Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland

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Abstract The study highlights the dangers of limiting recharge calculations in humid climates to meteorological and soil considerations. It highlights the importance of developing a conceptual understanding of the influence of geology on recharge mechanisms and recharge rates. Uncertainties in recharge estimates through tills are examined by a study of the available literature, combined with sensitivity analyses of soil moisture budget parameters and of hypothetical scenarios of till properties and hydraulic gradients that are realistic for Irish conditions. The sensitivity analyses demonstrate that till properties have a greater influence over recharge than the soil moisture budgeting parameters. Results are considered in terms of recharge coefficients, representing the proportion of effective precipitation that becomes actual recharge to the aquifer. The literature review identifies a range in recharge coefficients from 4% to 90% in selected field and catchment scale studies from bedrock aquifers in Ireland and the U.K. The sensitivity analyses are able to simulate a similar range in recharge coefficient of 2% to 80% by varying only till permeability, thickness and vertical hydraulic gradients. In the scenarios examined, the greatest sensitivity to vertical till permeability lies between 0.001 m/day and 0.01 m/day. The sensitivity to soil moisture budgeting parameters is much less apparent. It is concluded that this is due to the dominance of grassland in Ireland and the relatively wet summers, resulting in the limited development of soil moisture deficits by comparison with some parts of the U.K.

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Résumé Cette étude met en lumière les dangers résultants de la pratique consultant à limiter les calculs de recharge aux données météorologiques ainsi qu'aux considérations liées au sol. Elle met en lumière l'importance de développer des modèles conceptuels comprenant l'influence de la géologie sur les mécanismes de la recharge et les taux de recharge. Les incertitudes sur les estimations de la recharge à travers les argiles sont examinées à travers les données disponibles dans la littérature, combinées avec une analyse de sensibilité des paramètres du bilan hydrique et des scénarios hypothétiques reprenant les propriétés des argiles et les gradients hydrauliques qui sont réalistes dans le contexte irlandais de l'étude. Les analyses de sensibilité démontrent que les propriétés des argiles ont une plus grande influence sur la recharge que les paramètres du bilan hydrique des sols. Les résultats sont considérés en terme de coefficients de recharge, représentant la proportion de précipitation effective qui devient la recharge réelle de l'aquifère. La littérature identifie des coefficients de recharge allant de 4 à 90% sur des terrains sélectionnés à l'échelle de bassins-versants, sur les aquifères de socle en Irlande et au Royaume-Uni. Les analyses de sensibilité sont capables de simuler une variation aussi large de coefficients de recharge, en ne changeant rien que la perméabilité des argiles, leur épaisseur et les gradients hydrauliques verticaux. Dans les scénarios étudiés, la meilleure sensibilité à la perméabilité verticale se situe entre 0.001 et 0.01 m/jour. La sensibilité au bilan hydrique est beaucoup moins apparente. On en conclut que ceci est du à la dominance des prairies en Ireland et aux étés relativement humides, résultant des déficits en eau des sols relativement modérés en comparaison avec certaines zones du Royaume-uni.

Resumen El estudio resalta los peligros de limitar los cálculos de recarga en climas húmedos a las consideraciones meteorológicas y del suelo. Se destaca la importancia de desarrollar un entendimiento conceptual de la influencia de la geología en los mecanismos de recarga y los ritmos de recarga. Se examinan las incertidumbres en los estimados de recarga a través de tills mediante un estudio de la literatura disponible combinado con análisis de sensibilidad de parámetros de balance de humedad del suelo y de escenarios hipotéticos de las propiedades del till y gradientes hidráulicos que son realistas para condiciones típicas de Irlanda. Los análisis de sensibilidad demuestran que las

propiedades del till tienen una influencia más grande en la recarga que los parámetros del balance de humedad del suelo. Se consideran los resultados en términos de coeficientes de recarga, representando la proporción de precipitación efectiva que se convierte en recarga real al acuífero. La revisión de literatura identifica un rango de coeficientes de recarga que varía de 4% a 90% en estudios seleccionados de cuencas y escala de campo realizados en acuíferos de macizo rocoso en Irlanda y el Reino Unido. Los análisis de sensibilidad pueden simular un rango similar en los coeficientes de recarga de 2% a 80% al variar únicamente la permeabilidad del till, el espesor y los gradientes verticales hidráulicos. En los escenarios examinados, la relación de sensibilidad más grande con la permeabilidad vertical del till se encuentra entre 0.001 m/día y 0.01 m/día. La sensibilidad en relación a los parámetros del balance de humedad del suelo es mucho menos aparente. Se concluye que esto se debe a la predominancia de tierras con hierba en Irlanda y los veranos relativamente húmedos, lo que resulta en el desarrollo limitado de déficit de humedad de suelo en comparación con algunas partes del Reino Unido.

Keywords Groundwater recharge · Soil moisture budget · Baseflow · Glacial till permeability · Ireland

Introduction

Groundwater withdrawals for water supplies in the Republic of Ireland represent a small fraction of the available resource—one estimate in the 1980s indicated that the total abstraction for public water supply from the most important aquifers was less than 5% of recharge (Wright et al. 1982). Traditionally, therefore, groundwater recharge assessments have not been required to a high degree of accuracy. However, owing to the growing awareness of the importance of groundwater contributions to the environment and, more specifically, to the introduction of the European Water Framework Directive (European Commission 2000), the availability of reliable recharge estimates is now recognised as essential to the proper management of the country's water resources. Aside from resource issues, recharge assessments are closely linked under the European Water Framework Directive to assessments of groundwater vulnerability, diffuse pollutant loads and protection (safeguard) zones around drinking water supplies.

The thematic issue of *Hydrogeology Journal* on groundwater recharge published in 2002 highlighted the uncertainties involved in estimating groundwater recharge and the need for a better understanding of recharge processes (Scanlon and Cook 2002; Scanlon et al. 2002). The degree of uncertainty can be reduced by applying multiple techniques, although the results are often scale dependent (de Vries and Simmers 2002).

In Ireland, the majority of recharge estimates have been based on a combination of soil moisture budgeting and river baseflow analysis (Misstear 2000). A significant uncertainty relates to the influence of the glacial tills which cover most of the important aquifers in Ireland. In the present paper, uncertainties are examined in relation to:

– Key soil moisture budgeting variables (calculation methods, time steps, and vegetation conditions).
– Permeability and vertical hydraulic gradients within the tills.

Only recharge estimation in the regionally important aquifers is considered in this paper. In the less important aquifers, the properties of the aquifer materials themselves will present a significant additional influence on recharge.

It is stressed that this paper aims to examine the key uncertainties in recharge estimation rather than providing recharge estimates for particular study areas. Where appropriate, it has therefore been important to consider results from existing recharge studies as well as the results of original research. Both elements are presented in this paper.

Irish land use, climate and hydrogeology

Grassland is the overwhelmingly dominant crop type in Ireland, comprising approximately 93% of all agriculture and 64% of the total land area. Forestry is limited, comprising approximately 9% of the total land area (Brogan et al. 2002). Cereals can be important crops overlying productive aquifers in Irish midland regions, but grassland is dominant even in these specific areas.

Ireland experiences a temperate maritime climate, influenced by the mild sea temperatures of the Gulf Stream in the Atlantic and by moist south-westerly winds. Daly (1995) notes that:

– Rainfall ranges from 800 to 1,400 mm/year over the main aquifers and is well distributed throughout the year. Actual evapotranspiration ranges from 400 to 500 mm/year. Therefore, there is an excess of rainfall over evapotranspiration, ranging from 400 to 1,000 mm/year.
– There is a general increase in excess rainfall from east to west across the country and also with elevation. East of a line from Belfast to Cork there is a definite recharge period from mid-October to mid-March and, thereafter, a general recession period of up to 7 months in the southeast. West of this line recharge is more evenly distributed across the year with summer recession periods lasting as little as 1 month per year in the northwest.

A site location map can be found in Fig. 1 and an approximate distribution of excess rainfall is presented in Fig. 2.

The more seasonal climatic pattern in the eastern half of the country is reflected in unpublished borehole hydrograph data collected by the Geological Survey of Ireland. Selected hydrographs are presented in Fig. 3. Some of these provide evidence that short-term interruptions in the summer recession can occur; for example in mid-summer 1998 in the Woodsgift and Knocktopher boreholes.

The most important bedrock aquifers—referred to as 'regionally important aquifers'—occur in the Palaeozoic limestones and sandstones that underlie over 50% of the country; mainly in the lowland areas in the midlands, west and south. Daly (1995) summarises the key characteristics
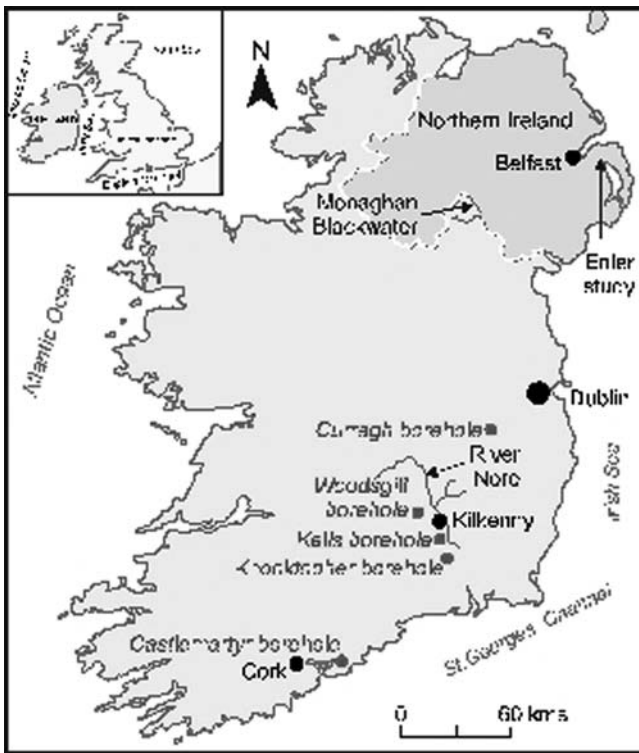
Fig. 1 Site location

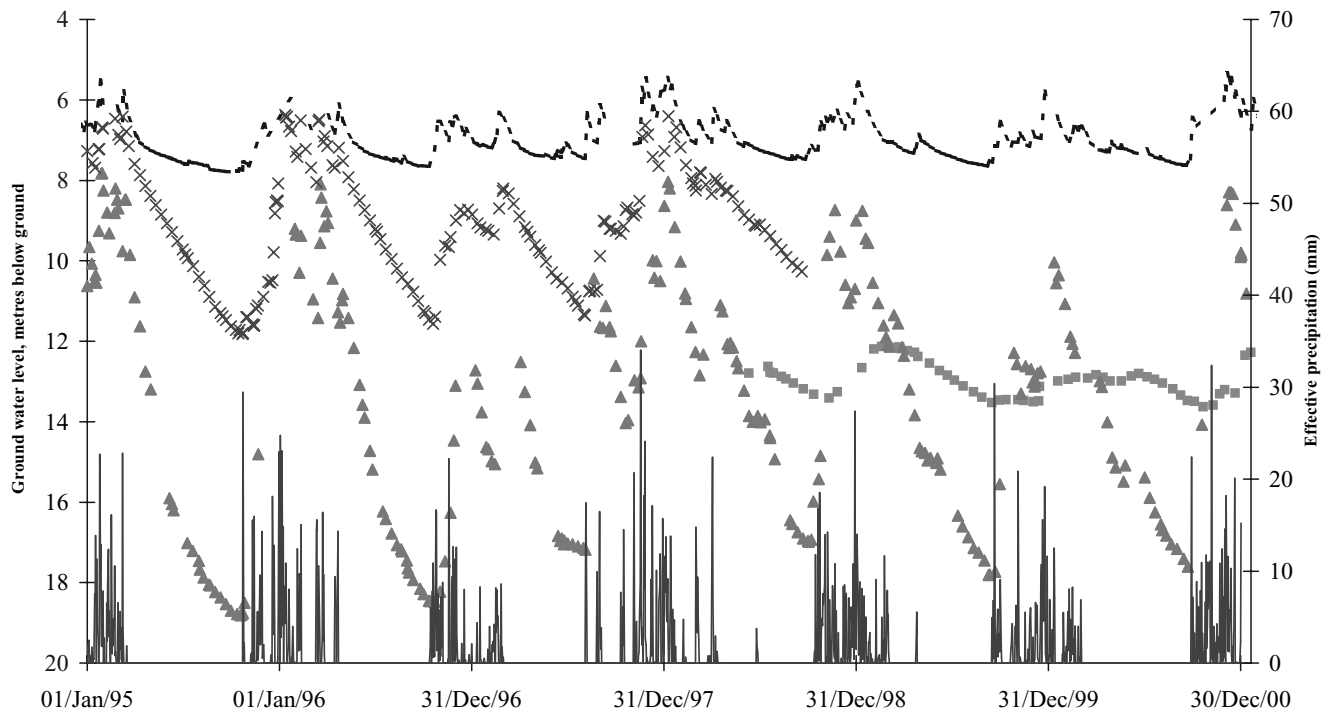**Fig. 2** Estimated soil moisture excess in mm/year after Collins and Cummins 1996

Fig. 3 Selected Irish fractured limestone aquifers and their response to recharge (the response of an intergranular gravel aquifer is included for comparison)

of these aquifers. The following are significant in the context of this paper:

– Fissure flow predominates and permeability is greatest, by an order of magnitude, in the top 30–40 m of bedrock.
– Storage is low and 75–80% of the groundwater flow occurs within the 20 m to 30 m interval below the summer water table.
– With some exceptions, the water table is generally less than 10 m below the ground surface, with an annual fluctuation of less than 5 m.
– Flow paths are relatively short, with groundwater discharging into springs or streams.
– Perched water tables are common in the winter in the strata overlying the bedrock aquifers.

The fissure flow characteristics and low aquifer storage often result in a rapid response to both the onset and ending of recharge. The examples in Fig. 3 demonstrate this effect. The estimates of effective precipitation presented in Fig. 3 have been taken from daily grassland simulations generated for the sensitivity analyses described later in this paper.

Most of the bedrock aquifers are covered by glacial deposits. These deposits are dominated by tills (boulder clays). Unpublished mapping currently being undertaken by the Geological Survey of Ireland indicates that tills cover approximately 65% of the regionally important aquifers. A formal definition of 'till' can be found in the literature, but the main aspects of relevance are: tills are generally unsorted, comprising a wide range in particle sizes, and their primary porosity is generally significant.

The Geological Survey of Ireland has used work by Lee (1999), O'Suilleabhain (2000) and Swartz et al. (2003) to develop a classification system for Irish tills. Those tills with an in-situ permeability in excess of 10^{-4} m/s or with a total silt and clay content of less than 8% by weight are classed as 'high' permeability. From field and laboratory testing of tills in Ireland, Swartz et al. (2003) suggest that the 'boundary between low and moderate permeability subsoils appears to be in the region of 10^{-9} m/s using falling head tests'. Lee (1999) and Swartz et al. (2003) go on to indicate that tills classed as 'low' permeability tills are often associated with a combination of one or more of the following characteristics;

– 'Surface water gley' soils. Gleys are soils in which the effects of drainage impedance dominate and which have developed under the influence of permanent or intermediate waterlogging. Where gley formation is due to a perched water table, the soil is referred to as a surface water gley.
– 'CLAY' textures [as defined by the British Standards Institution (1999) classification].
– More than 13% (by weight) clay size particles.

Though some tills have been classed as 'high' permeability, they are uncommon. Most tills in Ireland are classified as a 'moderate' or 'low' permeability and have not been mapped as aquifers. The till cover is often between 5 and 15 m thick and the lower permeability tills contain perched water tables at, or close to, ground level.

Groundwater recharge

Groundwater recharge has been defined as 'the downward flow of water reaching the water table, forming an addition to the groundwater reservoir' (Lerner et al. 1990). There are two main types of recharge: direct (vertical infiltration of precipitation where it falls on the ground) and indirect (infiltration following runoff). It is generally acknowledged that in temperate climates most recharge is direct (Simmers 1997), and this type is the focus of this paper. However, in certain geological situations, point recharge is a crucial additional component even in temperate regions.

Hulme et al. (2001) describe two key types of direct recharge; *potential* and *actual* recharge. '*Potential* recharge is the water that leaves the bottom of the soil zone. If the material in the unsaturated zone does not restrict the vertical movement of water, the *actual* recharge (the water reaching the water table) equals *potential* recharge.'

In Ireland, the strata overlying the most important aquifers are dominated by tills. Uncertainties in the vertical restrictions posed by the tills are the key focus of this paper. In order to allow comparisons between studies of river flow and recharge, the following terms have been adopted:

1. *Effective precipitation*: the soil moisture surplus that is available for direct recharge or runoff. Effective precipitation will be equivalent to potential recharge as defined by Hulme et al. (2001), except in areas where significant amounts of precipitation becomes overland flow without contributing to the soil moisture budget, or where precipitation can bypass the soil moisture store in significant quantities.
2. *Actual recharge*: downward percolating water that reaches the potentiometric surface *within the uppermost aquifer* below an area. The emphasis on the aquifer is important here as many Irish tills are not mapped as aquifers but contain perched water tables at or close to ground level. In this study, perched water tables are only of relevance in relation to the estimation of vertical hydraulic gradients between the till and the aquifer below.
3. *Recharge coefficient*: that proportion of effective precipitation that becomes actual recharge.

The current methodologies for assessing effective precipitation, actual recharge and recharge coefficients are considered in general terms below, followed by a summary of results from previous recharge studies in Ireland and, where relevant, the UK.

Effective precipitation assessments

In Ireland, effective precipitation predictions have been most commonly based on the estimation of soil moisture surplus through soil moisture budgeting techniques.

Lerner et al. (1990) state that the 'Penman-Grindley' model is the 'simplest and most widely used soil moisture budgeting model'. In this model, the amount of soil moisture surplus or soil moisture deficit is estimated from

Fig. 4 Concepts in the soil
moisture budgeting technique.
Taken from Lerner et al. (1990)
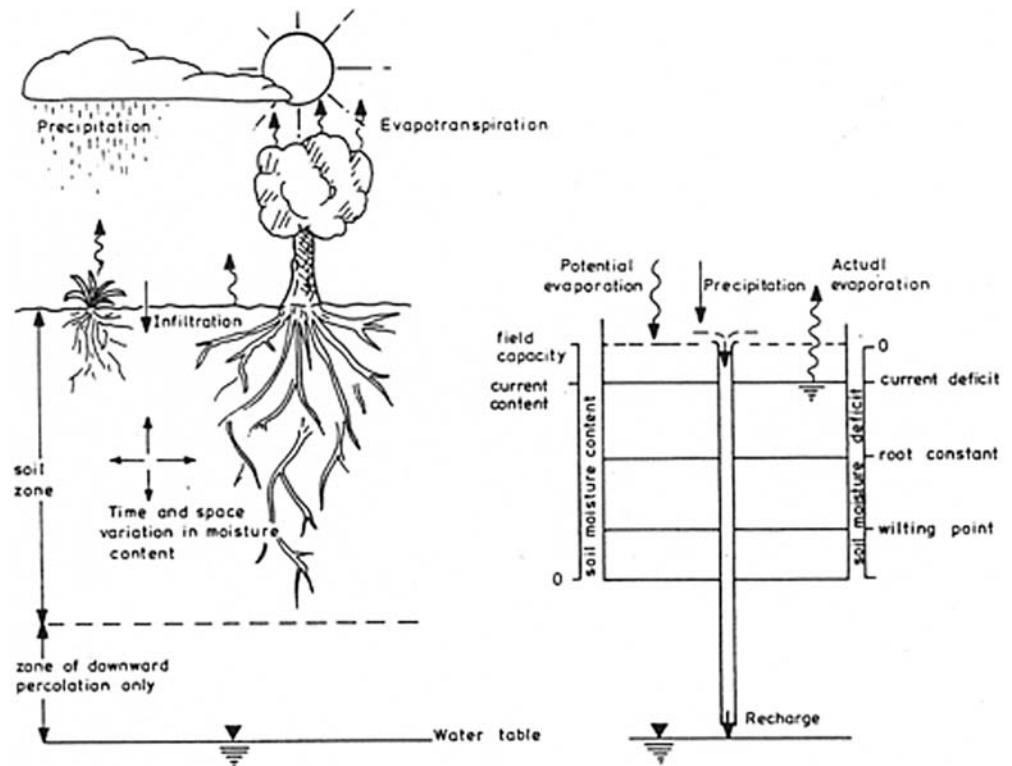
precipitation and potential evapotranspiration (PET) data, the latter calculated from the Penman or Penman-Monteith formulae (Fig. 4). The key difficulty is the derivation of *actual* evapotranspiration (AET), which is assumed to equal PET unless the soil moisture deficit is below a critical threshold beyond which the vegetation has difficulty in transpiring. This threshold was originally termed the 'root constant'. Penman (1949) developed the original concepts and a useful summary is provided by Rushton and Ward (1979).

The Aslyng (1965) soil moisture budgeting method has been commonly used in Ireland and follows the basic Penman-Grindley model. Typically, the ratio of AET to PET is assumed to decrease linearly from 1 to 0 as the soil moisture deficit increases from 30 to 120 mm. Cawley (1994), Daly (1994) and MacCarthaigh (1994) provide examples of the use of this method in Ireland.

Lerner et al. (1990) indicate that, in the U.K., the AET:PET ratio has been calculated in a number of different ways but is usually assumed to take a step change from 1 to 0.1 as the soil moisture deficit increases beyond the root constant and from 0.1 to 0 as the soil moisture increases beyond the 'wilting point'. In comparison with Ireland, greater attention has been paid to the influence of vegetation on the AET:PET ratio. This is a consequence of greater abstraction pressures and a greater variety of crop types in the U.K. Grindley (1970) defined root constants and wilting points for a variety of crop types and these were subsequently enhanced by Rushton et al. (1988). Lerner et al. (1990) provide a useful summary for the values "usually used" in the U.K.

Hulme et al. (2001) have recently proposed amendments to the Penman-Grindley model for the U.K., involving the incorporation of evaporation from bare soil (where appropriate), and changes to the relationship of AET to PET during times of low soil moisture. They also replaced the concept of 'root constant' with a similar concept of 'readily available water', using actual information about crop water requirements from the Food and Agriculture Organisation of the United Nations (FAO 1998).

A number of studies in the U.K. have attempted to include the more complex processes involved in interaction between precipitation and the soil moisture store. Bradbury and Rushton (1998), for example, modelled overland flow during times of precipitation, which has the effect of removing a proportion of precipitation from consideration in the soil moisture budget. Conversely, bypass flow can provide another complication in that a proportion of precipitation can become recharge without interacting with the soil moisture store; even at times of soil moisture deficit. These processes can vary on a very localised scale and are best examined in catchment-specific studies.

Assessments of actual recharge and recharge coefficients

Wright et al. (1982) and Daly (1994) use results from baseflow separation to assess the relation between effective precipitation and actual recharge in different geologic materials. These types of study have formed the basis of many actual recharge assessments in Ireland. Mau and Winter (1997) and Szilagyi et al. (2003) are examples of studies outside Ireland where recharge rates were estimated from baseflow separation exercises.

The baseflow separation process involves the estimation of the aquifer outflows through the examination of a runoff hydrograph at a river flow gauging station that is representative of a catchment where groundwater discharges to surface water and where lake/reservoir storage does not pose a significant impact on river baseflows. Over a long period, the aquifer outflow (discharge) should be equivalent to the inflow (recharge), after any abstractions (withdrawals) are taken into account. In suitable catchments and at suitable gauging stations, the baseflow component of a river is assumed to equate to both aquifer discharge and recharge. The proportion of total river water flow to baseflow is termed the baseflow index.

Halford and Mayer (2000) outline certain additional assumptions that are implicit in using runoff flow records to estimate recharge:

– there is a direct relationship between the timing of groundwater and surface runoff peaks;
– there is negligible evapotranspiration from lakes, rivers and wetlands compared to the total volume of groundwater baseflow;
– bank storage and river recharge effects are negligible; and
– there is minimal interaction between the superficial (also termed 'surficial') and deeper aquifers.

Some of these assumptions are consistent with the characteristics of Irish bedrock aquifers described earlier in this paper. Further, groundwater abstractions are generally a small proportion of the available resource (Wright et al. 1982) and the influence of abstractions can often be discounted. There will therefore be situations in Ireland, if runoff recharge is insignificant, where baseflow estimations can be used to help estimate catchment-scale recharge. In these situations, the recharge coefficient may be assumed to be broadly equivalent to the base flow index.

In Ireland, the baseflow separation process has historically been undertaken using manual hydrograph separation techniques, based on the judgement and experience of individual hydrogeologists. In the U.K., automated techniques are more commonly used. One of the most commonly used techniques was developed by the Institute of Hydrology (1989).

A number of major mine dewatering projects have been in progress for several years in bedrock aquifers of the Irish Midlands. Estimation of recharge rates represents an important element of these projects. They therefore provide an important new source of information, but results have yet to be discussed in the literature. In Britain, numerical modelling has been used more extensively to help examine actual recharge, primarily for water resources purposes. A number of models have been developed for till areas using the concepts of integrated catchment studies; involving estimates of soil moisture surplus, actual recharge, bypass flows and runoff recharge. The form of these models varies widely and the reader is referred to excellent examples in Senerath and Rushton (1984), Jackson and Rushton (1987), Bradbury and Rushton (1998), and Soley and Heathcote (1998).

Literature review

Results from selected recharge studies are presented in Table 1, augmented, where appropriate by the present authors' inferences on recharge coefficients, as explained below. Studies have been selected where the aquifer type would not normally be excepted to pose a limit on actual recharge and where the influence of tills has been examined. Where possible, results have been taken from studies in Ireland. These have been supplemented with selected studies from the U.K. where the glacial tills are similar and where more extensive studies have been carried out.

For comparative purposes, results from all these studies have been normalised by presenting them in the context of a recharge coefficient. As described above, it has been assumed that, under certain conditions in catchment-scale recharge studies, the recharge coefficient will be an approximation of the baseflow index for that catchment.

Where the cited papers present actual recharge estimates, but provide no corresponding estimations of effective precipitation, the authors have used geological and hydrological information from within the papers to infer approximations for recharge coefficients. The basis behind these inferences is indicated in the notes accompanying Table 1.

In the papers cited, the recharge coefficient in lower permeability or thicker tills ranges from 4 to 30% and the coefficient for thinner, more permeable tills ranges from 60 to 90%.

Senerath and Rushton (1984) highlighted an issue relating to the scale of investigation in low permeability till areas. They estimated direct recharge to the aquifer below the till to comprise 10% of total catchment recharge. However, they estimated that the total recharge generated over the till areas was almost double this figure. The difference comprised a portion of effective precipitation that became indirect recharge, being diverted to surface runoff over lower permeability areas, and then infiltrating to groundwater on reaching higher permeability strata.

An additional paper from the U.K. is worthy of further discussion. Rushton et al. (1988) used field observations and modelling to examine the influence of the 'drift' (i.e. tills and gravels) on recharge to the underlying sandstone aquifer. The authors developed 'drift factors' which represent the proportion of *actual* to *potential* recharge. Depending on the proportion of 'sandy clay' and the thickness, the estimated drift factors ranged from 2 to 65% in deposits over 2 m thick and from 70 to 100% in deposits less than 2 m thick. These drift factors were then adjusted to reflect predicted vertical hydraulic gradients between the till and the aquifer below.

Clearly, factors other than till properties (e.g. topography) may be influencing the cited ranges in recharge coefficient. The sensitivity analyses presented in the remainder of this paper will provide an assessment as to whether a similar range could be simulated by varying *only* soil moisture budgeting parameters and till properties within limits that are reasonable for Irish conditions.

Table 1 Selected examples of previous recharge and baseflow studies in aquifers overlain by glacial tills

Authors	Recharge estimation method and location (Fig. 1)	Description of bedrock aquifer	Description of till	*Actual* recharge (mm/year)	BFI[a] or recharge coefficient
Examples of studies where tills are assumed to be thick or low permeability[b]					
McConville and Kalin (1999)	Field measurement using environmental tracers	Triassic sandstone	>1.5 m thick. Surface water gley soils overlie tills[c]	22	4%[d]
Soley and Heathcote (1998)	Numerical modelling on a catchment in the U.K	Cretaceous Chalk and Quaternary gravel	Silty clay till[c] up to 60 m thick	10 to 36	5 to 20%[e]
Daly (1994)	Baseflows and monthly soil moisture budgets within the Nore catchment (2,388 km^2)	Carboniferous limestone/dolomite Devonian sandstone	Thick till or gley soils[c]	–	30%
MacCarthaigh (1994)	Baseflow analyses within the Monaghan Blackwater catchment (126 km^2)	Fissured and karstified Carboniferous limestone	*Thick, moderate to low permeability subsoils*[f]	–	27%
Jackson and Rushton (1987)	Numerical modelling on a catchment in the U.K	Cretaceous Chalk	'Boulder clay' >10 m thick. Permeability > 1.2×10^{-9} m/s[g]	24	13%[h]
Senerath and Rushton (1984)	Routing model for river flow prediction on a catchment in the U.K	Cretaceous Chalk and Quaternary gravel	'Boulder clay'. Permeability from 1.2×10^{-8} m/s to 1.2×10^{-11} m/s[g]	–	10 to 17%
Examples of studies where tills are assumed to be thin or permeable					
Daly (1994)	Baseflows and monthly soil moisture budgets within the Nore catchment (2,388 km^2)	Fissured and karstified Carboniferous limestone	Thin tills	–	60%
		Karstified Carboniferous limestone	Thin tills	–	90%
Soley and Heathcote (1998)	Numerical modeling on a catchment in the U.K	Cretaceous Chalk and Quaternary gravel	Silty clay till[c] up to 60 m thick	160	88%[e]

[a]Baseflow index

[b]Values in italics were not presented in the papers cited and represent inferences as described in the footnotes

[c]No specific permeability information was provided by the authors. However, in Ireland, these soil and till descriptions are typically associated with low permeability parent material (Lee 1999)

[d]No potential recharge information was provided by the authors. Using the data presented in Fig. 2, effective precipitation is assumed to be 600 mm/year for the area studied

[e]The authors quote an average "hydrologically effective precipitation" of 182 mm/yr. It is assumed this value is similar to effective precipitation as defined in this paper

[f]Description taken from Geological Survey mapping (Swartz and Daly 2002)

[g]Using the classification scheme proposed by Swartz et al. (2003), this recharge rate would be classed as "low" permeability

[h]The authors provide an estimate of actual recharge but no specific estimate of effective precipitation. The figure has been taken from estimates made by Soley and Heathcote from an adjoining catchment
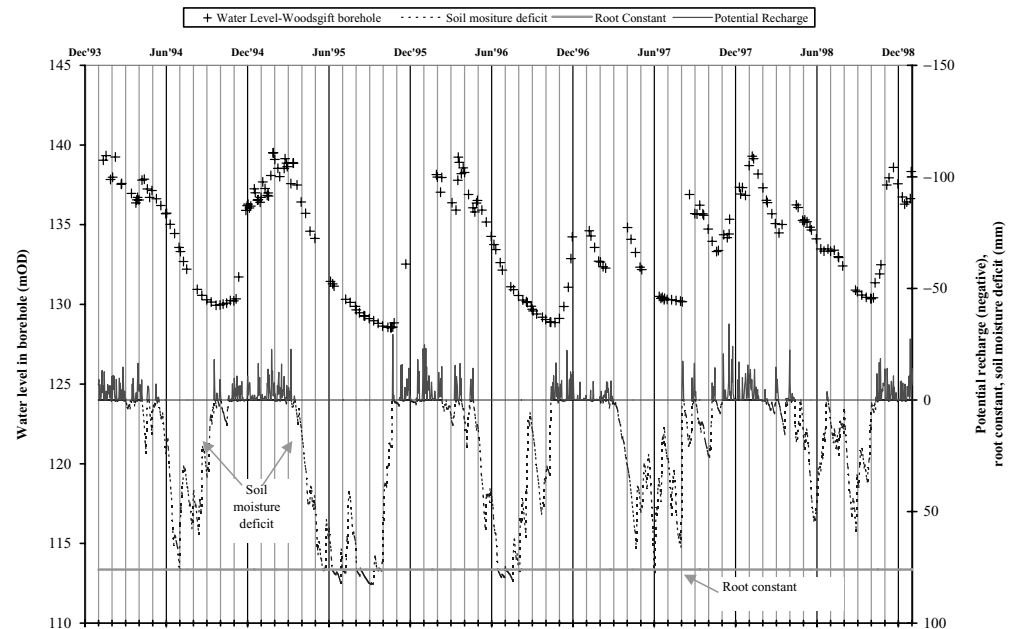
Sensitivity analyses—effective precipitation

Effective precipitation estimates are potentially sensitive to several meteorological, topographical, vegetation and soil parameters, but this paper focuses on sensitivity due to calculation methods, time steps, and vegetation conditions in the context of soil moisture budgeting techniques.

A baseline dataset of effective precipitation estimations was constructed for the Irish midlands. Kilkenny data were selected as the area lies in the south eastern midlands, where

Fig. 5 Effective precipitation: the interaction of the root constant, soil moisture deficit and recharge concepts

the summer soil moisture deficits are expected to be larger and more prolonged than in most areas of Ireland. The sensitivity of effective precipitation to factors such as vegetation is therefore likely to be greater in these areas. The following procedures and data were used to construct the baseline dataset:

(a) Daily time steps: daily precipitation and monthly Penman PET data were compiled from unpublished Met Eireann data from the Kilkenny synoptic weather station over the period from 1994 to 1998. The location of Kilkenny City is shown in Fig. 1. Daily PET values were inferred by the authors from daily pan evaporation data which were also available from Met Eireann. Monthly pan totals were adjusted to match the monthly PET data and the daily pan figures were adjusted by the same factor.

(b) The Penman-Grindley soil moisture budgeting model: the ratio of AET:PET was assumed to drop to 0.1 as the soil moisture deficits exceeded the root constant. Bypass flows, overland flows and runoff recharge were not modelled.

(c) Grassland vegetation: this crop was simulated using appropriate root constant and wilting point values from Lerner et al. (1990).

In Fig. 5, results for this baseline dataset are presented in the context of daily groundwater level readings from the 'Woodsgift' borehole. This borehole is constructed into an unconfined fractured limestone aquifer near Kilkenny City (Fig. 6a and b).

This baseline dataset was compared against the following:

– Different models: the Penman (Penman 1949; Grindley 1970), Aslyng (1965) and Hulme et al. (2001) soil moisture budgeting models were used. The three models were

run for grassland conditions using daily time steps and the same meteorological data.

– Variable time steps: both daily and monthly time steps were run for grassland conditions, the Kilkenny City meteorological data from 1994 to 1998, and the same 'Penman-Grindley' soil moisture budgeting model.

– Variable vegetation: cereals, rough grazing, and woodland crops were simulated using appropriate root constant and wilting point data from Lerner et al. (1990). All simulations were run using daily time steps, the Kilkenny City meteorological data from 1994 to 1998, and the same 'Penman-Grindley' soil moisture budgeting model.

Results from the sensitivity analyses are presented in Table 2. The last column of the table shows the results for each simulation as a percentage of the baseline grassland simulation. The timing of the main autumn recharge period is also indicated in Table 2 using the number of days by which each recharge simulation lagged behind groundwater levels observed in the Woodsgift borehole in October 1995 (Fig. 5).

The data presented in Table 2 and Fig. 5 suggest that the baseline grassland simulation provides at least one possible means to describe the timing of groundwater recharge in the aquifer monitored by the Woodsgift borehole. However, the key finding of this sensitivity analysis is that the calculated average annual effective precipitation is relatively insensitive to the factors examined. The total variation ranged from 121 to 91% of the baseline estimate. Moreover, the estimates for woodland and for rough grazing vegetation can be discounted. For woodland, the timing of autumn recharge in 1995 lags behind the hydrograph data and the grassland simulation by over 50 days and is more than double the next biggest lag time (September cereals). Simulations for 'rough grazing' do not seem applicable to conditions in the eastern midlands of Ireland because they
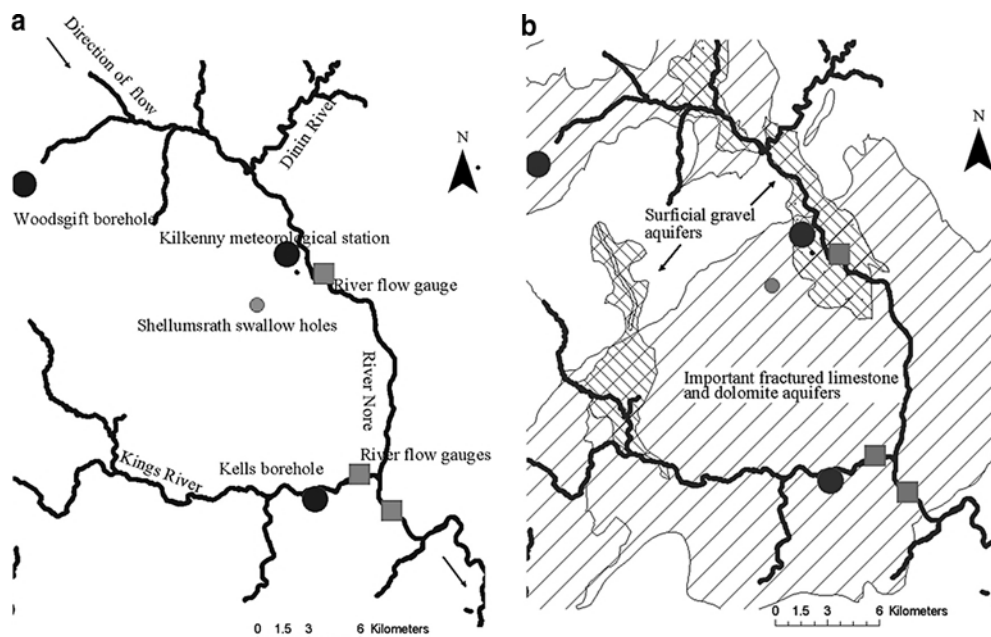
Fig. 6 **a** Sub Catchment in County Kilkenny—Location of key hydrological features and instrumentation. **b** Sub Catchment in County Kilkenny—Main aquifers

predict frequent recharge throughout the summer months, which is not reflected in the borehole hydrograph data in Fig. 5, or in any of the borehole hydrographs presented in Fig. 3. Consequently, it is considered reasonable to omit the results of the rough grazing and woodland simulations, resulting in a much smaller variation of only 101 to 95%. Clearly, woodland and rough grazing simulations will be important in certain catchment studies, but the national land use data presented in this paper suggest that these instances will be rare.

It is interesting to note that the variation is less than the variations determined by similar studies in the U.K. Howard and Lloyd (1979), for example, found that monthly estimates in Lincolnshire (in north east England) were as much as 43% less than daily estimates over the period from 1972 to 1974. The lower sensitivity to time step in Ireland is perhaps due to more limited development of soil moisture deficit when compared to some parts of the U.K. In areas where the soil moisture deficit is limited in comparison with the root constant, the average annual AET:PET ratio

Table 2 The sensitivity of effective precipitation estimates derived from soil moisture budgets

Input parameters				Results		
Method	Time step	Simulated crop	Root constant (mm)[a]	Ratio of simulated annual AET to annual PET (%)	Delay in simulation of autumn recharge in 1995[b]	Average annual recharge as a proportion of the baseline estimate
Penman-Grindley[c]	Daily	Grassland	76	88	3 days	Baseline estimate = 512 mm/yr
Penman-Grindley[c]	Daily	Cereals	25 (Jan)–140 (Jun)	93	24 days	95%
Penman-Grindley[c]	Daily	Woodland	203	98	59 days	91%
Penman-Grindley[c]	Daily	Rough grazing	13	67	Regular summer recharge	121%
Aslyng (1965)[d]	Daily	Grassland	30	87	3 days	101%
Hulme et al. (2001)[e]	Daily	Grassland	123 (Jan)–110 (Jun)	92	24 days	96%
Penman-Grindley[c]	Monthly	Grassland	76	91	-	97%

[a]Hulme et al. (2001) use the concept of readily available water

[b]As compared with the ending of the summer recession at the Woodsgift hydrograph on 21st October 1995

[c]AET:PET ratio can take a variety of forms but here the model used is a step change from 1 to 0.1 as the soil moisture deficit exceeds the root constant (as described by Lerner et al. 1990)

[d]AET:PET ratio declines linearly from 1 (at the root constant) to 0 (at a deficit of 120 mm)

[e]AET:PET ratio declines linearly from 1 (at the readily available water content of the soil) to 0 (at the total available water content of the soil)

is likely to be close to one. In these situations, monthly or even annual time steps are unlikely to derive significant differences to daily time steps. The simulation presented in Fig. 5 demonstrates this. In this example from the eastern midlands of Ireland, the soil moisture deficit exceeds the simulated root constant on only 24 days per year over the period examined. This represents only 16% of the total length of the period when soil moisture deficits generally occur and the average annual AET:PET ratio is almost 0.9.

The expected similarity of AET to PET in Irish grassland situations also helps to explain the limited sensitivity to the particular 'Penman-Grindley' method adopted, as the key difference between these models is the relationship of AET to PET when the soil moisture deficit exceeds the root constant. Grassland simulations using daily time steps with the Aslyng (1965) and Hulme et al. (2001) methods ranged from 101 to 96% of the baseline dataset. In Ireland and similar humid climates, the particular Penman-Grindley method used will only have significance in crops where the root constant is particularly small.

Sensitivity analyses—till properties

As described above, there has been little modelling of the influence of till properties on recharge in Ireland. In order to examine sensitivity, therefore, a similar approach to that used by Rushton et al. (1988) has been adopted whereby thickness, clay content/permeability and till thickness/vertical gradients have been considered. However, in contrast to Rushton et al. (1988), the aim here is to provide a sensitivity analysis using a relative comparison of recharge estimates in a range of hypothetical till scenarios. These scenarios were selected so as to be representative of the range of typical conditions in Ireland. Recharge was not predicted for a particular site and was not used to predict groundwater levels. Calibration or validation exercises were not applicable in this instance.

The hypothetical scenarios all shared the same basic conceptual model in which vertical flows were simulated through a unit plan area between three layers: a soil overlying a till, overlying a productive, fractured bedrock aquifer. In any one time step, effective precipitation leaving the base of the soil layer was controlled by standard soil moisture budgeting processes. The till layer had a finite capacity to accept this effective rainfall and this capacity was determined by the vertical permeability of the till and the vertical hydraulic gradient between the till and the aquifer below. Actual recharge to the aquifer was controlled by both the effective precipitation and the capacity of the till layer. Where this capacity was exceeded, actual recharge was less than the effective precipitation and, in concept, the difference was diverted laterally to surface water along the interface between the soil and till layers. The unit area modelled lay within a hypothetical area of thick, moderate to low permeability tills which formed part of a hypothetical aquifer system of several square kilometres in size. The portion covered in thick tills lay downgradient of the main recharge zone and upgradient of the discharge zone for the aquifer. Given the influence of the tills, recharge in

the area modelled was conceptualised as being insignificant compared to recharge to the aquifer system as a whole.

Given the emphasis on relative comparisons of model outputs, the accuracy of absolute estimates was not considered important and certain simplifying assumptions were adopted within the framework of the conceptual model. These assumptions were as follows:

1. Overland flows and bypass flows were assumed to be insignificant and effective precipitation was simulated using the baseline daily estimates described earlier in this paper (i.e. daily estimates using the 'Penman-Grindley' model, with grassland as the crop).
2. Lateral flows within the tills were assumed to be insignificant. This assumption was based on the fact that moderate to low permeability tills are not mapped as aquifers in Ireland.
3. Simulated actual recharge did not influence the head in the aquifer. Instead, the seasonal amplitude of head variation within the aquifer was represented by observed groundwater hydrograph data from the Kells borehole. This borehole lies near the confluence of the Nore and Kings Rivers (Fig. 6) and monitors an important fractured dolomite aquifer which is locally confined by 15 m of till. Groundwater heads in this data set fluctuate by 3.6 m annually. This borehole was selected because the aquifer and till conditions are representative of the characteristics of the Irish midlands described earlier in the paper.
4. Changes in storage were assumed to be negligible within the till layer. The release of water to the aquifer is assumed to occur only as a result of the piston effect of effective precipitation being added to the top of the till layer. In time steps when no effective precipitation occurred, it was assumed that no actual recharge could occur to the aquifer. In time steps when effective precipitation did occur, some actual recharge could be generated as long as there were downward vertical gradients between the till and aquifer layers, even when the aquifer layer was confined by the till layer.

In summary, it was assumed that simulated actual recharge in time step 'i' could not significantly influence water levels in time step i+1 in either the till or the aquifer. These heads were taken from pre-set, seasonally variable values.

Within this conceptual framework, *actual* recharge was estimated as follows:

$$TILLCAP_i = TILLK \times \Delta H_i \div TILLTHICK$$

$$\text{If } EFFRAIN_i > TILLCAP_i \text{ then } ACTUALRECH_i$$
$$= TILLCAP_i$$

$$\text{If } EFFRAIN_i \leq TILLCAP_i \text{ then } ACTUALRECH_i$$
$$= EFFRAIN_i$$
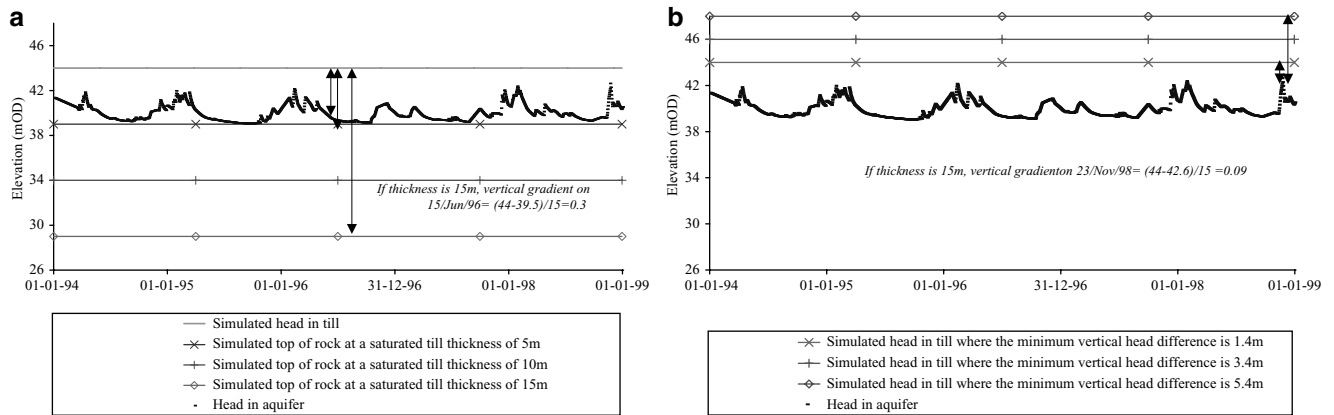
Fig. 7 **a** Example of simulating vertical hydraulic gradients by varying till thickness. **b** Example of simulating vertical hydraulic gradients by varying the relating position of the till and bedrock water levels

where i: is the daily time step over the period from the beginning of 1994 to the end of 1998, TILLTHICK is an assigned variable representing saturated till thickness, TILLK is an assigned variable representing till vertical permeability, $EFFRAIN_i$ is the effective precipitation estimated for each time step i using the baseline grassland dataset described earlier in this paper, $ACTUALRECH_i$ is the actual recharge estimated for each time step i, $TILLCAP_i$ is the maximum vertical flow that can occur through unit plan area of till in time step i, and ΔH_i is the difference between water levels in the till and the bedrock aquifer beneath.

Till permeability scenarios were adopted for tills with reference to the classification scheme proposed by Swartz et al. (2003) for 'moderate' or 'low' permeability tills:

– 'Low' to 'Moderate' permeability scenarios: 5×10^{-9} m/s (0.0004 m/day) and 1×10^{-8} m/s (0.0009 m/day).
– 'Moderate' permeability scenarios: 5×10^{-8} m/s (0.004 m/day) and 1×10^{-7} m/s (0.009 m/day).

Typical till thickness scenarios of 0, 5, 10, and 15 m were considered. In addition, the relative head difference between the average water level in the aquifer and the till was varied in four hypothetical scenarios such that the annual minimum vertical head difference over the whole time period was either 1.4, 3.4, 5.4 or 11.4 m (Fig. 7). In combination with the till thickness, these scenarios were used to examine typical vertical hydraulic gradients.

A total of 25 different scenarios of till permeability, till thickness and vertical hydraulic gradient were examined. The average annual recharge coefficient was calculated for each scenario and the results are summarised in Table 3 and Fig. 8.

The assumptions used to derive these results are clearly simplistic, and neither the method nor the results can be used to derive recharge estimates for specific sites unless in combination with other recharge assessment techniques. Nevertheless, the figures do provide an indication of the parameters for Irish tills where the greatest sensitivities and hence uncertainties occur.

Of the three till factors examined, recharge is predicted to be most sensitive to till permeability. Increasing permeability across a typical range of till values had the effect of increasing the predicted recharge coefficient by ten to fifteen-fold: from 6 to 66% for 5 m of till and from 2 to 31% for 15 m of till. Inferences from Fig. 8 suggest that the greatest sensitivity occurs in the range from approximately 1×10^{-7} m/s to 1×10^{-8} m/s (or approximately 0.001 m/day to 0.01 m/day). Further decreases in permeability above and below this range are expected to have little additional influence on the amount of recharge which can occur through the till.

Recharge is also sensitive to till thickness and vertical hydraulic gradient. For example, decreases in hydraulic gradient were modelled for a till permeability of 5×10^{-8} m/s (0.004 m/day) and a thickness of 15 m. Reducing the head difference between the aquifer and the till from 11.4 to 1.4 m reduced the annual minimum vertical gradient from 0.76 to 0.09 and the predicted recharge coefficient from 50 to 17%. This scenario might reflect, for example, the differing response of poor and important aquifers to recharge. For the same recharge, the head in the poor aquifer would be expected to rise to a higher level, due to its lower transmissivity and/or storage. This would result in a decrease in vertical hydraulic gradients and a decrease in *actual* recharge.

Discussion

Inferences drawn from previous studies showed that tills can have a significant influence on actual recharge and recharge coefficients. The inferred recharge coefficients range from 4 to 30% in productive aquifers covered by low permeability or thick tills. In areas characterised by thin or more permeable tills, the inferred recharge coefficients range from 60 to 90%.

The literature review has also provided some evidence to suggest that the scale of the recharge estimation procedure requires careful consideration, particularly for low permeability tills. In the low permeability till situations examined in this paper, recharge estimates from field

Fig. 8 Simulations of recharge through tills of differing permeability and thickness
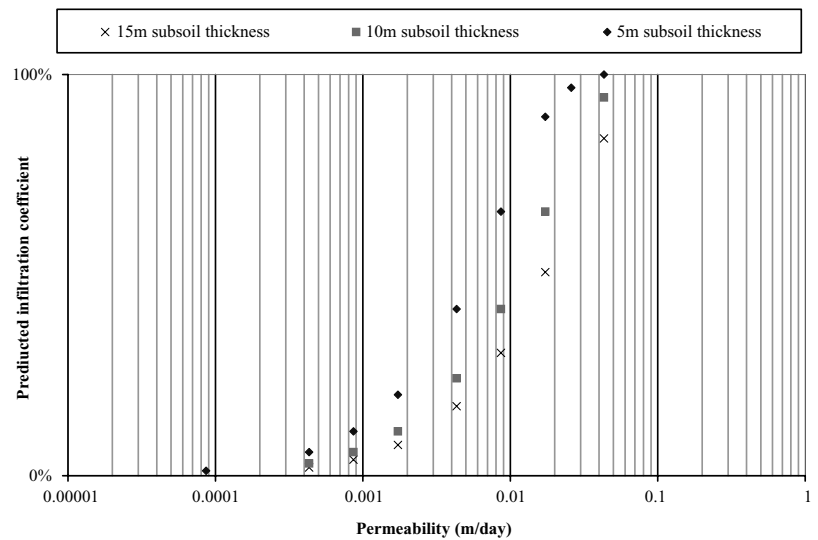
measurements are lower than those derived from sub-catchment scale modelling and baseflow separation exercises. The difference may often be due to the fact that some portion of potential recharge, initially rejected to surface water over low permeability areas, subsequently infiltrates to groundwater through the beds of streams once these streams reach higher permeability till areas.

The sensitivity analyses presented by the authors enhance the inferences from the literature review in four key aspects:

(a) Variations in the key parameters used in soil moisture budgeting could not produce the same ranges in recharge estimates as those identified in the literature review. Reasonable ranges in these parameters produce

Table 3 Sensitivity of simulated recharge coefficient to subsoil permeability, thickness and hydraulic gradients

Vertical permeability (m/day)	Thickness of saturated till (m)	Minimum head difference between till and aquifer (m)	Minimum hydraulic gradient between till and aquifer (m)	Simulated recharge coefficient (%)
0.0004 (5×10^{-9} m/s)	–	Unconfined	1	8
	5	1.4	0.27	6
	10	1.4	0.14	3
	15	1.4	0.09	2
0.0009 (1×10^{-8} m/s)	–	Unconfined	1	15
	5	1.4	0.27	11
	10	1.4	0.14	6
	15	1.4	0.09	4
	10	3.4	0.34	9
	10	5.4	0.54	12
0.004 (5×10^{-8} m/s)	–	Unconfined	1	54
	5	1.4	0.27	42
	10	1.4	0.14	24
	15	1.4	0.09	17
	10	3.4	0.34	35
	10	5.4	0.54	44
	15	3.4	0.22	25
	15	5.4	0.36	33
	15	11.4	0.76	50
0.009 (1×10^{-7} m/s)	–	Unconfined	1	80
	5	1.4	0.27	66
	10	1.4	0.14	42
	15	1.4	0.09	31
	10	3.4	0.34	57
	10	5.4	0.54	69

Table 4 Proposed recharge coefficients for Irish Tills

Refinements in recharge coefficient which may be achieved with an increasing level of conceptual hydrogeological understanding in an area				Main considerations which may help further refine the range in infiltration coefficient
Till cover	<5 to 90%	Thin, moderate permeability tills	50–90%	Vertical gradients/aquifer properties
		Moderate permeability, moderately thick (less than, say, 10 m) tills	40–80%	Aquifer properties/vertical gradients, quantified estimate of till permeability
		Moderate permeability, thick (greater than, say, 10 m) tills. Confined or partially confined conditions	20–60%	
		Low permeability (greater than, say, 5 m thick)	<30%	Appropriate scale of assessment

a range in simulated effective precipitation from 101 to 95% of the baseline estimate.

(b) The range could, however, be simulated using variations in key till properties. Reasonable ranges in till permeability and vertical hydraulic gradient produce a range in simulated recharge coefficients from 80 to 2% of the baseline estimate of effective precipitation. This represents a similar range to that inferred from previous studies.

(c) Of the parameters considered, recharge is most sensitive to the permeability of the till, and the greatest sensitivity lies in the permeability range from 1×10^{-7} m/s to 1×10^{-8} m/s (approximately 0.001 m/day to 0.01 m/day). The lower end of this sensitivity banding may help to build on preliminary work by Swartz et al. (2003) with regard to delineating the conceptual boundary between low and moderate till permeability classes in Ireland.

(d) Till thickness is linked closely to vertical hydraulic gradients, and the theoretical exercise indicated that infiltration can be significantly reduced in areas of lower vertical gradient. Lower vertical gradients can occur, for example, in confined aquifers and in aquifers with low transmissivity and low storage where the depth to water is often shallow.

Table 4 provides a synthesis of the recharge coefficients examined in this paper. The estimates are inferred primarily from field measurements and river baseflow indices in Ireland. They are generally supported by the references cited from studies in the UK that used baseflow indices and numerical modelling studies linked to field observations of groundwater and river flows. The results of the sensitivity analyses are used to inform estimates in relation to specific geological conditions.

Rushton and Ward (1979) and Hulme et al. (2001) emphasised the importance of understanding recharge mechanisms. The data and inferences presented in this paper endorse this view. As depicted in Table 4, moderate to low permeability till cover can present considerable uncertainty in the estimation of recharge rates. However, the uncertainty can be refined for particular study areas through the development of a conceptual understanding of recharge processes and appropriate estimates of till permeability, thickness, aquifer properties and saturation conditions, along with an understanding of the appropriate scale of investigation.

Conclusions

Soil moisture budgeting parameters are often the main focus of recharge studies in temperate climates. However, the data presented in this paper provide evidence to suggest that the properties of the till cover can have a more important influence on recharge than many of the soil moisture budgeting parameters. This greater sensitivity will be particularly important in climatological/vegetation situations where the soil moisture deficits rarely exceed the root constant. Recharge estimates in till areas appear to be most sensitive to till permeability, particularly in the range that straddles the divide between moderate and low permeability categories (as used in the assessment of groundwater vulnerability in Ireland). However, till thickness also has an influence, in that it can provide an important influencing factor on vertical hydraulic gradients. These gradients affect recharge uncertainty in conditions of high perched water tables, in groundwater discharge zones, and in poor aquifers.

The literature review and sensitivity analyses presented in this paper highlight the dangers of limiting recharge calculations in temperate climates to meteorological and soil considerations and highlight the importance of developing a conceptual understanding of the influence of geology on recharge mechanisms and recharge rates.

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