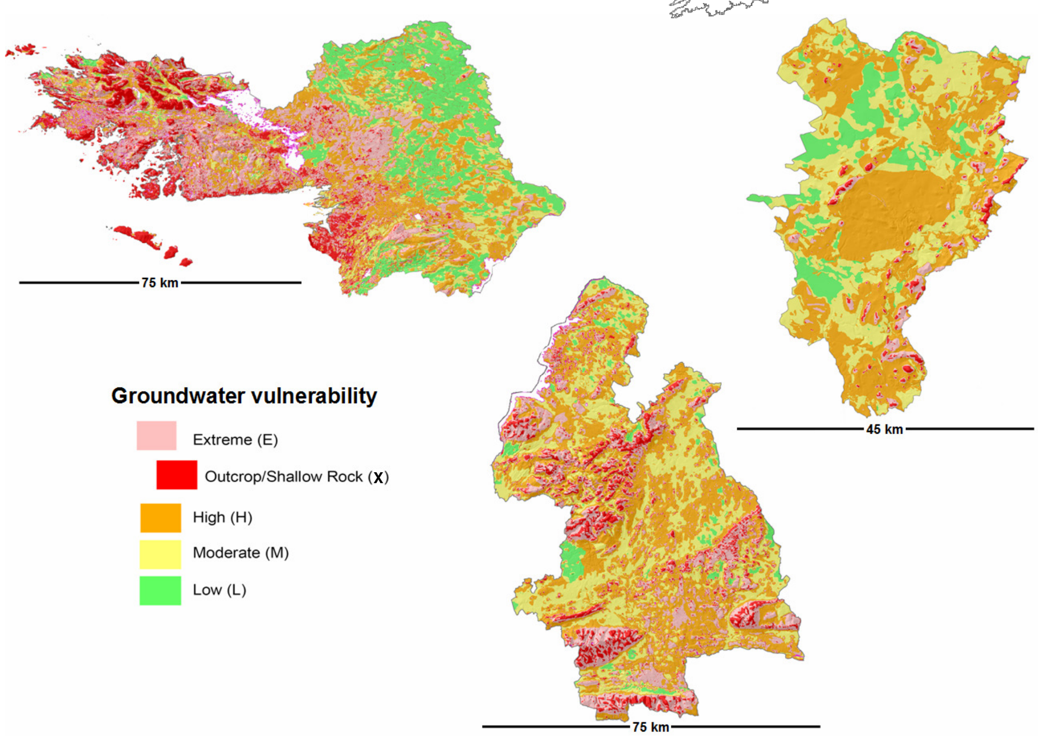


Figure 2 Subsoil permeability maps

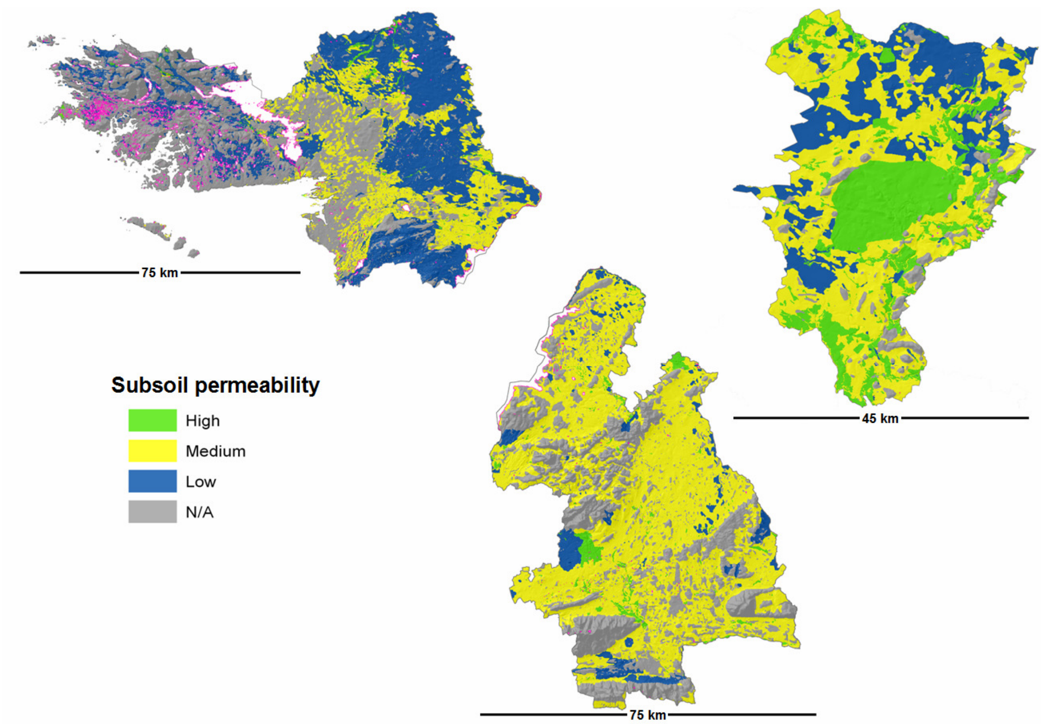


Figure 3 Soil drainage maps

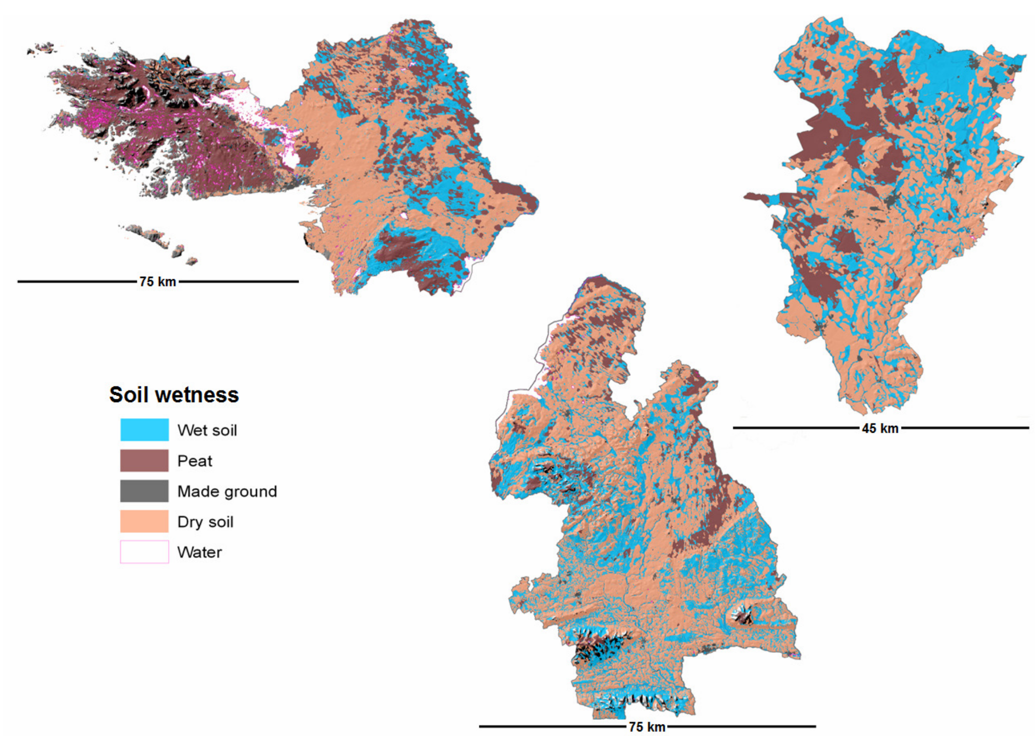


Figure 4 Aquifer maps

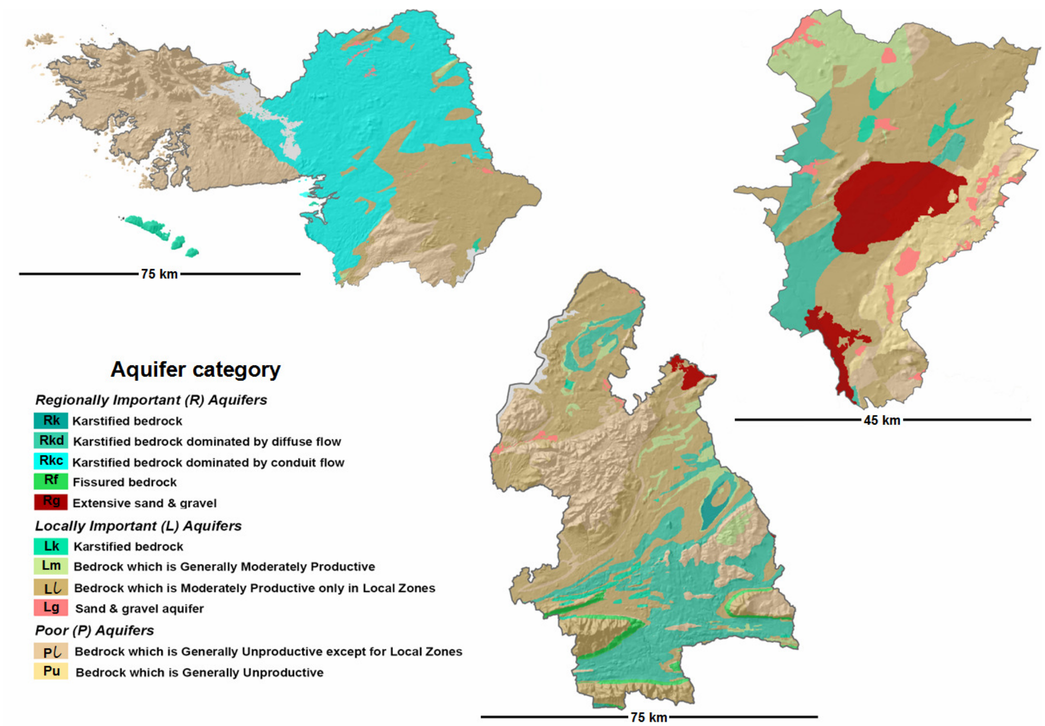
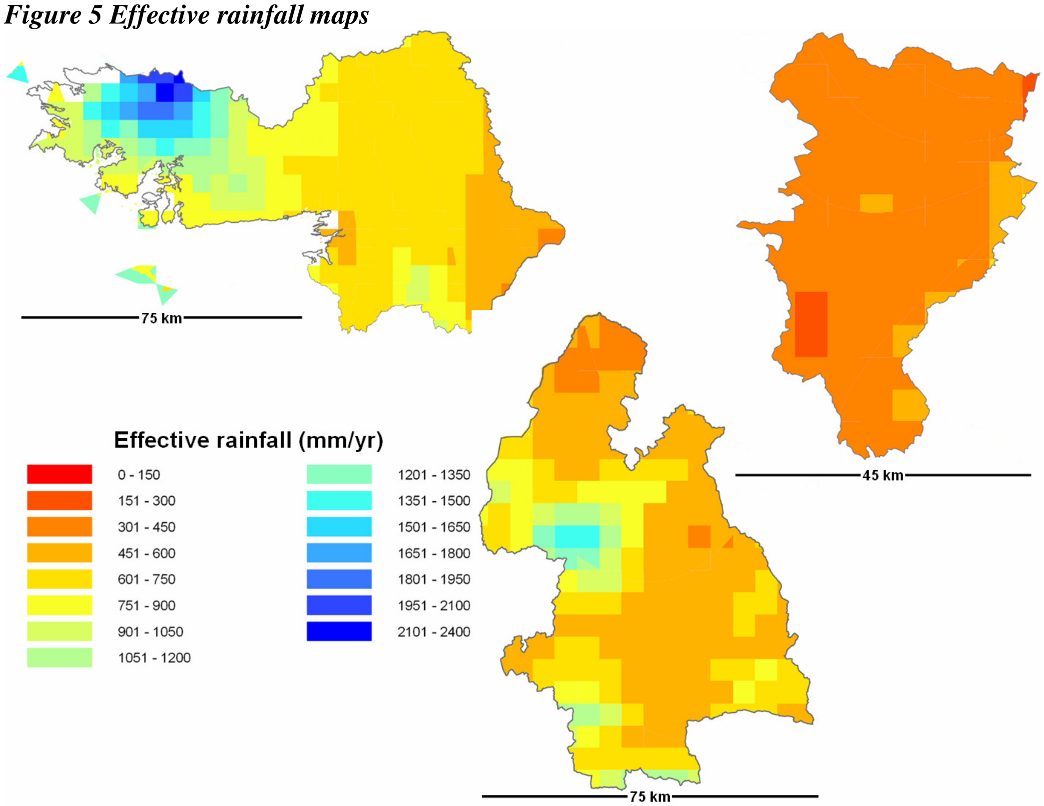


Figure 5 Effective rainfall maps



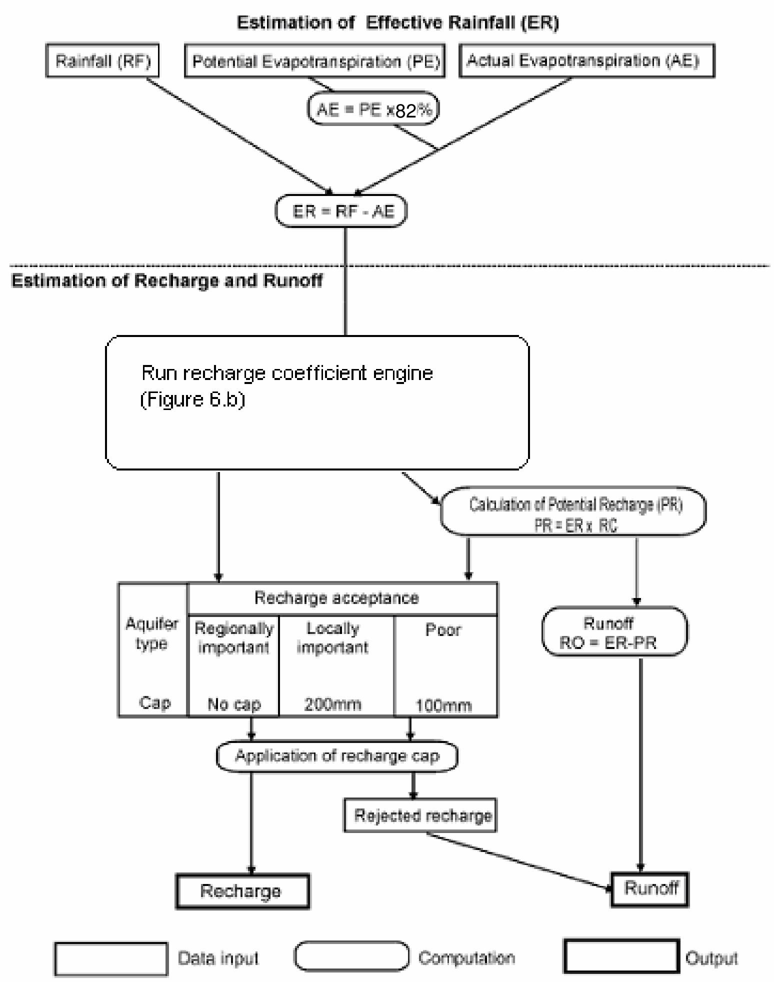
4.3 Integration of data layers

The data layers are combined in a GIS to achieve the hydrogeological scenarios in Table 2. For each hydrogeological scenario, the middle of the inner range of the recharge coefficients is used. Figure 6 indicates the general process used. In essence, the steps are:

1. Produce a layer estimating effective rainfall (ER).
2. Using soils, subsoils and vulnerability maps, calculate recharge coefficients (RC).
3. Estimate potential groundwater recharge using the equation: recharge = ER x RC.
4. Amend recharge value in areas underlain by poorly productive aquifers where potential recharge exceeds the natural recharge capacity.

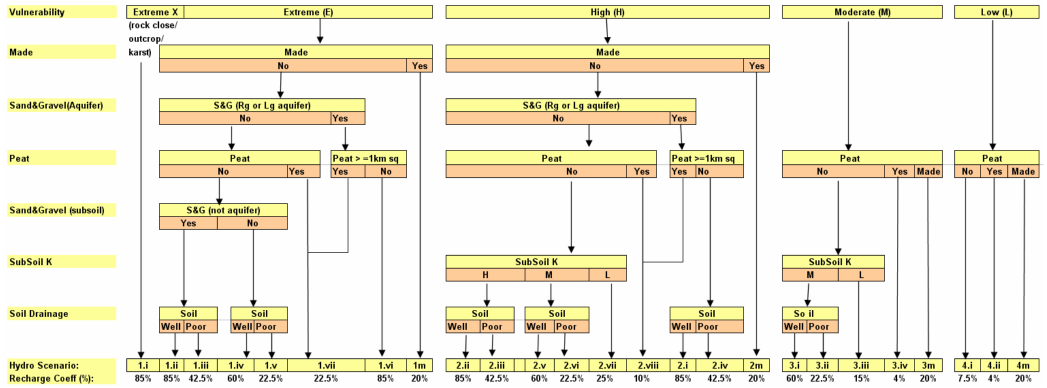
In practice, the process is not quite as straightforward as indicated, as care must be taken to ensure that, at each combination step, areas are not overwritten or omitted.

Figure 6a. Indicative structure and methodology of GIS-based tool for estimating recharge *(adapted from Misstear et al. 2009)*



RF total rainfall, PE potential evapotranspiration, AE actual evapotranspiration, ER effective rainfall, PR potential recharge, RC recharge coefficient, RO runoff.

Figure 6b. The GIS 'recharge coefficient engine' decision structure (adapted from Dublin City Council, 2009; note that High/Low vulnerability scenarios – 5.i to 5.v – are omitted for clarity)



4.4 Average annual groundwater recharge maps

Groundwater recharge maps for the highlighted counties are shown in Figure 7, and the national interim groundwater recharge map is shown in Figure 8. These maps represent a 30 year average diffuse groundwater recharge for average hydrogeological scenarios. Groundwater recharge estimates range from more than 1,500 mm/yr in the western karst areas, to typically 40-150 mm/yr in areas underlain by low permeability subsoils or poor aquifers. Variations in effective rainfall (with higher values in western areas, and over the more mountainous areas) influence the pattern of estimated groundwater recharge. A major influence on calculated groundwater recharge values is the recharge acceptance capacity of the Pl, Pu and Ll bedrock aquifers, which are extensive in Ireland (Figure 8).

Figure 7 Average annual groundwater recharge maps

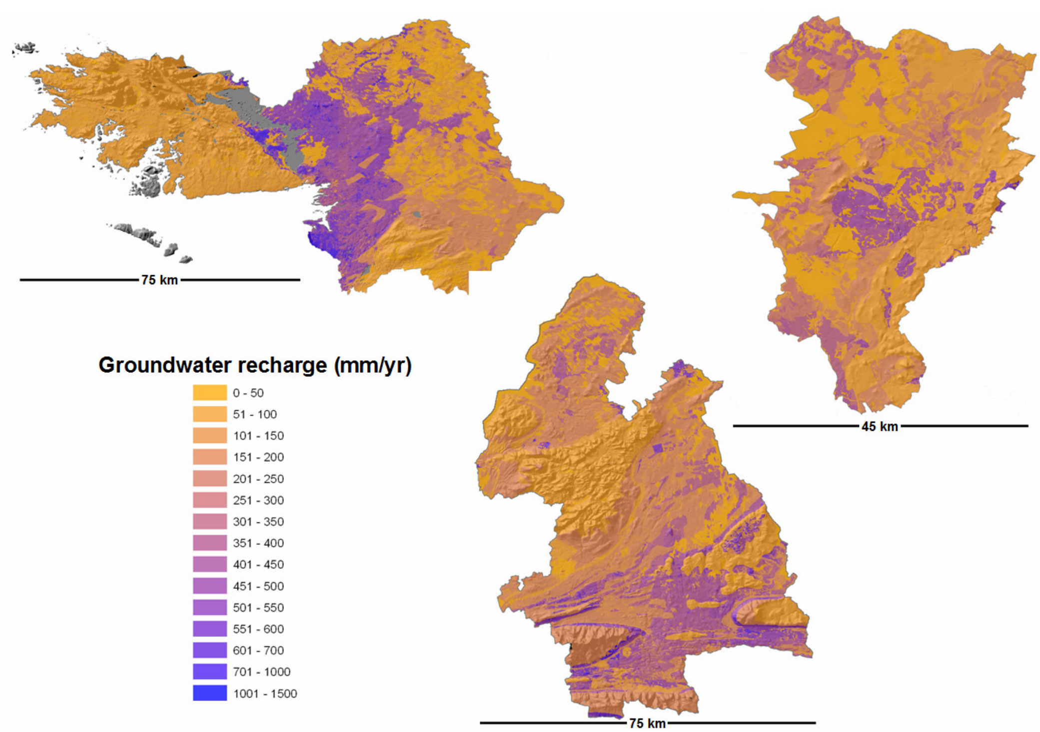
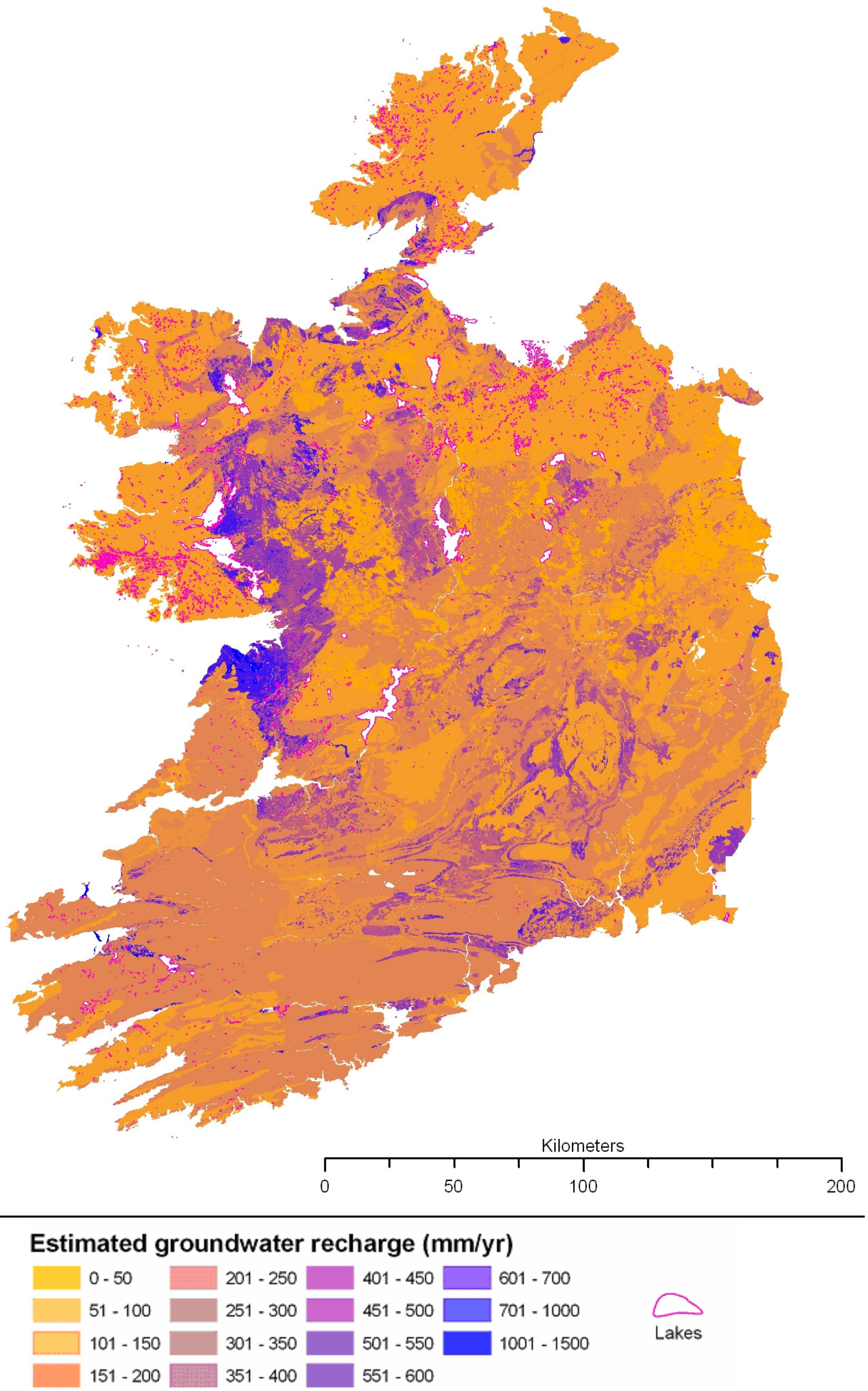


Figure 8 National annual average groundwater recharge map
(estimates are interim for west and north Co. Cork and Co. Kerry until 2012)



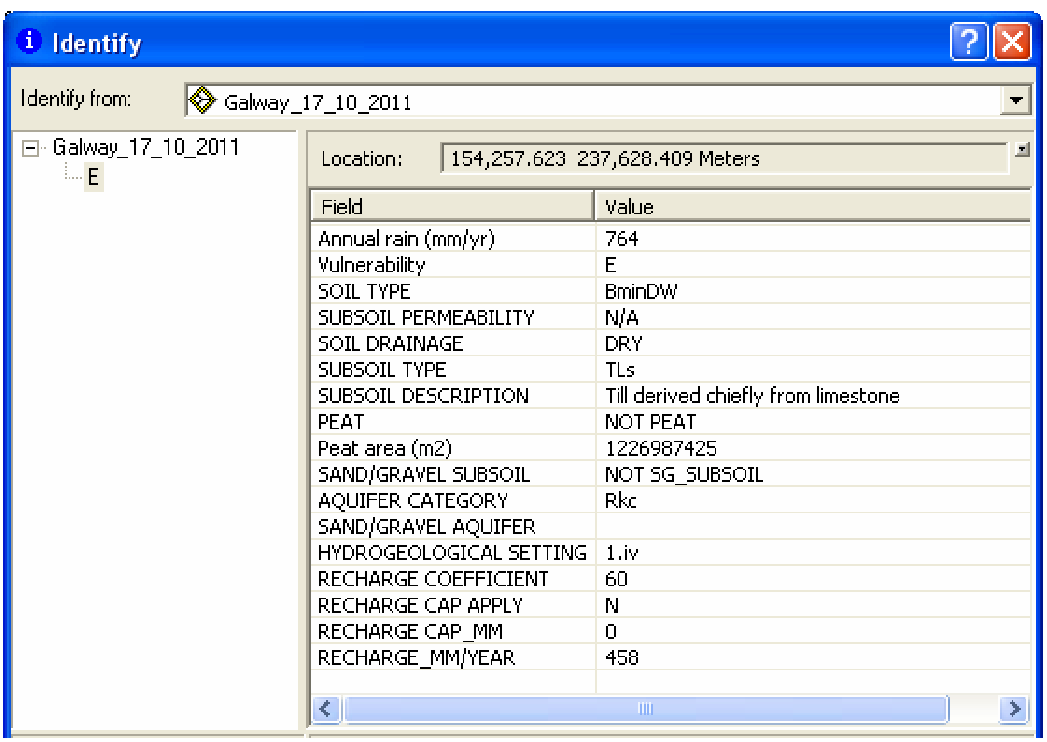
Sand and gravel aquifers, in contrast, are able to accept nearly all effective rainfall. The outline of the Curragh can be discerned in Figure 7, although it is dissected by the large peats, made ground associated with conurbations such as Kildare and Naas, and wet soils associated with river alluvium. Estimated groundwater recharge through dry areas in the Curragh is 361-406 mm/yr, and 45-51 mm/yr through wet areas. This contrasts with 284 mm/yr reported in Misstear *et al.* (2009) from water balance over a three year period (2002-2005), possibly suggesting that the effective rainfall used in the groundwater recharge map is too high. However, the three year estimation is made on climatic data that may differ from the 30 year average, and may incorporate areas of both dry and wet soils (high and low recharge areas).

The influence of the major karst aquifer in the centre of Co. Galway can be seen, with estimated recharge values in the range 500-1000 mm/yr. In the Burren, in Co. Clare, estimated recharge exceeds 1000 mm/yr. It is questionable whether these extremely high values represent abstractable groundwater resources, since the high transmissivity/low storage properties of the aquifer do not lend themselves to retaining recharge.

4.5 Groundwater recharge map background data

In addition to viewing the recharge map, a map of the recharge coefficients may be viewed instead. Further, because of the extensive GIS processing undertaken, it is possible to examine all the parameter values used in deriving the recharge value, including a statement of the hydrogeological scenario as given in Table 2. An example of this is shown in Figure 9. This enables the user to consider the results more fully, and determine whether the median recharge coefficient used in the national recharge map is appropriate for their site, or whether climatic data from a local weather station or seasonally varying effective rainfall are most useful for their study.

Figure 9 Information behind the groundwater recharge map



5. Applications of GW recharge map

5.1Utilities

The groundwater recharge map is currently used to assess the impact of groundwater abstractions and define groundwater body quantitative status as part of Ireland's WFD obligations. The map is also used in groundwater source protection delineation studies.

Other uses include (but are not limited to):

- Runoff estimation cross-check: Runoff (including interflow) may be calculated from the effective rainfall that does not become potential recharge, plus any rejected recharge.
- Baseflow estimate calibration.
- Estimating dilution factors/loading in Tier 1/2 risk assessments of discharges to ground (EPA, in production) and other groundwater risk assessments (e.g. Herlihy and Burden, 2008).
- Assessments of the impacts of climate change on groundwater resources, by integrating the recharge coefficients map with effective rainfall predictions for different climate change scenarios.

5.2 Qualifying considerations

Spatial & temporal resolution of the data are variable, and each of the input data sets have associated precision and accuracy considerations. Bedrock aquifer maps are published at 1:100,000, groundwater vulnerability and subsoil permeability at 1:50,000; and soils data at 1:25,000. Rainfall data are interpolated on a 5 km x 5 km grid. The recharge map presented uses 30 year average climatic data (1971-2000).

For more detailed studies it is preferable to calculate effective rainfall as both monthly and annual averages, so that seasonality of recharge can be taken into account.

Within the bands of minimum, inner range and maximum recharge coefficient for each hydrogeological scenario, the hydrogeologist must decide which part of each range is the most appropriate for the particular conditions encountered. For example, recharge coefficients from near the upper or lower end of the range would be taken if a moderate-permeability subsoil is close to the moderate-high permeability boundary (1×10^{-4} m/s), or the moderate-low permeability boundary (1×10^{-8} m/s).

When undertaking detailed water balances, consideration should be given to whether indirect recharge may be occurring at the edge of low permeability and/or wet soil areas. If point recharge is known to occur, local information should be used to estimate its significance and the likely catchment area of the inflow to the groundwater system.

Misstear *et al.* (2008) point out that inflow approaches such as soil moisture budgets, zero flux plane and application of tracers in the unsaturated zone tend to give estimates of potential recharge, whereas the aquifer response and outflow approaches consider the water that has reached the aquifer. The groundwater recharge estimate from the national groundwater recharge map should if possible, therefore, be cross-checked against estimates made using other recharge methods. These include well and river groundwater hydrograph analyses.

For these reasons, it should be borne in mind that the map is indicative of conditions that may be found at a given site, and the site-specific data should take precedence.

6. Future improvements

The 2011 version of the national groundwater map represents a step forward in the creation of a national dataset that may be applied to a variety of end uses by state, academic and private sectors. There are still improvements to be made, however, which include:

- Incorporation of Co. Cork and Kerry mapping to give full groundwater vulnerability and subsoil permeability coverage in 2012;
- Further consideration of values used for AE and, hence, effective rainfall;
- Re-examination of the values used for the poorly productive aquifer recharge capacities;
- Assessment of the recharge retention capacity of the high transmissivity karst aquifers;
- Consideration of point recharge;
- Consideration of the influence of water table position and ground slope on groundwater recharge.

7. Summary and conclusions

Hydrogeological datasets and the results of groundwater recharge studies have been utilised to produce a national interim map of groundwater recharge coefficients and annual average groundwater recharge.

The current version of the map is part of a series of groundwater recharge maps that have been created primarily for use in WFD groundwater water balance and quantitative status assessments, and incorporates several improvements, including fuller coverage of groundwater vulnerability mapping and better representation of the influence of peats on groundwater recharge.

Other applications include groundwater source protection zone mapping, producing improved assessments of the impact of climate change on groundwater resources, and providing an independently-derived estimate of runoff that can be used to validate and cross-check runoff estimates made using other methods.

The data used to create the map have particular spatial and temporal resolutions. It is important, therefore, to appreciate that this GIS-based map provides a tool for making initial estimations of recharge as part of a project desk study and should not replace the detailed hydrogeological characterisation and recharge assessment that are required at any study site. However, the highly transparent data content of the map enables the user to establish what exactly the map represents, and also to tailor the recharge map with site-specific geological and meteorological data.

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