GROUNDWATER RECHARGE AND ITS RELATIONSHIP TO RIVER FLOW IN IRELAND

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ABSTRACT

The relationship between groundwater recharge and groundwater vulnerability was quantified during a recent EPA-funded research project. Recharge coefficients (the proportion of hydrologically effective rainfall that becomes recharge) were derived for a range of hydrogeological conditions. The main factor influencing the recharge coefficient is the permeability of the subsoil covering the aquifer. The recharge coefficients can be input into a GIS system in order to make preliminary estimates of recharge. Furthermore, a high recharge coefficient equates to a low runoff coefficient, and *vice versa*, and so the research findings can be used to provide preliminary estimates of surface runoff. As part of the research, four case studies were completed, involving the investigation of recharge coefficients using a variety of techniques. One of the most common approaches for estimating groundwater recharge is the use of river hydrograph separation techniques. The project highlighted that hydrograph separation can often lead to high estimates of baseflow, even where other indicators suggest that groundwater contributions to baseflow are small. These findings are in line with an earlier river hydrograph separation study, in which the sensitivity of the results to the time base parameter was investigated.

INTRODUCTION

Groundwater recharge has been estimated in Ireland using a variety of approaches. These approaches can be grouped as follows: inflow methods (including soil moisture budgets), aquifer response methods (including well hydrograph analyses) and aquifer outflow methods (including river hydrograph analyses) (Misstear, 2000; Misstear *et al*., 2006). This paper will focus on the latter approach, highlighting some of the issues involved in estimating the groundwater contributions to river hydrographs. The paper will draw on the results of a recent EPA-funded project which sought to establish a quantified link between groundwater recharge and aquifer vulnerability. An earlier study into the sensitivity of hydrograph separation results will also be summarised. The paper will end by explaining how these research projects, together with a project known as the groundwater-surface water interactions study (RPS, OCM, ESBI, GSI, EPA 2008), have led to a new project which is aiming to develop an improved understanding of flow and pollution pathways.

Before describing the results of these research studies, it may be helpful to remind readers of the conceptual model that is often applied to the analysis of river flow hydrographs. Three main flow components are distinguished: overland flow, interflow and baseflow (e.g. Chin, 2006). Overland flow is generally regarded as sheet flow occurring on the land surface (Shaw, 1994). It is sometimes termed surface runoff or direct runoff and produces a rapid response in a stream hydrograph. The term interflow is described in the literature in different ways, but it can broadly be considered to encompass any lateral flow in the subsurface that occurs between the ground surface and the water table (Dingman, 2002; Nash *et al*., 2002; Chin, 2006). As such, interflow can occur in both the topsoil and subsoil, and may include unsaturated matrix flow, bypass or macropore flow, saturated flow (from locally perched water tables) and possibly field drainage.

Overland flow and interflow together are sometimes referred to as quickflow (Chin, 2006). In contrast to quickflow, the term baseflow is used to describe the “slow flow” contribution to the river hydrograph from groundwater discharge. Chin (2006) notes out that baseflow is typically ‘(quasi-) independent’ of the rainfall event and depends on the difference between the water table elevation in the aquifer and the water surface elevation in the stream. The proportion of baseflow to total runoff is often referred to as the baseflow index (Institute of Hydrology, 1980; Shaw; 1994). The BFI can be used to derive a recharge coefficient for an aquifer, which is the proportion of hydrologically effective rainfall (total rainfall minus actual evapotranspiration) that becomes groundwater recharge (Fitzsimons and Misstear, 2006; Misstear and Brown, 2008a,b; Misstear *et al*., 2009a).

RELATIONSHIP BETWEEN RECHARGE AND VULNERABILITY

Project background and main results

Groundwater vulnerability is assessed mainly on the basis of the permeability and thickness of subsoil that overlies an aquifer (Daly and Warren, 1998; DoELG *et al*., 1999, Misstear and Daly, 2000). A GIS-based system is used to compile vulnerability maps at a scale of 1:50,000. This GIS includes layers with information on depth to bedrock, rock outcrop, subsoil permeability and the presence of karst features. There is a relationship between groundwater vulnerability and groundwater recharge, since recharge would normally be expected to be low where vulnerability is low and high where vulnerability is high or extreme. This relationship between vulnerability and recharge in Ireland was investigated in a recent EPA STRIVE project (Misstear and Brown, 2008a,b), and resulted in the development of a series of recharge coefficients (the proportion of hydrologically effective rainfall that becomes recharge). These coefficients can be input into the GIS system in order to make preliminary estimates of recharge. In essence, the hydrologically effective rainfall (calculated by deducting actual evapotranspiration from total rainfall) multiplied by the recharge coefficient provides an initial estimate of recharge. The main factor that influences the recharge coefficient is the permeability of the subsoil that overlies the aquifer.

The project included estimations of groundwater recharge in four study areas of contrasting subsoil and aquifer properties, as summarized in Table 1 below. Because all methods for estimating recharge involve a significant degree of uncertainty, more than one method was normally applied in each study area. The approaches applied were: soil moisture budgeting (all areas); environmental tracers, specifically chlorofluorocarbon analyses (Curragh, County Kildare; Galmoy, County Kilkenny; Knockatallon, County Monaghan); well hydrograph analyses (Curragh and Knockatallon); river baseflow analyses (Knockatallon; Callan-Bennettsbridge lowlands, County Kilkenny); water balances (Curragh, Galmoy and Knockatallon); and numerical modelling (Curragh).

Table 1: Summary table of the main results of the Recharge and Vulnerability case studies

Study area	Main aquifer, subsoil and topographic setting	Methodology	Recharge coefficient
Curragh aquifer, County Kildare	Regionally important gravel aquifer. Thin (generally <3 m), moderate to low permeability till cover; high vulnerability. Lowland setting.	Soil moisture budget (SMB), hydrograph analysis, numerical modelling, natural tracers and catchment water balance.	81-85%
Galmoy mine, County Kilkenny	Regionally important limestone aquifer. Till cover generally 5-10 m thick and of moderate permeability. Lowland setting	Soil moisture budget, natural tracers and water balance using dewatering discharges.	55-65%
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.	Soil moisture budget, baseflow analysis.	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.	Soil moisture budget, pumping discharges, baseflow analysis and natural tracers.	<17% (and probably <5%)

Detailed accounts of the soil moisture budget and water balance studies in the Knockatallon and Curragh aquifers can be found in Misstear *et al*. (2008) and Misstear *et al*. (2009b), respectively. The following section will consider some of the findings of the river hydrograph analyses in the Knockatallon and Kilkenny areas.

River hydrograph analyses

River hydrograph analyses were carried out in the Knockatallon/Tydavnet area in north County Monaghan and in two neighbouring catchments within the Nore basin in County Kilkenny, including the King's River. Two hydrograph separation methods were used in each area: the Institute of Hydrology and the Boughton 2-parameter algorithm. The automated method developed by the Institute of Hydrology (IoH, 1980 and 1989) involves the identification of runoff minima at fixed time intervals and the selection of key 'turning points' from these minima. The length of this time interval is referred to as the 'time base' N, and represents the number of days after a peak in the hydrograph when runoff is assumed to cease. The number of days depends on catchment size.

The Boughton method is an analytical technique (Boughton, 1993, 1995; Chapman, 1999) for calculating baseflow $Q_{b.}$ The algorithm originally incorporated only one parameter k, which is the recession constant during periods of no run-off, but Boughton subsequently modified his equation to incorporate a second parameter C, which replaced 1-k (Boughton, 1995):

$$Q_b(i) = \frac{k}{1+C} Q_b(i-1) + \frac{C}{1+C} Q(i)$$

Figure 1 shows an example of baseflow separation using the Institute of Hydrology method. This is for the Monaghan Blackwater, which drains part of the Knockatallon area. This analysis was performed using a time base value N of 10, and resulted in a baseflow index of 32%. Changing the time base values to 5 and 20 gave baseflow indices of 41% and 25%, respectively. However, the subsoils in this drumlin area consist of up to 50 m of low permeability tills. Moreover, the limestone bedrock aquifer is classified as locally important and water levels (at the time of analysis) had been drawn down significantly by abstractions from the local group water scheme. It would therefore be anticipated that the extent of hydraulic connection between the bedrock aquifer and the surface drainage system would be small and hence that groundwater discharges would also be small. Consequently, it is considered very unlikely that these baseflow indices represent the bedrock groundwater contributions to the river. It is more likely that the baseflow represents interflow and discharges from gravel deposits found along the river valley. Applying the 2-parameter Boughton algorithm to the same dataset gave a more plausible range of baseflow indices (12-15%, Figure 2), but this was achieved partly because the Boughton method allows for a great deal of flexibility in choosing values for the parameters k and C.

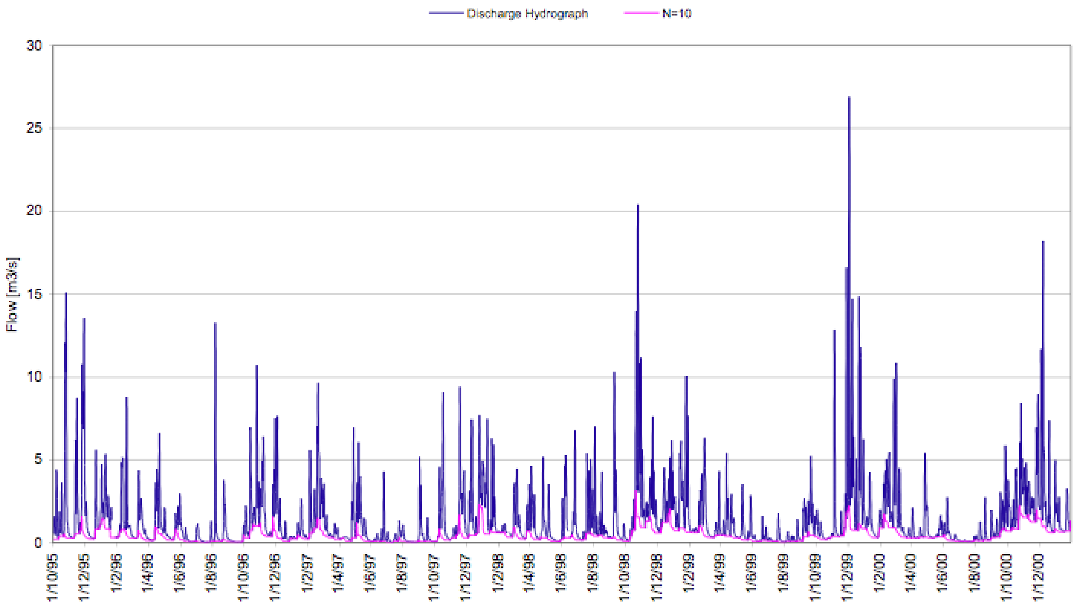

Fig. 1 Hydrograph of the River Blackwater (Cappog Bridge gauging station) showing an example of baseflow separation using the IoH method of separation (N=10 days)

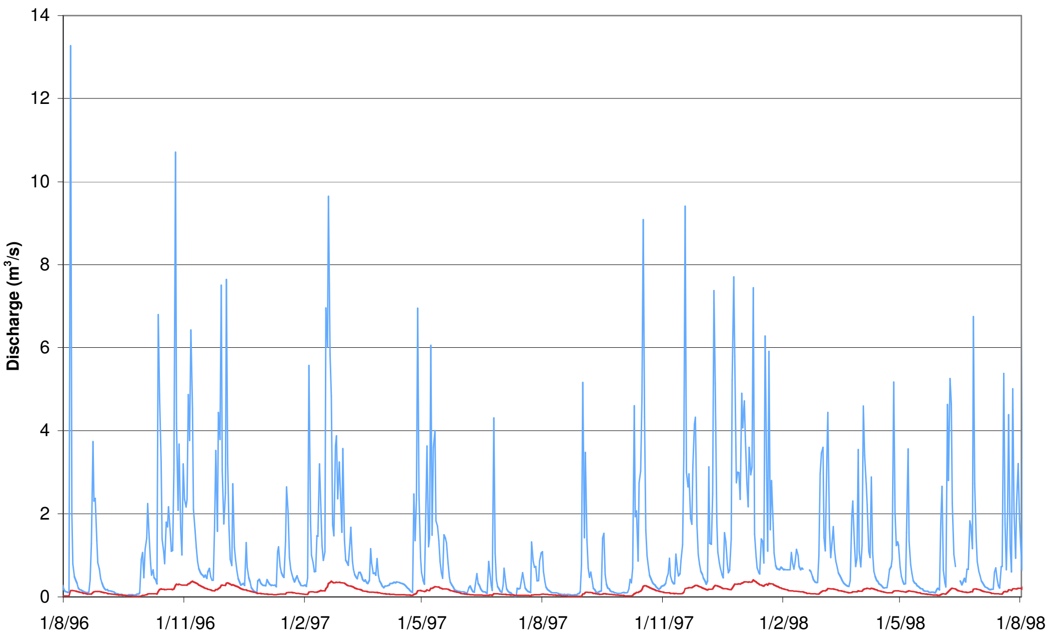

Fig. 2 Hydrograph of the River Blackwater (Cappog Bridge gauging station) showing an example of baseflow separation using the 2-parameter Boughton method

The effect of varying the *k* and *C* parameter values in the Boughton method is illustrated by the hydrograph in Figure 3 for the King's River catchment in County Kilkenny. The King's River is a tributary of the River Nore which joins the right bank of the main river at Annamult, just upstream of Mount Juliet. The King's River is one of two subcatchments that are part of the Callan-Bennettsbridge lowlands referred to in Table 1. The higher and lower estimates of baseflow resulting from the two sets of parameter values were 60% and 36%, respectively, but clearly it would have been possible to produce other baseflow values using this subjective method.

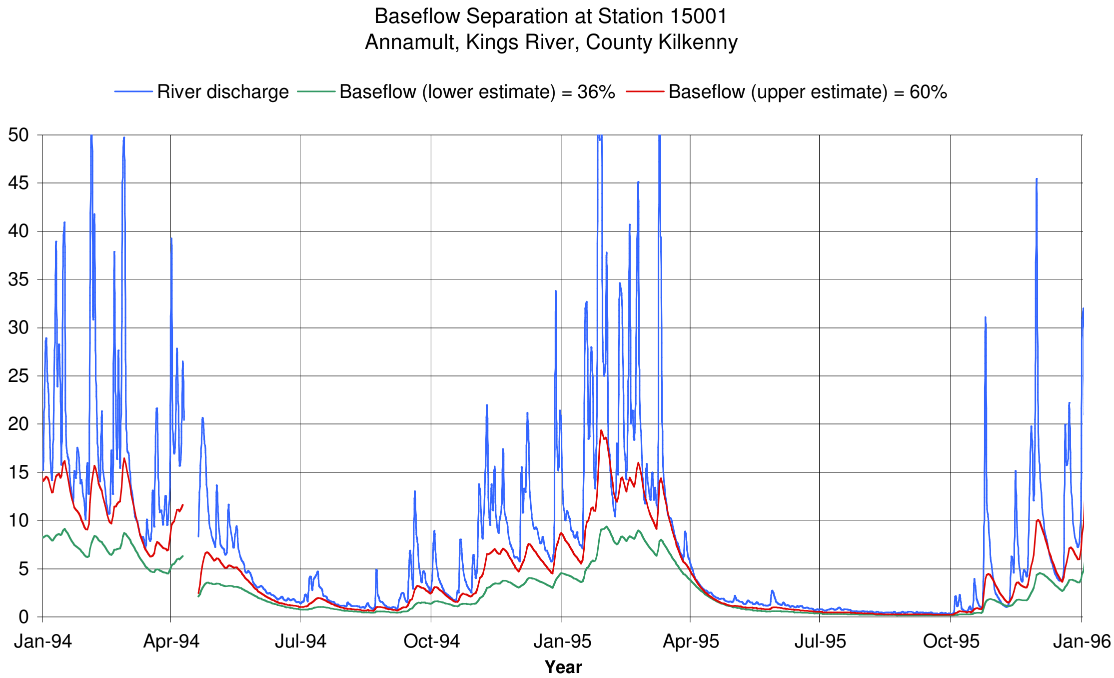

Fig. 3 Baseflow analysis on the King's River at Annamult, using the Boughton (1995) two-parameter algorithm (k=0.95, C=0.028 for lower estimate; k=0.94, C=0.09 for upper estimate)

SENSITIVITY STUDY OF BASEFLOW ANALYSIS IN NORE SUBCATHCMENTS

Misstear and Fitzsimons (2007) examined the sensitivity of river hydrograph analysis to the time base parameter used in the Institute of Hydrology method. The study was based around three catchments within the Nore basin: a hybrid subcatchment, lying south of Kilkenny city; the Kilkenny Blackwater; and the River Dinin. (The hybrid subcatchment was delineated by isolating the discharges upstream of St John's Bridge in Kilkenny city and upstream of Annamult on the King's River from the discharges downstream at Mount Juliet on the main Nore; this subcatchment was also the second of the two subcatchments studied in the Callan-Bennettsbridge lowlands as part of the Recharge and Vulnerability project).

Using the IoH method the value of the 'time base' N was calculated from the catchment area, and was then varied by plus or minus one day, giving a range of 3 to 5 days. For the hybrid subcatchment, a well hydrograph was used to assess the appropriateness of the time base responses (well hydrographs were not available for the other two subcatchments). The results of the sensitivity analysis are summarised in Table 2. It can be seen that, even when using only this single baseflow separation method, there is a large variation in predicted baseflow within each subcatchment. The largest variation is in the Dinin, which is the most upland catchment, with low permeability soils and subsoils, and underlain by a poorly productive aquifer. Therefore, the baseflow index values of between 46% and 65% are unlikely to represent the contribution from bedrock groundwater, and probably include contributions from interflow pathways.

Table 2 Examples of the sensitivity of groundwater baseflow to the time base parameter (Misstear and Fitzsimons, 2007)

Gauge	Hydrogeological Setting	Catchment to gauge	Estimate of time base (N) from N=Catchment Area$^{0.2}$	Range in time base values (N)	Range in baseflow indices[1]
Hybrid flow record: derived from upstream and downstream gauges	Lowland. Typically moderate permeability till (~5m thickness) and some high permeability gravel subsoils.	Nore (1140 km^2)	4	3, 5	58% to 68%
Scart	Upland. Thin subsoils. Locally important fractured sandstone aquifer.	Kilkenny Blackwater (108 km^2)	3	1, 3	60% to 76%
Castlecomer	Poor to locally important aquifers. Generally low permeability subsoils of varying thickness. Small gravel body occurs close to central river.	Dinin (153 km^2)	3	1, 3	46% to 65%

[1]Note: Baseflow was estimated by the IOH method (IOH, 1989).

The baseflow separations for the hybrid subcatchment are illustrated in Figures 4 and 5. By comparing the hydrograph separations with the observed fluctuations in a nearby borehole, it can be seen that the baseflow separation using a time base (N) value of 3 (Figure 4) represents the frequency of winter recharge events better than the analysis with a time base of 3 (Figure 5).

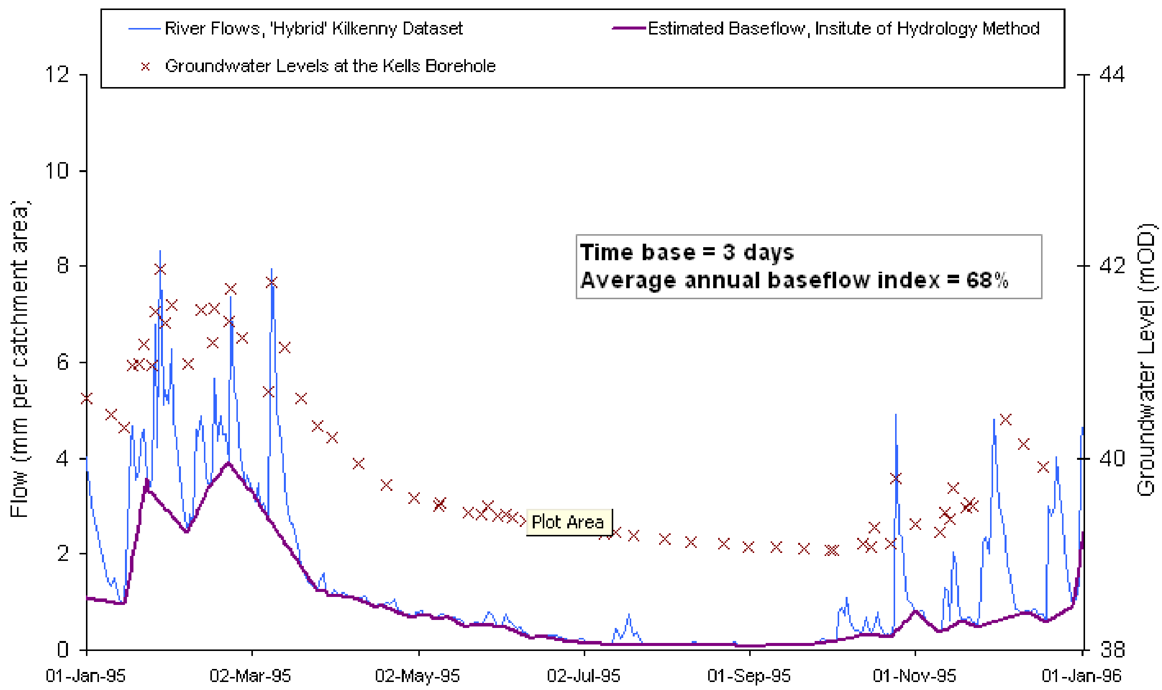

Fig. 4 IoH baseflow separation for Nore hybrid catchment, using N=3 (Misstear and Fitzsimons, 2007)

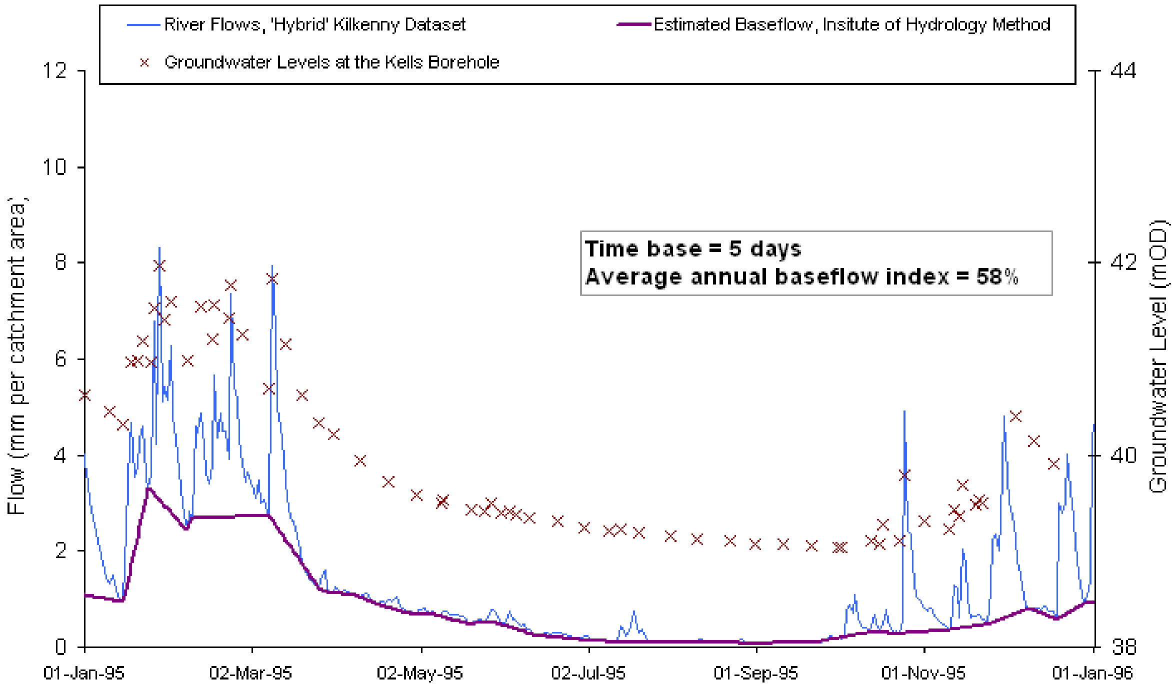

Fig. 5 IoH baseflow separation for Nore hybrid catchment, using N=5 (Misstear and Fitzsimons, 2007)

RECHARGE, VULNERABILITY AND SURFACE RUNOFF

The Recharge and Vulnerability project also led to a simple quantification of the relationship between subsoil permeability (the main factor influencing groundwater vulnerability and recharge coefficient) and surface runoff. In general terms, areas covered by thick low permeability subsoils would be expected to have low recharge potential, and correspondingly high surface runoff (overland flow), whereas the converse should apply in those areas where subsoils are permeable or thin. Based on the results of the case studies (and on a table linking recharge coefficients to hydrogeological setting, which was developed by the Working Group on Groundwater, 2005), the proposed linkages are summarised in Table 3 below. High recharge coefficient is defined as 70-90% of effective rainfall, with intermediate RC = 30-70% and low RC = 5-30%. High recharge coefficient corresponds to low runoff; intermediate recharge = intermediate runoff; and low recharge = high runoff. Hence, for example, the high runoff category corresponds to 70-95% of hydrologically effective rainfall.

Table 3 The linkages between subsoil permeability, recharge, runoff and aquifer vulnerability (Misstear *et al*., 2009a)

Subsoil		Recharge	Runoff	Aquifer vulnerability
Permeability	Thickness			
High	1-3 m	High	Low	Extreme
	>3 m	High	Low	High
Moderate	1-3 m	High	Low	Extreme
	3-10 m	Intermediate	Intermediate	High
	>10 m	Intermediate	Intermediate	Moderate
Low	1-3 m	Intermediate	Intermediate	Extreme
	3-5 m	Low	High	High
	5-10 m	Low	High	Moderate
	>10 m	Low	High	Low

This table gives a rather simplistic picture since, in areas where subsoil conditions might suggest high groundwater recharge, other factors such as the ability of an aquifer to accept this potential recharge (which is limited in locally important and especially in poorly productive aquifers) also need to be taken into account (Misstear *et al.*, 2009a). Nevertheless, the relationships can provide a useful starting point when considering the major contributions to river flow in a catchment.

SURFACE WATER – GROUNDWATER INTERACTIONS STUDY

A study entitled *An integrated approach to quantifying groundwater and surface water contributions of stream flow* was completed by RPS and others in 2008 (two of the authors of the current paper were involved on the project steering group). The study was based on a conceptual model of flow pathways developed in the Geological Survey of Ireland by the second author (Figure 6). Five main pathways were identified: a) overland flow, b) interflow, c) shallow groundwater flow, d) deep groundwater flow and e) discrete fault or conduit flow. The relative importance of different pathways varies according to the characteristics of a catchment, such as topography, soil and subsoil type, bedrock geology and, rainfall. For example, as illustrated in the diagram, deep groundwater flow is more important in productive aquifers than in poorly productive aquifers.

The Danish NAM model was applied to simulate the river flow hydrograph and its main components. This model essentially separates rainfall into three different stores: overland flow, intermediate flow and groundwater flow. Several approaches were employed to constrain the different hydrograph components. Unit hydrograph theory was applied to separate the overland flow from the other hydrograph components. The Boughton baseflow separation technique and master recession curves were both used to identify the deep groundwater component. The deep groundwater flow estimates were also checked against groundwater throughput calculations (using Darcy or Dupuit-Forchheimer relationships).

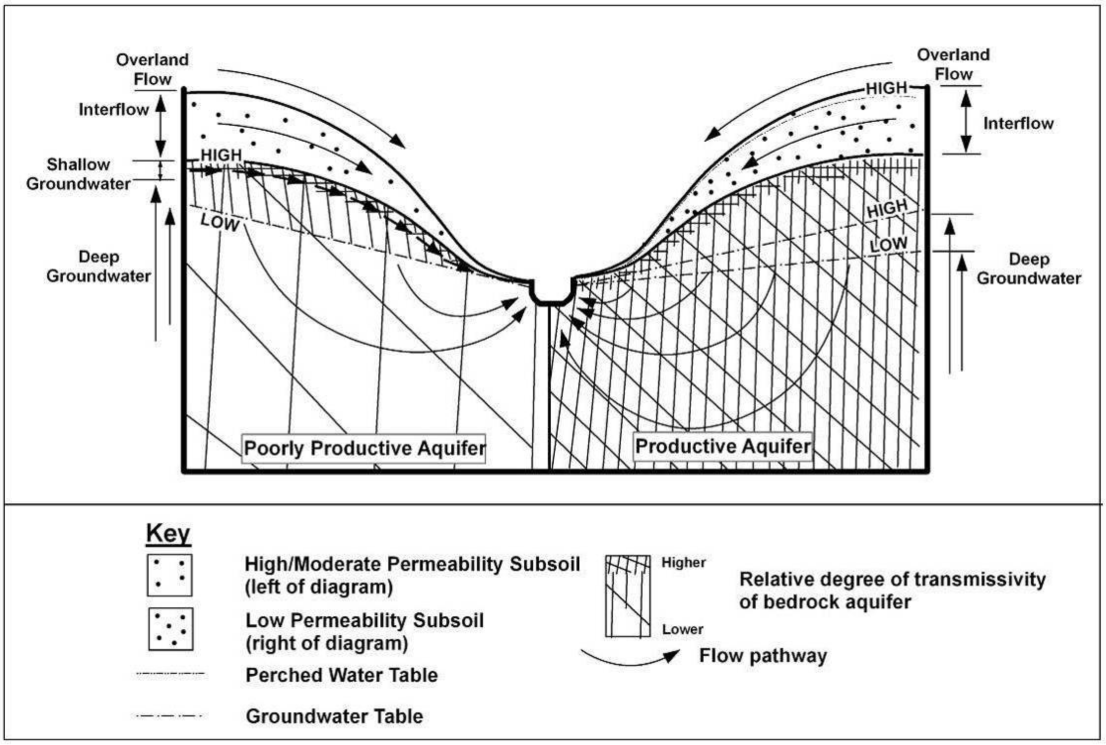

Fig. 6 Components of surface water and groundwater flow in poorly productive (left) and productive (right) bedrock aquifer settings (RPS, OCM, ESBI, GSI, EPA 2008). This conceptual model was developed by D. Daly.

Using these approaches it was possible to develop decision tables for selecting parameters for future modelling studies; these decision tables were based on key hydrogeological descriptors, including aquifer type, subsoil and soil characteristics, topography (slope), land cover and percentage of lakes within the catchment. It was not possible, however, to separate out the individual components of intermediate flow, which, for a particular catchment could include any or all of the following: interflow, shallow groundwater flow in bedrock, discrete fault or conduit flow, and discharges from peat layers.

THE PATHWAYS PROJECT

The research described in this paper, together with the requirements of the Water Framework Directive, have led to a major new EPA STRIVE research project concerned with contaminant movement along pathways (known as the "Pathways project"). This project is being led by Queen's University Belfast, with Trinity College Dublin and University College Dublin as partners. The project, which is to completed in 2013, aims to:

1. Identify significant hydrological pathways within River Basin Districts.
2. Quantify flows along the main hydrological pathways.
3. Identify significant pathways for the transport and attenuation of diffuse pollutants, particularly nutrients, sediments and microbes.
4. Identify critical source areas for diffuse pollutants reaching groundwater, surface water and relevant ecological receptors.
5. Develop a catchment management tool suited to Irish conditions and to the proposed end user.

A project inception report, containing an extensive literature review, will shortly be available on the EPA's website (Archbold *et al*., 2009).

DISCUSSION AND CONCLUSIONS

The different research projects described above have all included analyses of river flow hydrographs, with the main objective of developing a better understanding of the groundwater contributions to river flow and hence of aquifer recharge. The main conclusions that can be drawn include:

a) More than one approach should be used when analysing a river flow hydrograph.
b) The methods need to be based on a valid conceptual model of the catchment, including the main flow pathways.
c) The results of hydrograph separation should be subjected to sensitivity analysis.
d) The baseflow separation can be aided by comparing the river hydrograph with a groundwater level hydrograph in a nearby borehole.

For the new Pathways project, it is proposed to augment traditional graphical and physically based approaches for river hydrograph separation with the use of chemical tracers. Chemical tracer methods have been used for hydrograph separation in other countries for many years (one of the first applications was described by Pinder and Jones in the USA in 1969), but we are aware of only one detailed study to date in Ireland. This was a doctoral study carried out by Kane (*pers comm*., 2009) in the Oona catchment in Co. Tyrone, in which silica and SAC^{254} were used to distinguish three end members in the hydrograph: overland flow, shallow soil water (~10 cm) and deep soil water (~30-40 cm). In the Pathways project, it is proposed to carry out event-based sampling and apply chemical tracer methods in four study catchments.

It is intended that the Pathways project will lead to an improved understanding of the components of the river hydrograph by also using:

- shallow lysimeters and tensiometers to collect better information on interflow in one study catchment.
- groundwater level data and simple hydrogeological analytical equations to improve the reliability of hydrograph separation results.
- flow duration curves to gain insights into the contributions of the different flow pathways.
- lumped parameter and possibly distributed or semi-distributed models to represent flow along the relevant pathways in the study catchments.

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