RPS

Further Characterisation Study

An Integrated Approach to Quantifying Groundwater and Surface Water Contributions of Stream Flow

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Section 1: Introduction

1.1 Background

The management of water resources in Ireland prior to the Water Framework Directive (WFD) has focussed on surface water and groundwater as separate entities. A critical element to the successful implementation of the WFD is to improve our understanding of the interaction between the two and flow mechanisms by which groundwaters discharge to surface waters. An improved understanding of the contribution of groundwater to surface water is required for the classification of groundwater body status and the determination of groundwater quality thresholds.

The study has been led by the Southwestern River Basin District (RBD) under Further Characterisation and has included support from the Southeastern RBD (RPS and OCM) and Western RBD (ESB International). The project was funded through the National Development Plan.

1.2 Aims and objectives

The overall aim of this study is to estimate the contribution of groundwater to surface waters, particularly river flows. The results will be used to assist in determining the groundwater quality thresholds for chemical parameters that are linked to surface water body EQS requirements. The annual average groundwater flow component will be used in this case.

The results also have a wider application to/in many areas of the WFD. In particular, it will assist in:

1) the prediction of the impact on rivers and lakes from groundwater abstraction;
2) further characterisation of catchment hydrology: results from this study will contribute to studies estimating low flow conditions in ungauged catchments;
3) an improved understanding of groundwater flow in poorly productive bedrock aquifers.

This is a difficult study to undertake in an Irish context because the physical settings can be very complex. In many surface water catchments, the groundwater flow regime is heterogeneous, and the aquifers underlying the catchment often comprise a mixture of types. Further, the rainfall is highly variable across the country: the west typically has higher rainfall amounts and more frequent rainfall events than the east of Ireland. Some catchments in the west may have previously experienced few drought conditions, so it can be difficult to identify the component of groundwater flow from the bedrock aquifer in a surface water hydrograph.

1.2 Study framework and conceptual model

The study uses a water balance approach to apportion components of the hydrograph to flow from surface water and groundwater.

In Irish surface water catchments underlain by bedrock aquifers, the pathways by which rainfall becomes surface water flow are conceptualised as (1) overland runoff, (2) interflow, (3) shallow groundwater flow, (4) discrete fault or conduit flow, and (5) deep groundwater flow. These components of surface water flow are described in more detail below, and are illustrated schematically in Figure 1.1.

In most Irish bedrock aquifers, groundwater flow is through faults, fractures and joints. Due to differences in the degree and connectivity of fracturing and fissuring in the bedrock, some bedrock aquifers are more transmissive than others (transmissivity is a measure of how much groundwater a particular thickness of aquifer can convey, and is the product of hydraulic conductivity and effective aquifer thickness). Poorly productive bedrock aquifers have low transmissivities, whilst productive fissured bedrock aquifers have high transmissivities. In certain types of limestone bedrock that are susceptible to dissolution by infiltrating waters, the fissures become significantly enlarged into conduits and even caves. These bedrock aquifers are known as karstified aquifers. All of the bedrock aquifers have low storage capacities, since their porosity is low. In the main, bedrock aquifers are unconfined, or locally confined only by overlying subsoils. The water table is likely to be flatter in productive bedrock aquifers (also karst and gravel aquifers) than in poorly productive bedrock aquifers during both wet and dry seasons (Figure 1.1).

The main differences between the groundwater flow pathways in productive and poorly productive fissured aquifers are shown in Figure 1.1, and include variation in:

(a) effective aquifer thickness: the depth to which well-connected fractures and fissures extends is less in poorly productive aquifers than in productive fissured aquifers.
(b) water table elevation: in general, the groundwater level in poorly productive aquifers fluctuates more than in productive fissured aquifers[1]. It also tends to be closer to the top of the aquifer in winter.
(c) summer (low water table) and winter (high water table) transmissivity: due to water table fluctuations, the transmissivity of poorly productive aquifers can decrease significantly in summer, because the groundwater level is below the most fractured and permeable weathered zone at the top of the aquifer. Due to the greater degree and depth of fracturing, the reduction in saturated aquifer thickness during summer has proportionally less impact on the transmissivity.
(d) groundwater flow system size: in productive fissured aquifers (and karst), groundwater flow paths can be several kilometres long, whereas in poorly productive aquifers, groundwater flow path lengths are generally less than about 300 m.

Sand and gravel deposits are also sometimes large enough to be considered as aquifers in their own right. These aquifers have very different flow and transport properties to the fractured bedrock aquifers they overlie, and have high porosity, storage and transmissivity. The conceptual model shown in Figure 1.1 does not apply to sand and gravel aquifers.

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[1] Note, however, that the greatest fluctuation in groundwater levels can be recorded in highly transmissive karst aquifers.

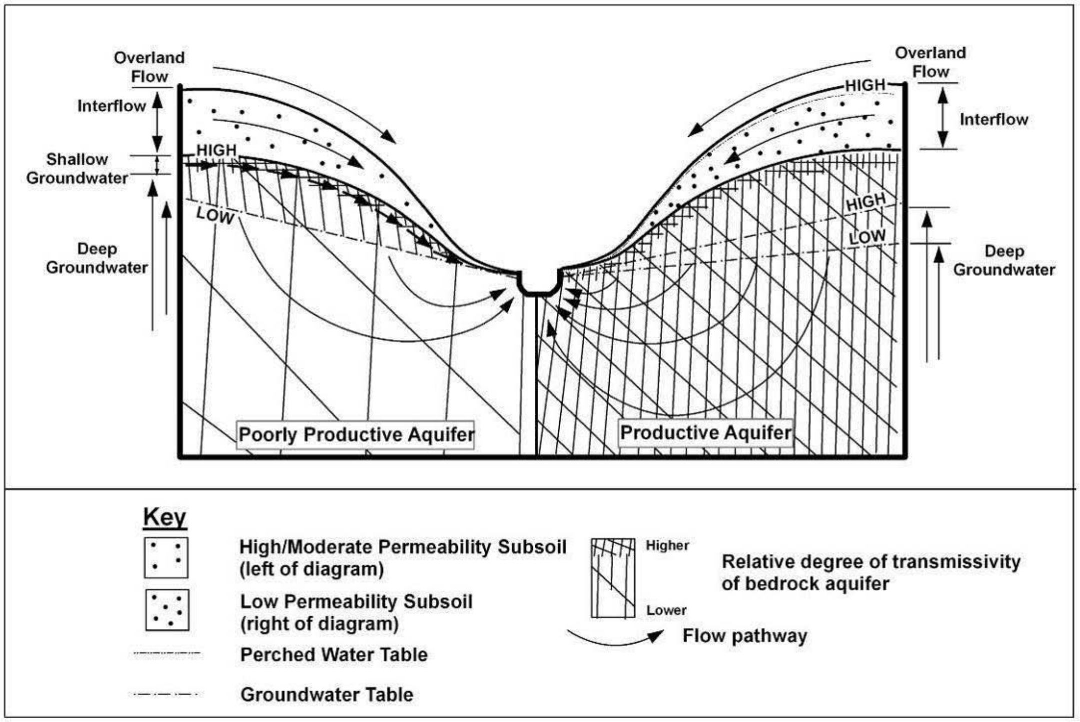

Figure 1.1. Components of surface water and groundwater flow in poorly productive (left) and productive (right) bedrock aquifer settings. Different permeability subsoils can overlie either aquifer type. The alluvium of the rivers crossing the aquifer may have high or low permeability, and is not necessarily dependent on aquifer type.

1.2.1 Overland Flow

Overland flow is precipitation runoff over the landscape and land drains. It is traditionally conceptualized as occurring when a soil's maximum saturation level is exceeded. High runoff rates can detach and transport large amounts of soil as well as transport the associated nutrients and pesticides e.g. phosphates (Figure 1.2). The portion of the precipitated rainfall or snowmelt that does not become overland flow is evaporated, transpired, or soaks (infiltrates) into the subsurface. The maximum rate at which water can soak into a soil in a given condition is the infiltration capacity.

1.2.2 Interflow

For the purposes of this report, interflow is defined as the subsurface water in soils and subsoils (with the exception of sand/gravel) that contributes to surface water/stream flows. It may occur in saturated and unsaturated conditions.

Figure 1.2. An example of overland flow containing excessive sediment as well as water[2].

1.2.3 Shallow groundwater flow

Groundwater flow within the bedrock aquifer is subdivided into two components: shallow and deep. This division is designed to allow for the variation in depth of aquifer fracturing and transmissivity, and also to capture the effect on sustainable groundwater resources of the interaction between seasonally fluctuating groundwater levels and the decreasing transmissivity and storage with depth.

'Shallow' groundwater flow is conceptualised as generally occurring within the high permeability top few metres of the bedrock aquifer, in the fractured and weathered zone and upper part of the rock (Figure 1.3). The groundwater flow paths tend to be relatively short. The weathered, fractured layer may be absent in places, perhaps due to erosion during glaciation. In higher transmissivity productive aquifers, away from discharge zones, the water table is generally below the weathered zone. Therefore, this pathway is used to describe groundwater flow in poorly productive bedrock aquifers.

1.2.4 Deep groundwater flow

Deep groundwater flow occurs in the main body of the bedrock aquifer, below the weathered zone at the top of the aquifer. The groundwater flow system is in hydraulic continuity with the shallow groundwater system, and is connected to surface water flow systems. Due to the differences in fracturing intensity, connectivity and depth, deep groundwater flow volumes are greater in productive fractured aquifers than in poorly productive aquifers.

Deep groundwater flow is conceptualised as being equivalent to the long-term sustainable yield of a groundwater flow system.

[2] (a) http://topsoil.nserl.purdue.edu/nserlweb/weppmain/overview/runoff.html;

1.2.5 Discrete fault or conduit groundwater flow

Although almost all groundwater flows through fractures, joints and faults, these fissures are distributed to a greater or lesser degree through the rock mass. However, larger fault zones that can transmit significantly larger quantities of groundwater than the surrounding less fractured bedrock aquifer also occur. Fault zones occur in all bedrock aquifers, but tend to be more frequent and transmissive in productive fissured aquifers, and also better-connected to the network of smaller fractures. In pure limestone aquifers, there are frequently large conduits that are capable of transmitting very large quantities of groundwater.

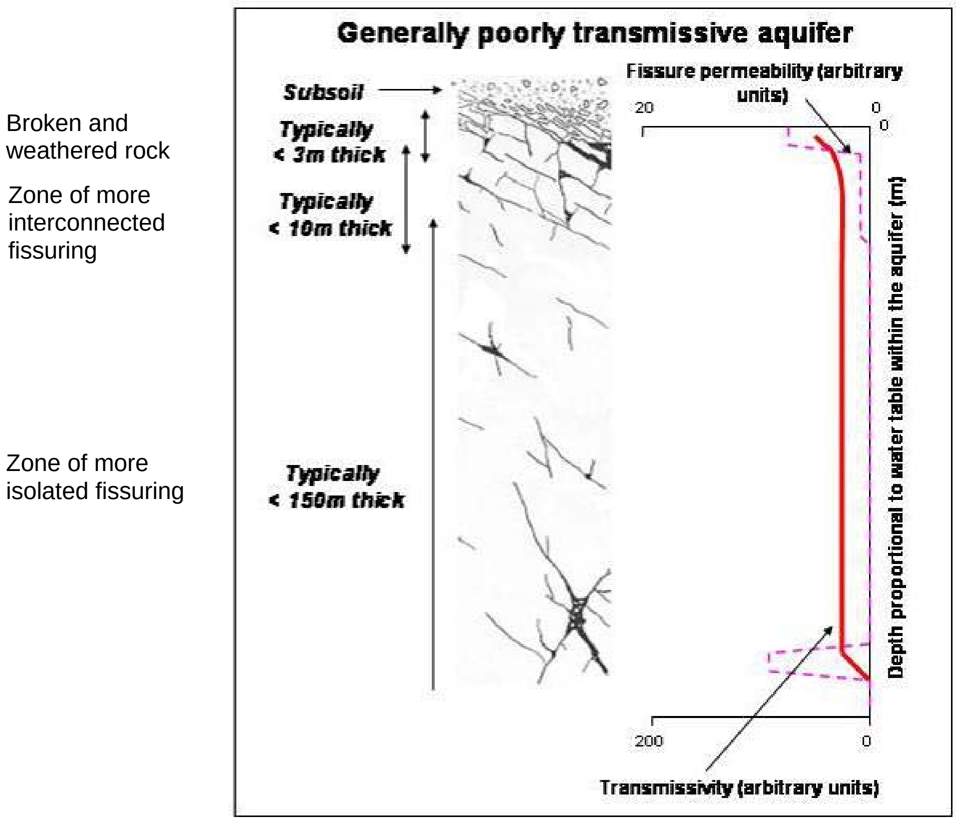

Figure 1.3. Conceptual variation of transmissivity and fissure permeability with depth through a generally poorly productive aquifer (amended from Geological Survey of Ireland, 2003). Shallow groundwater occurs in the upper part of the bedrock (typically <3m).

1.2.6 Interaction of the hydrogeological elements of the conceptual model

In addition to being dependent on the type of bedrock aquifer, the volumes of shallow and deep groundwater contributing to streamflow are dependent on the permeability of the overlying subsoils and on the permeability of the stream bed.

The type and thickness of the subsoils overlying the bedrock aquifers can have a profound influence on the nature of the interaction between groundwater and surface water, and on the amounts transmitted via the various pathways shown in Figure 1 and described below. In Figure 1, the poorly productive aquifer is shown as being overlain by moderate or high permeability subsoils; these readily allow infiltration of effective rainfall into the subsurface. In contrast, the low permeability subsoils shown as overlying the productive fissured aquifer inhibit the recharge of the groundwater, and infiltrating rainwater can become ‘perched’ in the subsoils.

The examples described above and shown in Figure 1 illustrate that understanding the interaction between the pathway elements in the hydrological system is important in the development of the conceptual model and, therefore, being able to quantify components of stream flow. Note that, in the examples given, the scenarios could be reversed, such that moderate-high permeability subsoils overlie productive fissured aquifers, and low permeability river sediments underlie rivers crossing poorly productive aquifers.

1.3 Approach for quantifying streamflow components

A water balance approach was used to quantify the components of streamflow identified in Section 1.2 for seven pilot catchments. Several different hydrograph separation techniques methods were applied to river flow data from the pilot catchments. The pilot catchments were selected to represent the main hydrogeological scenarios occurring in the Republic of Ireland. Particular emphasis was placed on selecting catchments that contain poorly productive aquifers, since about 65% of the country is underlain by these aquifers.

As part of this study, numerous hydrograph separation techniques for determining the groundwater and surface runoff contributions to river flows were considered. These are outlined in a supplementary literature review (“Hydrograph Separation Techniques and Recharge in Ireland”). Two complimentary hydrograph separation methods were selected and applied to measured river flow data to determine overland and deep groundwater flows in the pilot catchments. Forward groundwater modelling provided estimates for deep groundwater flow in fractured bedrock aquifers. The chosen hydrograph separation techniques that have been applied, and the forward groundwater modelling, are discussed further in the methodology section of this document.

Hydrograph separation techniques cannot determine all pathway components, and involve an element of subjectivity in their application. The forward groundwater modelling provided only one component of the groundwater contribution to surface water. Therefore, to interpret more fully river flow data in terms of the components of stream flow in the conceptual model, numerical modelling calibrated against recorded surface water hydrographs was undertaken. The results from the hydrograph separations and forward groundwater modelling were used to condition the numerical model parameters.

Although five components of stream flow were identified in the conceptual model, the analysis and modelling methods are, by their nature, unable to discriminate all of them. Thus, the components of flow that can be identified and quantified are: overland flow, deep groundwater flow, and intermediate flow. The meaning of overland and deep groundwater flow are as described in Section 1.2. “Intermediate flow” encompasses interflow as well as shallow groundwater flow in many cases.

"Deep groundwater flow" is synonymous with "baseflow" in its true sense (Daly, 1994; Misstear *et al.*, 2006). However, since the term baseflow is frequently used differently between hydrologists and hydrogeologists, and between different studies, it is not used in this document so as to avoid confusion and misunderstanding of the streamflow component being quantified.

1.3.1 Methodology

Complimentary methods were used to determine the deep groundwater and overland flow contributions identified in the conceptual model (Section 1.2). They were applied in tandem with the ultimate aim of providing a range of values with which to condition a water balance model. The selection of hydrograph separation techniques has focussed on established methods that can be used for catchments in an Irish hydrological and hydrogeological context. The techniques chosen to analyse hydrographs include:

(1) Master Recession Curve analysis analysis (Sujono *et. al.,* 2004; Doctor and Alexander, 2005; Fenicia, 2005) to quantify the deep groundwater contribution, or a combination of deep and shallow groundwater components of flow;
(2) the 'Boughton two-parameter algorithm' (1993) to apply the results of the Master Recession Curve analysis and separate the deep groundwater contribution of flow;
(3) Unit Hydrograph methodology (U.S. Soil Conservation Service, 1972) to quantify and separate overland flow.

These methodologies were applied to hydrographs from seven pilot catchments. The results of the hydrograph disaggregation along with groundwater throughput calculations for bedrock aquifers were used to constrain and calibrate the parameters of a numerical model. The numerical model used was the NAM (NedbØr-AfstrØmnings-Model) rainfall-runoff model, which is a module of DHI's MIKE 11 modelling suite. In general, NAM can separate three components of stream flow. The contributions of flow that have been apportioned and constrained within NAM for the pilot catchments are overland flow, intermediate flow and deep groundwater flow. This study is especially interested in quantifying the contribution of deep groundwater flow to surface waters. The results from the seven pilot catchments were used to develop a decision model to select NAM parameters on the basis of descriptors from the geographical information system (GIS) datasets. The national coverage of necessary GIS datasets has allowed the application of the numerical model to be extended to regional catchments across Ireland. The results of the deep groundwater contribution of to stream flow for regional catchments have been cross-validated against the Article V Characterisation Report recharge values.

1.3.2 Pilot Catchment Selection

The selection of pilot catchments was based on a number of criteria, especially: hydrogeology, the availability of suitable surface water and groundwater hydrographs, and rainfall timeseries. Poorly productive bedrock aquifers comprise approximately 65% of Irish bedrock aquifers, so the catchment selection focussed on those underlain by Pl and Ll aquifers. Ll aquifers have a limited and relatively poorly connected network of fissures and joints, giving a low fissure permeability which tends to decrease rapidly with depth. Pl aquifers are similar to Ll aquifers, but generally have poorer connectivity between fissures and joints (see Figure 1.4 and Appendix 1 for the definition of Ll, Pl, Pu and other aquifer categories).

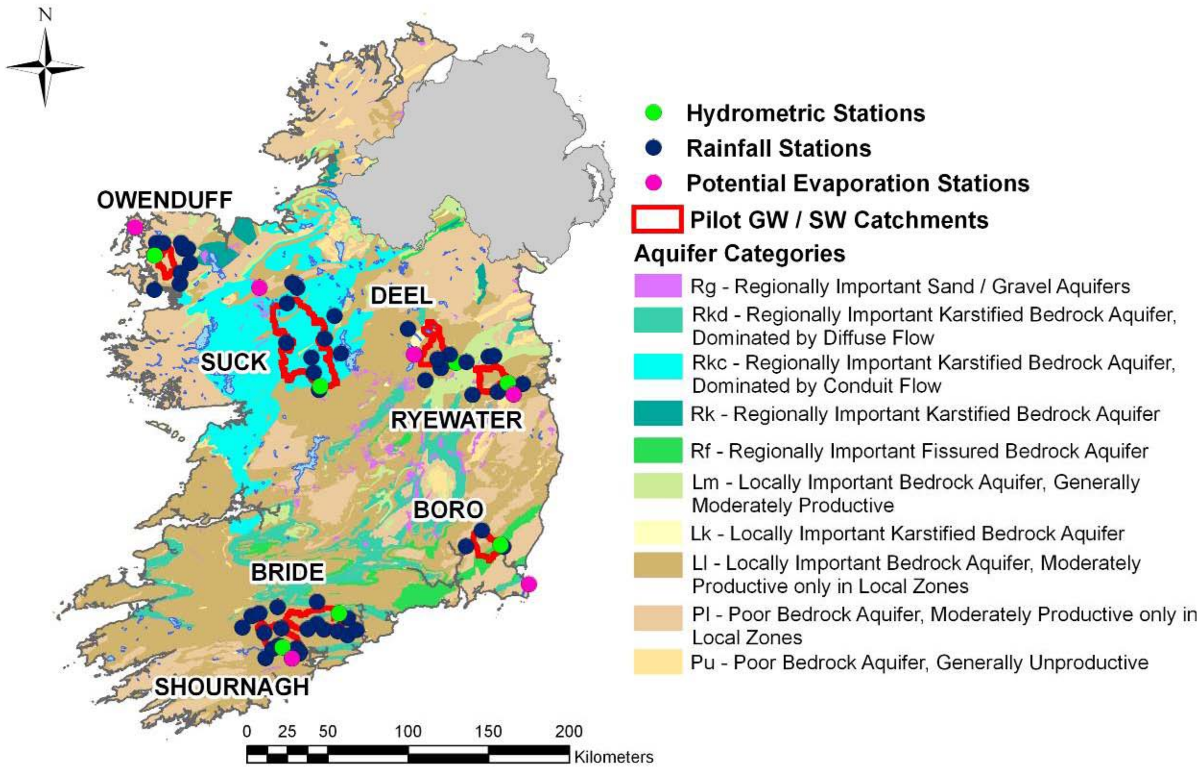

Figure 1.4. Pilot catchments selected for the surface water–groundwater interaction study, and locations of the river flow and meteorological data that were collected for their analysis.

Surface water hydrographs that are of at least fair quality were chosen. Lakes can have the effect of storing water in a catchment and affect the resulting hydrograph. Therefore, for the purposes of selecting the pilot catchments, catchments containing large lakes were avoided where possible. The hydrogeological scenarios and catchments selected to represent them are shown in Figure 1.4, and are:

(1) Poorly productive (Pl) aquifer with shallow/no soils (excepting peat), which in a very generalised sense typifies the hydrogeology and hydrology in the Connacht region and north-west of Ireland. The Owenduff catchment gauged at Srahnamanragh (33006) was selected.
(2) Poorly productive (Ll) aquifer with free draining soils and subsoils and with little peat, which is hydrogeologically and hydrologically typical of the south-west of Ireland. The Shournagh catchment gauged at Healy’s Bridge (19015) was selected.

(3) Poorly productive (Ll) aquifer in a moderate-low vulnerability setting which is a hydrogeological scenario that can be found in the Midlands. The Deel[3] and Ryewater catchments gauged at Killyon (7002) and Leixlip (9001) respectively were selected.
(4) Karst aquifer with free-draining soils and subsoils, and with little or no peat. The Suck catchment[4] gauged at Bellagill (26007) was selected.
(5) Highly productive fractured aquifer with free-draining soils and subsoils. The Boro catchment gauged at Dunanore (12016) was selected.
(6) 'Southern Synclines' scenario, which occurs in the Munster region where mountainous slopes of Old Red Sandstone (Ll aquifer category) surround and drain towards a karstic aquifer in the valleys. The Bride catchment gauged at Mogeely (18001) was selected.
(7) Gravel aquifer – no suitable catchment could be found for the study[5].

The catchment descriptions and conceptual model for expected flow pathways to streams for each of the pilot catchments is described in Appendix 2.

1.4 Acknowledgements

The following are acknowledged for their assistance and guidance throughout this study.

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OCM: Gerry Baker (Currently White Young Green)
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[3] The Deel catchment contains two large lakes in the uppermost reaches of the catchment (Loughs Lene and Bane), the largest being Lough Lene (416 hectares). This is contrary to initial requirements but, for a variety of reasons, catchments other than the Ryewater were not suitable.

[4] The Suck catchment contains peat, contrary to initial requirements but other catchments were not suitable.

[5] The difficulty in finding a suitable catchment for the hydrogeological scenario where a gravel aquifer discharges to a stream is because, to assess flows, a hydrometric gauge is required upstream and downstream of the aquifer. The place that this occurs is on the Castlecomer Plateau in the Southeastern RBD. Unfortunately, stream flow within the catchment is complex and the catchment was discounted (Daly pers. comm. 2006).