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

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Abstract

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 results of the study will also have a wider application to many areas of the WFD.

A subcommittee of the WFD Groundwater Working Group (GWWG) has been formed to develop a methodology to estimate the groundwater contribution to Irish Rivers. The group has selected a number of analytical techniques to quantify components of stream flow in an Irish context (Master Recession Curve, Unit Hydrograph, Flood Studies Report methodologies and hydrogeological analytical modelling). The components of stream flow that can be identified include deep groundwater, intermediate and overland. These analyses have been tested on seven pilot catchments that have a variety of hydrogeological settings and have been used to inform and constrain a mathematical model. The mathematical model used was the NAM (NedbØr-AfstrØmnings-Model) rainfall-runoff model which is a module of DHIs MIKE 11 modelling suite. The results from these pilot catchments have been used to develop a decision model based on catchment descriptors from GIS datasets for the selection of NAM parameters. The datasets used include the mapping of aquifers, vulnerability and subsoils, soils, the Digital Terrain Model, CORINE and lakes. The national coverage of the GIS datasets has allowed the extrapolation of the mathematical model to regional catchments across Ireland.

1.0 Introduction

A WFD study has been carried out by a subcommittee of the Groundwater Working Group (GWWG) to enable the proportion of flows for rivers in Ireland that arise from groundwater to be estimated. The study was led by the Southwestern River Basin District (RBD) and has included support from the Environmental Protection Agency (EPA), Geological Survey of Ireland (GSI), Southeastern RBD (RPS and OCM) and Western RBD (ESB International). The project was funded through the National Development Plan.

Quantifying the contribution of groundwater to surface waters is important, and will allow:

(1) further characterisation of the hydrology of catchments (the low flow conditions of many of the ungauged rivers are not known);
(2) prediction of the impact on rivers and lakes from groundwater abstraction and pollution;
(3) development of groundwater standards and thresholds, many of which will be based on river and lake environmental quality standards;
(4) establishment of chemical and quantitative status for Groundwater Bodies;
(5) assessment of the WFD Programme of Measures.

2.0 Conceptual Model

There are at least five pathways for rainfall or snowmelt to reach surface waters. They include:

(1) overland flow:- runoff of rainfall over the landscape, which occurs when a soil's maximum saturation level is exceeded;
(2) interflow:– the portion of the subsurface waters that moves laterally within soils and subsoils in the unsaturated zone above the aquifer;
(3) shallow groundwater flow:– flow along relatively short paths in the upper fractured/weathered zone of the bedrock (generally occurs in the top several metres of poorly productive bedrock aquifers);
(4) discrete fault or conduit flow:– fault and fracture zones or karst conduits (e.g. caves, cavities) can act as a pathways for groundwater flow;
(5) deep groundwater flow:– flow that occurs in the bedrock aquifer below the groundwater table and beneath the upper fractured/weathered layer, and is connected to the surface water flow system.

The components of flow that can be identified by the hydrograph separation techniques used in this study are overland flow, intermediate flow[1] and deep groundwater flow. Note that although it refers strictly to deep groundwater flow, the term 'baseflow' is not used in this paper. This is because the term is often used more broadly in other studies to describe different components of stream flow, and can therefore lead to confusion.

3.0 Pilot catchments

To quantify the components of stream flow, a water balance approach was applied to seven pilot catchments. The pilot catchments are representative of distinct hydrogeological scenarios that occur in Ireland. The scenarios represented and catchments selected are shown in Figure 1 (includes definition of aquifer types). They include:

(1) *Poorly productive (Pl) aquifer, shallow/no subsoils (excepting peat).* This typifies hydrogeological scenarios in the Connacht region and north-west of Ireland – Owenduff catchment gauged at Srahnamanragh (33006) was selected;
(2) *Poorly productive (Ll) aquifer, free draining soils and subsoils, and little peat.* This hydrogeological scenario represents large parts of south-west Ireland – Shournagh catchment gauged at Healy's Bridge (19015) was selected;
(3) *Poorly productive (Ll) aquifer, moderate-low vulnerability setting.* This hydrogeological scenario typifies much of the Midlands – Deel[2] and Ryewater catchments gauged at Killyon (7002) and Leixlip (9001) respectively were selected;
(4) *Karst aquifer, free-draining soils and subsoils, little or no peat* – Suck catchment[3] was selected gauged at Bellagill (26007);

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[1] "Intermediate flow" is the combination of components of flow that occur between overland flow and deep groundwater flow i.e. interflow and shallow groundwater flow.
[2] 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 catchments other than the Ryewater were not suitable.
[3] The Suck catchment contains peat, contrary to initial requirements but other catchments were not suitable.

(5) *Highly productive fractured aquifer, free-draining soils and subsoils* – Boro catchment gauged at Dunanore (12016) was selected;
(6) *'Southern Synclines' scenario, where mountain slopes of Old Red Sandstone (Ll aquifer) surround and drain towards a karstic aquifer in the valleys of the Munster region* – Bride catchment gauged at Mogeely (18001) was selected.

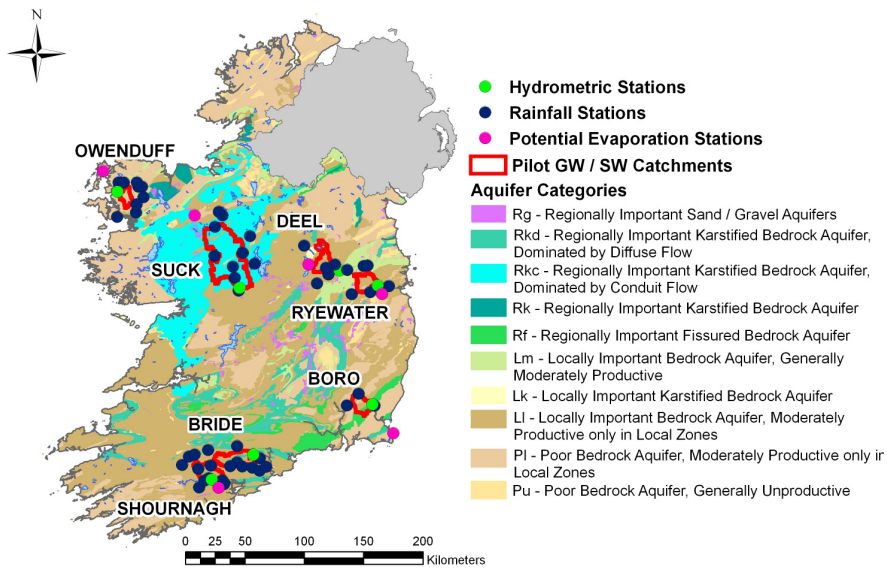

Figure 1. Pilot catchments selected for the surface water-groundwater interaction study, shown on map of Irish bedrock and gravel aquifers

Groundwater flow in poorly productive bedrock aquifers is not well understood, so the catchment selection focussed on scenarios including Pl and Ll aquifers (which, with Pu aquifers, comprise approximately 70% of all Irish bedrock aquifers). Ll aquifers have a limited and relatively poorly connected network of fractures, fissures and joints, giving a low fissure permeability which tends to decrease with depth. Pl aquifers are similar to Ll aquifers, but generally have poorer connectivity between fractures, fissures and joints.

Catchment selection was also determined by the availability of suitable surface water and groundwater hydrographs, and rainfall timeseries. It was important to ensure that the hydrometric stations had at least a fair rating for a range of flows. Lakes store water in a catchment and can therefore affect the hydrograph. So, candidate pilot catchments containing large lakes were avoided where possible. Daily mean flow data for rivers were collected from the EPA and OPW for the seven pilot catchments. The study was especially concerned with low flows, therefore years with long recessions (1974 to 1978, 1984, 1995 and 1996) were of particular interest. To enable numerical catchment modelling, the longest continuous records between 1990 and present of daily mean flows were also collected. Other data sets were collected for the same time periods as the daily mean flow data: Met Éireann daily rainfall; EPA groundwater levels for monitoring points in the pilot catchments or adjacent similar catchments. Mean potential evapotranspiration values (for grass) were estimated using the Penman formula, for use in the numerical modelling.

The pilot catchment characteristics were determined in a GIS. The characteristics that have been found by the study to have the greatest influence on surface water-groundwater interactions include aquifer type, groundwater vulnerability, subsoil permeability, soil type,

catchment slope, land cover (based on CORINE 2000 mapping), and lakes. These are summarised in Table 1.

Table 1. Pilot catchment descriptors. See Figure 1 Legend for aquifer descriptions.

Catchment Descriptor	Poorly Productive Aquifer				Karstic Aquifer	Mixed Productive & Poorly Productive Aquifers	
	Owenduff	**Shournagh**	**Deel**	**Ryewater**	**Suck**	**Bride**	**Boro**
Hydrometric Station	33006	19015	7002	9001	26007	18001	12016
Area (km^2)	119	205	285	209	1207	334	174
Extremely Vulnerable Areas	38.4	34.5	12.5	2.9	22.9	24.9	27.9
% Poorly Drained Soil	96.4	2.1	32.5	72.5	60.1	3.4	21.3
% Low Subsoil	53.8	0.1	23.6	77.5	33.9	1.7	47.3
% Lakes	0.5	0.1	2.1	0.0	0.4	0.0	0.0
% Peat <3m	46.9	0.0	22.7	0.8	31.0	0.1	0.0
% Urban	0.3	3.5	0.3	2.5	0.2	0.0	0.0
% Forest	0.5	3.3	1.9	2.1	1.5	7.5	6.3
% Pasture	0.8	63.4	78.6	78.4	62.5	62.3	50.6
% Karstic Aquifer (Rkc, Rkd, Rk, Lk)	0.0	1.0	9.5	0.2	86.8	12.6	0.0
% Productive Fissured Bedrock Aquifer (Rf, Lm)	0.0	0.0	0.5	1.6	1.6	0.0	36.2
% Poorly productive Ll Bedrock Aquifer	0.1	98.7	88.1	79.4	11.6	86.5	46.0
% Poorly productive Pl Bedrock Aquifer	99.9	0.0	1.6	18.8	0.0	1.0	17.7
% Gravel	0.0	0.0	0.9	0.0	0.0	0.0	0.0
Average Slope (%)	14.9	6.3	2.2	1.5	1.9	5.6	6.0

4.0 Hydrograph separation techniques

There are several different types of separation techniques that can be applied to hydrographs (e.g. graphical, analytical, automated, geochemical). However, the quantification of the components of stream flow can be arbitrary without real measured data. Consequently, the hydrograph separation techniques chosen for this study are flexible enough to allow for expert judgement to be considered. The methods used are: the Unit Hydrograph (UH) method (U.S. Soil Conservation Service 1972) – to determine the component of overland flow; Master Recession Curve (MRC) analysis (Sujono *et. al.* 2004, Doctor and Alexander 2005, Fenicia 2005) – to estimate the volume of the deep groundwater storage zone; the Boughton 'two-parameter' algorithm (Boughton 1993) – to separate the deep groundwater component from the pilot catchment hydrographs; MRC results were used to select suitable recession constants (Fenicia 2005) for the Boughton analyses.

The hydrograph separation techniques were used to inform and constrain a numerical rainfall-runoff model, NAM ("Nedbør-Afstrømnings-Model"). Deep groundwater separations were compared to groundwater hydrographs, where available.

In the following sections, analyses results are reported volumetrically (in mm/yr) rather than as a percentage of rainfall, since annual rainfall varies by hundreds of millimetres across the country.

4.1 Unit Hydrograph (UH) method

Flood events in the measured hydrographs were checked for possible seasonal variations, and each UH was estimated in two stages: (i) the point on the hydrograph where the quick response ends was estimated using the Flood Studies Report (FSR) (NERC, 1975) method, based on the observed time lag between the centroids of rainfall and peak runoff; (ii) the UH shape was determined using the Nash Cascade (Nash 1957) which gave better results than the FSR triangular shape.

Each flood event was examined, and a straight line used to separate overland flow. This routine was applied to the full hydrograph, and a continuous line separating overland flow from total flow was plotted by making reasonable assumptions on conditions between flood events. The UH method was initially applied to mean daily flow data. Hourly flow data were used for the smaller, 'flashy' catchments (the Boro, Owenduff and Shournagh catchments).

4.2 Master Recession Curve (MRC) analysis

Recession curves are the parts of the hydrograph that are dominated by the release of water from storage, generally assumed to be groundwater storage. The entire discharge-time relationship of the MRC is expressed as (Doctor and Alexander, 2005):

$$Q(t) = \sum_{i=1}^{N} q_0^i e^{-(\alpha_i)t}.$$

Where: Q is discharge at time t,
N is the number of exponential segments of the recession,
q_o^i is the discharge at the beginning of each recession segment,
α_i is the recession coefficient (rate of depletion of a reservoir) for each segment.

An MRC is derived from multiple recession segments on a semi-logarithmic plot. In this study, two methods for generating MRCs were applied to daily mean flow data: the Matching Strip and Tabulation methods (Sujono *et. al.* 2004). The recession segment with the smallest recession coefficient represents the slowest reservoir to drain (i.e. the aquifer). The deep groundwater volume store is estimated by integrating the fitted exponential line of slowest reservoir to drain.

4.3 Analytical through-flow calculations

The quantity of deep groundwater flow from the MRC analysis and NAM modelling for the seven pilot catchments was also constrained using through-flow calculations based on aquifer permeability, aquifer effective thickness, groundwater gradient and flow path length.

4.4 Nedbør-Afstrømnings-Model (NAM) hydrological runoff model

The NAM rainfall-runoff model is a module of DHIs MIKE 11 modelling suite (DHI, 2000). It is a deterministic conceptual lumped-sum model. The model continuously accounts for water in three interconnected storage zones: surface, lower zone and groundwater (Figure 2). The water discharged from the model is released through three linear reservoirs to overland, intermediate and deep groundwater flow. In this study, modelled discharges were constrained by the results from hydrograph separation analyses and through-flow calculations.

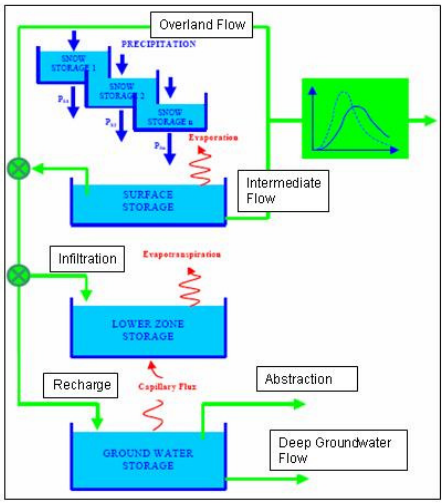

Figure 2. The inter-relationship of the storage zones that are considered by the MIKE 11 NAM model.

The key part of the model is a soil moisture content module, which apportions the rainfall between deep groundwater recharge, surface water runoff, intermediate flow and actual evapotranspiration, depending on the soil moisture content. Overland flow can only occur if the surface storage zone is completely replenished and aquifer recharge only occurs if the soil moisture content is above a certain threshold. Similarly, discharge from the overland and intermediate flow components can only occur if the soil moisture content in the model is above independently controlled thresholds. The deep groundwater contribution to river flow is released with an independent time constant.

NAM has nine catchment parameters (seven surface water and two groundwater) that can be adjusted to control the contributions of overland, intermediate and deep groundwater to total flow.

5.0 Pilot catchment hydrograph analysis and modelling results

When modelling each study catchment, the NAM parameters were altered to achieve contributions of flow that were within the ranges indicated by the hydrograph separation techniques, along with a good Nash Sutcliffe correlation (R^2 value) and water balance calibration between the observed and simulated discharges. The results of UH modelling, MRC analyses, through-flow calculations and NAM modelling are summarised in Table 2. The deep groundwater, intermediate and overland flow estimates from each technique are given, along with the NAM calibration results.

In general there is a good agreement between the NAM modelling for overland flow of the catchments and the results from the UH method (R^2 = 0.95, Figure 3). For the Suck catchment however, NAM modelling predicts less overland flow than the UH estimate. It is likely that both of the methods of hydrograph separation for overland flow have not been able to take into account complex groundwater flow through karst systems.

Constraint of the NAM deep groundwater flow component is achieved mainly by the groundwater through-flow calculations, but also by the MRC analyses for the Ryewater and Suck catchments. A comparison between the through-flow calculations and MRC analyses

estimates suggests that MRC analysis identifies other components of slow flow as well as deep groundwater flow for many of the catchments (e.g. low permeability tills, peat, shallow groundwater). In reality, it is difficult to separate deep groundwater flow from Irish river hydrographs, because of the wet climate and few drought periods.

Table 2. Summary of results for the quantification of deep groundwater flow (red), intermediate flow (green) and overland flow (blue) for the pilot catchments. Abbreviations: NAM (mathematical model); MRC (Master Recession Curve); UH (Unit Hydrograph method); GSI (Geological Survey of Ireland).

Pilot catchment	Hydro-geological scenario	NAM Model Calibration		Overland Contribution Estimate		Intermediate Contribution Estimate	Deep Groundwater Contribution Estimate			
		R^2	WB	UH (mm/y)	NAM (mm/y)	NAM (mm/y)	Groundwater through-flow calcs., min. and max. (mm/y)		MRC (mm/y)	NAM (mm/y)
Boro	**Fissured Volcanic aquifer (includes Ll / Pl)**	0.83	0.2	**215**	**231**	**217**	**238**	**271**	**388** (includes another component)	**240**
Bride	**'Southern Synclines' (Ll and Karst)**	0.81	-0.7	**336**	**352**	**269**	**183**	**219**	**537** (includes another component)	**200**
Deel	**Ll Limestone**	0.90	-0.1	**168**	**120**	**210**	**91**	**201**	**323** (includes another component)	**159**
Owenduff	**Pl Poorly Productive**	0.75	0.3	**1074**	**1322**	**318**	**83**	**173**	**441** (includes another component)	**128**
Ryewater	**Ll Limestone**	0.82	0.0	**191**	**171**	**85**	**91**	**201**	**110**	**121**
Shournagh	**Ll Old Red Sandstone**	0.72	-0.7	**357**	**383**	**205**	**183**	**219**	**321** (includes another component)	**220**
Suck	**Karstic limestone**	0.91	0.1	**354**	**124**	**362**	No calc.	No calc.	**234**	**171**

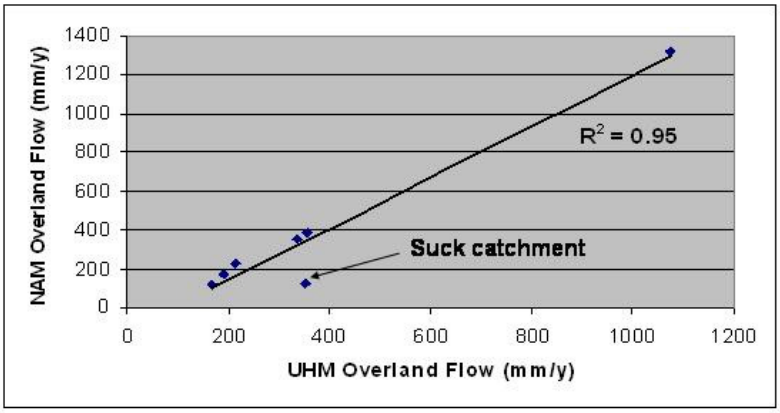

Figure 3. Correlation between the simulated contributions of overland flow from the Unit Hydrograph (UH) method and NAM model.

6.0 Poorly Productive Bedrock Aquifers

The Pl bedrock aquifer in the Owenduff catchment is less permeable and has fewer zones of higher permeability compared to an Ll bedrock aquifer. This is reflected by the quantity of the deep groundwater flow component for the Owenduff catchment (128 mm/year) compared to the catchments composed of Ll bedrock aquifers (up to 220 mm/yr, Table 2). Even though the Ryewater catchment (Ll aquifer in a moderate to low vulnerability setting) has less deep

groundwater flow (121 mm/year) there is significantly more effective rainfall available for recharge in the west of Ireland compared to the east. The NAM results for the Owenduff catchment demonstrate that there is a cap on the amount of flow available from the deep groundwater flow, as well as the intermediate component (Figure 4).

The NAM results for the deep groundwater flow from the poorly productive aquifers are corroborated by the assumptions made for Article V Characterisation groundwater abstraction risk assessment (WFD Groundwater Working Group, 2004). A cap on the recharge amount was determined (200 mm/yr for Ll aquifers, 100 mm/yr in Pl aquifers) to account for poorly productive aquifers being incapable of accepting all available potential recharge due to their low transmissivity. The exception to this cap is in the Shournagh catchment, for which through-flow calculations indicate that there could be up to 219 mm/year deep groundwater flow.

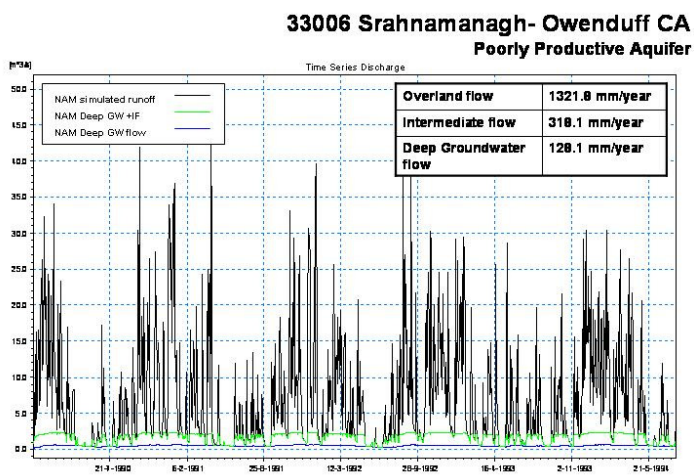

Figure 4. An example of the hydrograph separation from the NAM model for the Owenduff catchment at the Srahnamanagh hydrometric station (33006) for the period 1990 to 1994.

7.0 Regionalisation of NAM Parameters using Decision Tables and GIS

NAM parameter values were constrained during calibration by results from hydrograph separation and through-flow calculations. Relationships between four of the NAM parameter values and the key catchment parameters established from the GIS were determined heuristically. These NAM parameters include:

(1) *coefficient for overland flow (CQ_{OF})* – affects the volume of overland flow and recharge;
(2) *maximum water content in the surface storage (U_{MAX})* – affects overland flow, recharge, amounts of evapotranspiration and intermediate flow;
(3) *intermediate flow drainage constant (CK_{IF})* – affects the amount of drainage from the surface storage zone as intermediate flow;
(4) *time constant for deep groundwater flow (CK_{BF})* – affects the routing of groundwater recharge in the regional aquifers.

The relationships have led to the development of decision tables for determining typical NAM parameter value ranges for different hydrogeological and catchment settings. Expert judgement was used where hydrogeological scenarios weren't covered by the study pilot catchments (e.g. gravel aquifers). An example of the decision table for the *coefficient for overland flow (CQ_{OF})* is presented in Table 3. The decision tables and model parameter values can be used to model further catchments based on the key GIS catchment descriptors

defined in Table 1. An understanding of the conceptual model of a catchment is incorporated by selecting parameters for NAM modelling based on hydrogeological characteristics.

Table 3. The decision table for the determination of the NAM *coefficient for overland flow (CQOF).*

NAM Parameter	Regional Aquifers	Broad range of NAM parameter value	Characteristics of vulnerability, suboils, soils and slope datasets		Refinement of NAM parameter value
CQOF	Pl / Pu / Ll	0.5 – 0.9	High % of poorly drained soils (>30%)		**0.9** if poorly drained soils >50%
					0.8 – 0.9
			Low % of poorly drained soils (<30%)	High % of low permeability subsoils (>50%) or slope >5%	**0.8**
				Low % of extreme vulnerability (<30%)	**0.7 – 0.85** Tend towards **0.85** if slope >5%
				Otherwise	**0.5 – 0.7**
	Rkd / Rkc	0.5 – 0.7	High % of extreme vulnerability (>30%) or low % of low permeability subsoils (<30%)		**< 0.5**
			Otherwise		**> 0.5**
	Rf / Lm	0.5 – 0.8	High % of poorly drained soils (>30%)		**0.7 – 0.8**
			Low % of poorly drained soils (<30%)		**0.5 – 0.7**
	Rg / Lg	0.2 – 0.6	Proximity to river	Gravels close to river	**0.6**
				Gravels not close to river	**0.2**

The remaining five NAM parameters should initially be based on modelling of catchments undertaken for Northern Ireland (Bell *et al.,* 2005). A point to note in the modelling of further catchments is that lakes act as storage in a catchment and can affect the observed hydrograph. NAM modelling for catchments including large lakes should ensure that there is a good water balance between observed and simulated discharges and not focus on a good Nash Sutcliffe correlation.

Thirty-two regional catchments across Ireland were selected for further NAM modelling to quantify components of overland, intermediate and deep groundwater flow. The selection of further catchments nationally adds another complexity. River catchments are not necessarily composed of one aquifer type and more often than not contain a mixture of aquifers. For catchments that contain a mixed aquifer scenario the estimation of the NAM parameters were based on the area proportion of each type of regional aquifer in the catchment.

8.0 Summary

Seven pilot catchments were selected based on hydrogeologically distinct scenarios in Ireland to quantify the different components of stream flow. Deep groundwater, intermediate

and overland components of flow have been estimated for the pilot catchments by using a number of established analytical techniques including Master Recession Curve, the Unit Hydrograph method and through-flow estimations for bedrock aquifers. The results of the analyses have informed the NAM rainfall-runoff model and constrained the quantities that flow from its three storage units.

The results from these pilot catchments have been used to develop a decision model for the selection of NAM parameters using GIS-based hydrological and hydrogeological catchment descriptors. Basing parameter values on such catchment descriptors incorporates the conceptual model into the NAM modelling. Limitations to employing the NAM model include: having suitable discharge and meteorological time series that overlap over greater than a five year period; selecting relatively large catchments that are – in general – greater than 200 km^2; and modelling catchments containing no large lakes.

The application of the integrated approach will be used to inform groundwater status classification. Many of the groundwater standards and thresholds will be based on river and lake environmental quality standards. Groundwater classification will consist of a number of tests for both chemical and quantitative status of the Groundwater Body. The results of the study will also have a wider application to many areas of the WFD.

9.0 Acknowledgements

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10.0 References

Bell, A. K., Higginson, N., Dawson, S., Glasgow, G., and Elsaesser, B. 2005. Understanding and managing hydrological extremes in the Lough Neagh Basin, Tullamore National Hydrology Seminar, Proceedings, 1-10.

Boughton, W. C. 1993. A hydrograph-based model for estimating the water yield of ungauged catchments, in Hydrol. and Water Resour. Symp., Institution of Engineers Australia, Newcastle, NSW. pp. 317-324.

DHI. 2000. NAM Technical Reference and Documentaion, Water & Environment, Hørsholm, Denmark.

Doctor, D. H., and Alexander Jr, E. C. 2005. Interpretation of water chemistry and stable isotope data from a karst aquifer according to flow regimes identified through hydrograph recession analysis. U.S. Geological Survey Karst Interest Group Proceedings, Report 2005-5160.

Fenicia, F., Savenije, H. H. G. , Matgen, P., and Pfister. L. 2005. Is the groundwater reservoir linear? Learning from data in hydrological modeling. Hydrology and Earth System Sciences Discussions, 2, 1717-1755.

Nash, J. 1957. The form of the instantaneous unit hydrograph. International Association of Science and Hydrology 45(3): 114–121.

Natural Environment Research Council (NERC). 1975. Flood Studies Report. Institute of Hydrology, Wallingford, Oxford.

Sujuno, J., Shikasho, S., and Hiramatsu, K. 2004. A comparison of techniques for hydrograph recession analysis. Hydrological Processes, 18, 403-413.

U.S. Soil Conservation Service. 1972. National Engineering Handbook, Section 4, Hydrology, United States Department of Agriculture.

WFD Groundwater Working Group, 2004. Guidance on the assessment of the impact of groundwater abstractions. Guidance document no. GW5. 23pp. Available on the www.wfdireland.ie website.