GROUNDWATER RECHARGE ASSESSMENT: A KEY COMPONENT OF RIVER BASIN MANAGEMENT

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ABSTRACT

Groundwater recharge estimates are required for the management of river basin districts under the new Water Framework Directive. Different recharge estimation techniques are described in this paper according to the following categories: inflow estimation, aquifer response analysis, outflow estimation and catchment water balance. Examples of their application in Ireland are provided. All estimates involve a significant degree of uncertainty, and it is therefore essential to employ more than one method. The choice of methods will depend on the conceptualisation of the flow system and the specific objective of the study.

INTRODUCTION

To the hydrologist concerned with flood flows, the difference between precipitation and evapotranspiration may be considered as surface runoff plus losses. To the hydrogeologist, on the other hand, this effective rainfall is often referred to as potential recharge. This paper will highlight the importance of recharge in the context of river basin management. Approaches to recharge assessment will be reviewed briefly, with examples of their application in Ireland. However, it is not the purpose of this paper to provide detailed descriptions of the different methodologies: these are covered in major texts such as Lerner *et al*. 1990, Bredenkamp *et al*. 1995 and Simmers 1997.

WHAT IS GROUNDWATER RECHARGE?

Groundwater recharge may be defined as 'the downward flow of water reaching the water table, forming an addition to the groundwater reservoir' (Lerner *et al*. 1990). The point about recharge being water that reaches the water table is important: some methods of recharge estimation, such as soil moisture fluxes, assume that all water moving below the soil zone eventually contributes to recharge. However, this may not be the case where there are lateral flows in permeable subsoils or within fractured bedrock above the water table.

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, whereas in arid regions most recharge occurs from surface runoff. However, this distinction does not always hold true: there are some situations in temperate regions where indirect recharge dominates, most notably in karst areas (where recharge occurs from losing rivers and via swallow holes and other solution features). The estimation of indirect recharge in karstic limestones was an important element of the South Galway Flood Study (Southern Water Global 1998). Although the remainder of this paper will focus on direct recharge, the significance of indirect recharge in karst areas in Ireland should not be underestimated.

The factors that influence the amount and type of recharge include:

- precipitation (volume, intensity, duration)
- topography
- vegetation (cropping pattern, rooting depth) and evapotranspiration
- soil and subsoil types
- flow mechanisms in the unsaturated zone
- bedrock geology

- available groundwater storage
- presence of influent rivers
- presence of karst features.

Some of these – most notably, the thickness and permeability of subsoil – also control groundwater vulnerability, and hence recharge studies can assist in the assessment of groundwater vulnerability (Lee 1999).

IMPORTANCE OF GROUNDWATER RECHARGE

The estimation of groundwater recharge is an implicit requirement of the new Water Framework Directive (WFD). Article 4 states that Member States shall '*prevent deterioration of groundwater status and ensure a balance between abstraction and recharge of groundwater*'. Again, under Annex II, Member States (as part of the initial characterisation of groundwater bodies) shall identify '*land use in the catchment or catchments from which the groundwater body receives its recharge…..*'

Reliable estimates of groundwater recharge are needed for a number of reasons, including:

- quantifying groundwater resources within river basin districts
- issuing of abstraction licences (licences will be required for major groundwater abstractions under the WFD)
- assessing the groundwater contributions to rivers (baseflow) and to sensitive wetland habitats, and hence for the protection of these resources (a notable example of a groundwater-fed wetland is Pollardstown fen in Co. Kildare)
- assessing groundwater vulnerability (high recharge implies high vulnerability)
- delineating Source Protection Areas around major wells and springs (the size of the zone of contribution (ZOC) depends on the recharge)
- delineating Nitrate Vulnerable Zones (again requiring the ZOC to be identified)
- identifying implications of changes in land use and/or climate on water resources.

APPROACHES TO RECHARGE ASSESSMENT

The various approaches for estimating groundwater recharge can be grouped as follows:

a) Inflow estimation
b) Aquifer response analysis
c) Outflow estimation
d) Catchment water balance.

INFLOW ESTIMATION

The different approaches for estimating inflows include:

- soil moisture budgets
- infiltration coefficients
- soil moisture flux approaches
- lysimeters
- tracers
- direct observations.

Soil moisture budgets

Soil moisture budgets involve the calculation of soil moisture surpluses and deficits, and hence actual evapotranspiration, from precipitation and potential evapotranspiration (usually Penman) data. The Grindley method is often used in Britain, whereas the Danish Aslyng scale (Aslyng 1965) has been applied in a number of Irish studies (e.g. Cawley 1990, Daly 1994 and MacCarthaigh 1994). The calculations are normally performed on a catchment or sub-catchment scale.

Monthly, 10-daily or daily timesteps can be used. The shorter timesteps are preferable: Howard and Lloyd (1979), for example, found that daily and 10-daily calculations gave higher recharge estimates than monthly calculations in a study of the Humberside Chalk. One of the reasons for this is that short timesteps may produce short periods in summer when the soil moisture deficit is eliminated, thus providing potential recharge.

As well as being sensitive to the length of timestep, the calculations can also be strongly influenced by the values used for the root constant (RC) and wilting point (WP). For example, under the Grindley model, permanent grass has an RC = 76 mm and a WP = 127 mm, whereas for 'rough grazing' these values are reduced to 13 mm and 51 mm respectively. Such variations are obviously an important consideration in Ireland, where about 80% of the lowlands are covered by grass.

The Institute of Hydrology has used a soil moisture budgeting approach to develop a simple nomograph for estimating groundwater recharge in the Chalk and Permo-Triassic sandstone aquifers of England and Wales (Finch *et al*. 1997). On the nomograph, recharge is interpolated from annual rainfall and potential evapotranspiration data (based on the Meteorological Office rainfall evaporation calculation (MORECs) system). The methodology does not apply to areas covered by subsoil, as only a small allowance is made for runoff: 14% for soils on the Permo-Triassic Sandstones – based on the Hydrology of Soil Types (HOST) classification - and zero for soils on the Chalk. For the Chalk, it is recognised that bypass flow through the soil store can be significant and an allowance of 15% of daily rainfall is allowed for recharge by this process.

Infiltration coefficients

A soil moisture budget yields a figure for the moisture surplus or potential recharge. It is necessary to split this into recharge and runoff (or other losses such as interflow). Wright *et al.* (1982) proposed a series of infiltration coefficients that can be applied to the potential recharge to calculate actual recharge in Irish conditions: 0.2 for poorly permeable clayey till, 0.5 for moderately permeable sandy till and 0.8 for permeable sand and gravel (or thin subsoil). Daly (1994), in his study of the Nore basin, produced slightly different coefficients: 0.3 for e.g. thick till or gley soils, 0.6 for e.g. thin till and 0.9 for thin permeable soils overlying karst.

Rushton *et al*. (1988), in a study of the Permo-Triassic sandstones of the Liverpool area, developed a series of infiltration coefficients that take account of the hydraulic gradient as well as the thickness and lithology of the subsoil. It may be worth attempting to apply this approach to the Irish situation, perhaps enhancing it further by also taking account of factors such as topography and rainfall intensity.

It is of course possible to make spot measurements of infiltration rates using e.g. double-ring infiltrometers but, in the author's experience, these produce very varied results.

Soil moisture flux approaches

These include the zero flux plane approach and Darcy flux calculations. Applications in Ireland include studies of sites in counties Galway and Limerick by Carey (1994) and Eckholm (1997), respectively. The ZFP is a useful concept for estimating recharge and actual evapotranspiration, based on measurements of matric potential and soil moisture. However, it can only be applied in summer. In winter, when there is no ZFP, Darcy flux calculations can be performed. These require soil characteristic curves relating soil moisture, matric potential and hydraulic conductivity.

The limitations of these approaches are that measurements are generally only available for fluxes in the topsoil (and perhaps shallow subsoil), they require a lot of (relatively expensive) measurements, and the findings may be site specific. Furthermore, soil physics approaches assume piston flow and may not identify macropore (bypass) flow.

Lysimeters

These are very useful for measuring drainage through soils and hence can give an indication of groundwater recharge. However, most lysimeters have relatively small surface areas (1 m^2) and are shallow (I m), so the drainage measured may not be fully representative of the flows that would reach a relatively deep water table below a thick subsoil. Ideally, for recharge estimation, a lysimeter should be large and deep and extend into the water table (Jones & Cooper 1998). However, it is seldom practicable - and usually expensive - to construct a lysimeter such as that at Fleam Dyke in Cambridgeshire, which has a surface area of 25 m^2 and a depth of 5 m.

Tracers

Groundwater recharge can be estimated using both environmental and applied tracers. Lerner *et al.* (1990) separate the methods into *signature* methods and *throughput* methods. Applied tracers (such as tritium) are normally only used in the signature methods (whereby a parcel of water containing the tracer is tracked and dated). Throughput methods involve a mass balance of tracer, comparing the concentration in precipitation with the concentration in soil water below the ZFP (or sometimes with the concentrations below the water table). Piston flow is generally assumed in most tracer studies. However, tracers can be used to investigate flow processes, including the occurrence of preferential pathways. A Canadian study using natural tritium found evidence of water movement in preferred pathways to a depth of 7 m in a fractured till (Hendry 1983). A number of tracer studies involving isotopes have been carried out in Northern Ireland in recent years, including a study of O^{18} profiles in the Enler catchment in Co. Down (McConville & Kalin 1999).

Chloride is probably the most widely used environmental tracer for the throughput method (Hendrickx & Walker 1997, Wood 1999). It is particularly effective in arid zones where there is significant concentration through evaporation. The mass balance can be complicated by additional chloride inputs from decaying vegetation, localised run-in and from fertilisers, and by losses through dry precipitation and vegetation uptake. Nevertheless, it is a relatively inexpensive method and may be worth applying here in Ireland. It would also be useful to apply tracers (in the signature method) to investigate contaminant transport processes in subsoils.

Direct observations

Finally, inflows can sometimes be estimated directly, notably where indirect recharge is occurring into karst systems. Infiltration can also be monitored in cave systems and in underground mine workings.

AQUIFER RESPONSE ANALYSIS

The response of the aquifer to recharge can be investigated both qualitatively and quantitatively. A qualitative analysis might involve the examination of water level hydrographs for evidence of e.g.

summer recharge. Recharge can be estimated quantitatively from water level fluctuations using a relationship of the following form (Kruseman 1997):

$$R = \Delta h.S_y + Q_a + Q_l$$

where R = recharge, Δh = change in water table elevation, S_y = specific yield, Q_a = groundwater abstraction during the period under consideration, and Q_l = the difference between lateral subsurface outflow and lateral subsurface inflow during the same period. Bredenkamp *et al*. (1995) describe a number of methods for taking account of Q_l, involving analysis of hydrograph recession when no recharge is occurring.

Water level fluctuations have been analysed for recharge in a number of Irish studies, including those by Cawley (1990) and Ekholm (1997). The major difficulty for these and other studies is in the estimation of specific yield. There are relatively few reliable estimates of specific yield available for Irish aquifers. Short-term pumping tests seldom produce useful figures. It may be possible to acquire a better understanding of S_y from major aquifer dewatering schemes such as the on-going dewatering at the Galmoy mine (pumping tests prior to mine development suggested S_y values for the Waulsortian dolomite of between 1 and 2%,).

As well as analysis of water level fluctuations, another type of aquifer response analysis involves the estimation of groundwater throughflow using the Darcy equation. Under steady-state conditions this gives a good approximation of recharge, provided there are reasonably reliable data on aquifer boundaries, hydraulic gradient and transmissivity.

OUTFLOW ESTIMATIONS

This normally involves the separation of the baseflow component from runoff at suitably located surface flow gauging stations. Over a long period, the aquifer outflow should be equivalent to the inflow, after any abstractions are taken into account. Detailed estimates of recharge from outflows have been made by Daly (1994) for the Nore basin, MacCarthaigh (1994) for the Blackwater (Monaghan), Finn, Glyde and Dee catchments, and by Aslibekian (1999) for several other small catchments. Although a very useful method, the results tend to be very sensitive to the baseflow separation technique used. Moreover, it is often difficult to ascribe the results to individual aquifer areas upstream of the gauging station.

CATCHMENT WATER BALANCE AND MODELLING

Estimates of recharge derived from inflow, aquifer response or outflow methods are normally incorporated in an overall catchment water balance to check the reasonableness of the recharge estimate. The water balance can also help identify any additional unaccounted inflows (e.g. subsurface inflows from neighbouring catchments) or outflows (e.g. ungauged outflows). The reports mentioned above by Daly (1994) and MacCarthaigh (1994) include detailed water balance calculations. For example, the water balance for Nore basin was carried out for 10 years of data (1972-1981) using the relationship:

$$P = AE + Q + U + \Delta S_g + \Delta S_m$$

where P = precipitation, AE = actual evapotranspiration, Q = runoff, U = net unmeasured outflows, ΔS_g = change in groundwater storage, and ΔS_m = change in soil moisture content. For this water balance, as noted earlier, AE and ΔS_m were derived using the Aslyng scale, and Q was separated into its surface runoff and groundwater recharge components.

Recharge can be estimated using a variety of mathematical models, ranging from relatively simple lumped parameter water balance models to more sophisticated distributed groundwater models. Cawley (1994) describes a water balance model that computes monthly streamflow (as 'fast discharge' and 'slow discharge', the latter being equivalent to baseflow) from monthly values of precipitation and potential evapotranspiration. The model was applied to three catchments, the Brosna, Nore and Suir, and produced good results when compared with actual streamflow measurements.

Recharge can be estimated from numerical groundwater models using inverse techniques. Knowing the boundary conditions, aquifer properties and head distribution, the model can be used to estimate recharge. However, models do not produce unique solutions, so should not be relied upon as a sole technique for estimating recharge.

DISCUSSION

Groundwater recharge estimates are required for the management of river basin districts under the Water Framework Directive. Recharge is important both for quantifying available water resources and for assessing groundwater vulnerability.

Recharge is very difficult to estimate reliably, and more than one method should be used. The choice of methods will depend on the conceptualisation of the flow system and the accuracy required in a given situation. For example, a regional water resources study where abstractions account for a very small percentage of the available resource, may warrant only a simple (and inexpensive) recharge estimate based on say a soil moisture budget, baseflow analysis and overall catchment water balance. On the other hand, and somewhat paradoxically in view of the smaller area involved, the delineation of a Source Protection Area or Nitrate Vulnerable Zone may justify a more detailed analysis using e.g. soil moisture flux and/or tracer studies.

For the Irish situation, more research is needed on recharge mechanisms through tills and other subsoils. Matrix flow and possible preferred pathways should be investigated. Applied and environmental tracers could be used at a selection of sites representing different subsoils. It would also be useful to develop the concept of infiltration coefficients for different soils and subsoils further to take account of hydraulic gradients, topography and rainfall intensity.

Although this paper has concentrated on direct recharge, indirect recharge is important in karst areas in Ireland. Much useful research has already been carried out on flow systems in karst, but there remains a need for more quantitative information on recharge.

Finally, it may worth considering the implications of climate change on recharge. Although there is significant 'rejected recharge' in many Irish situations, and winter rainfall is likely to increase according to many prediction scenarios (e.g. Arnell & Reynard 2000), a decrease in summer rainfall and increase in evapotranspiration (again as predicted in a number of scenarios) would lengthen the period of soil moisture deficit and thus prolong the period when relatively little recharge occurs. This might have a significant impact on groundwater levels, baseflows and spring discharges in late summer in Ireland, since most of the bedrock aquifers have low storativity.

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