Section 2: Methodology

2.1 Introduction

There are several hydrograph separation techniques available for quantifying components of stream flow (graphical, analytical, automated and geochemical). Various techniques suitable for undertaking hydrograph separation have been considered in the literature review (supplementary document). Those selected by the subcommittee of the Groundwater Working Group to quantify components of deep groundwater, intermediate and overland flow that contribute to stream flow include the Unit Hydrograph method and two recession curve analysis methods. Estimates for deep groundwater flow throughputs were also undertaken by the Geological Survey of Ireland, based on aquifer permeability, aquifer effective thickness, groundwater gradient and flow path length. Results from each of these analyses have been applied to the seven pilot catchments to inform and constrain the the numerical model, NAM ("Nedbør-Afstrømnings-Model"). The results from the quantitative characterisation of the pilot catchments have been used to develop a decision model based on catchment descriptors from GIS datasets for the selection of NAM parameters. The numerical model has been extended to regional catchments in Ireland, many of which contain mixed aquifer scenarios, to quantify the components of stream flow in those catchments. The Article V Characterisation Report recharge values have been used to validate the results of the numerical modelling of regional catchments.

2.2 Datasets

The datasets used for the study can be broken down into three broad categories: (1) recorded flow timeseries and (2) meteorological timeseries to input into the hydrograph separation models, and (3) GIS datasets to determine catchment physical characteristics.

2.2.1 Recorded Flow datasets

Daily Mean Flow data for rivers was obtained from the EPA and OPW. Hydrometric stations were chosen based on their location in relation to the hydrogeology upstream (for the pilot catchments), their rating curve quality, and the size of the catchment draining to the station. Low flows are of particular use to the study, so data were collected for years with long recessions (1974 to 1978, 1984, 1995 and 1996). Daily Mean Flow data were also collected for the longest record of continuous data between 1990 and present, to incorporate into the numerical modelling. The hydrometric stations that Daily Mean Flow data were collected for are listed in Appendix 3. Groundwater level data for EPA monitoring locations within the pilot catchments, or in similar bedrock aquifers, has also been collected for periods of time overlapping with the daily mean flow data.

Hourly river flow data were derived from 15 minute flow data by the EPA using the software package WISKI for the hydrometric stations Dunanore (12016: Boro River), Healy's Bridge (19015: Shournagh River) and Srahnamanragh (33006: Owenduff River). The hourly data were used for overland flow modelling for which catchment response times are considered to be less than 24 hours.

2.2.2 Meteorology

Meteorology data were collected from Met Éireann for the same periods of time as the recorded flow data,. The data required for the study included actual rainfall (daily) and potential evapotranspiration. Only Pan Class A potential evaporation data are available for 1990 onwards. Potential evaporation data does not take account of soil moisture and transpiration from vegetation. For this reason, Penman formula estimates of mean values of the potential evapotranspiration from grass (millimetres) between the period 1958 and 1982 were used for the numerical modelling. The meteorological stations for which data have been collected are listed in Appendix 4.

2.2.3 GIS datasets

GIS datasets have been used to determine the characteristics of the selected pilot catchments. The physical characteristics of each catchment, derived from the GIS, have been used to develop a decision model to select parameter values for the numerical model. GIS datasets were also used to determine the physical characteristics of each of the regional catchments, so that the NAM parameter values needed to model these catchments could be determined. In this respect, the estimation of physical characteristics in the GIS can be related to the conceptual model for flow (Section 1.2) in order to numerically model gauged and ungauged catchments. The characteristics that have greatest influence on surface water-groundwater interactions, and for which GIS datasets exist, include aquifers, groundwater vulnerability, subsoil permeability, soil type, catchment slope, land cover, and lakes.

The aquifer, groundwater vulnerability and subsoil permeability maps were provided by the GSI[6]. The Corine 2000 Land Cover mapping and lakes datasets were provided by the EPA. The EPA and Teagasc’s final soils layer has been used to identify poorly drained soils. The poorly drained soil categories in the dataset include those identified in Table 2.1.

The EPA’s Digital Terrain Model was used to derive a slope layer for each of the River Basin Districts. The method used to calculate the average slope for each catchment was an area average method using an ESRI application, ‘Hawth’s Tool’.

Other datasets that provide information on catchment characteristics, and that have been used in the pilot catchment selection process, include the EPA’s River Segment class, which is based on the 1:50,000 Ordnance Survey of Ireland’s water vector layer, and the OPW’s channelisation dataset.

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[6] Some counties only have interim vulnerability mapping complete at present (extreme vulnerability and rock close/near to the surface) that was undertaken by external groundwater consultants for the River Basin District Projects.

Table 2.1. Parameters in the EPA/Teagasc final soils GIS dataset used to derive a poorly drained soils map.

Poorly Drained Soils		Well drained Soils
Wet Soils	**Peat Soils**	**Dry Soils**
AlluvMRL	BktPt	AeoUND
AminPD	Cut	AminDW
AminPDPT	FenPt	AminSW
AminSP	RsPt	BminDW
AminSPPT		BminSW
AminSRPT*		MarSands
BminPD		Scree
BminPDPT		
BminSP		
BminSPPT		
BminSPRT*		
Lac		
MarSed		

* If AminSRPT and BminSRPT are within poor aquifers, they were classed as 'wet' and if not, they were classed as 'dry'.

2.3 Separation techniques

The following methodology sections outline each of the techniques selected to quantify the components of overland, intermediate and deep groundwater flow.

2.3.1 Unit Hydrograph approach

The Unit Hydrograph is a graphical method of separating the overland flow component of selected flood events. It was selected by the subcommittee of the Groundwater Working Group to be applied to the seven pilot catchments, despite being somewhat subjective.

Although variations in hydrogeological and soil moisture conditions may be complex, during a flood event the combined contribution of groundwater components of flow (deep and shallow groundwater, and intermediate) will vary within relatively small bounds. The average contribution of overland flow can be estimated reasonably accurately using the unit hydrograph technique. The critical question is the identification of the point on the hydrograph where the quick response ends.

Initially, the flood events in the recorded hydrographs were checked for possible seasonal variations (summer and winter conditions). Each unit hydrograph was estimated in two stages:

1. calculation of the time to peak flow – the Flood Studies Report (1975) method was applied, based on the recorded time lag between centroid of rainfall and peak runoff;

2. determination of the unit hydrograph shape – the use of the Nash Cascade (Nash 1957) was shown to provide improved results compared to the Flood Studies Report triangular shape.

Each flood event was examined, and a straight line to separate the surface runoff was applied. The slope of the line was varied and tested with the unit hydrograph to examine the most appropriate fit, by eye. Repeating this for a number of events provided heuristic guidance on the common regime of the combined groundwater flow components.

This methodology was applied to the full hydrographs, and a continuous line separating overland flow was plotted underneath the total flow by making reasonable assumptions on conditions between flood events. This exercise was completed by hand for many of the catchments. In some instances it was possible to derive a simple formula for the graphical separation of a catchment.

The method was applied initially using mean daily flows. This was changed to hourly flows for the smaller 'flashy' catchments (the Boro, Owenduff and Shournagh catchments). For some of the flashy catchments, there was inadequate hourly representation of rainfall in the catchment. In these cases, the range of potential surface runoff separation methods were applied without testing using the unit hydrograph. The most appropriate method was chosen based on experience with unit hydrographs on other catchments where rainfall data was available.

2.3.2 Master Recession Curve Analysis and Boughton two-parameter separation algorithm approach

The combined groundwater components of the stream flow time series (deep and shallow groundwater, and intermediate) can be separated using data processing or filtering procedures as well as by graphical procedures. Filtering methods tend not to have any hydrological basis – as with graphical methods – but aim to generate an objective, repeatable and easily automated index that can be related to the groundwater response of a catchment.

2.3.2.1 Boughton two-parameter algorithm

Filters are a weighted average of the stream flow and the groundwater at the previous time interval. Of the numerous methods tested, the *Boughton two-parameter algorithm* was considered most suitable by the subcommittee of the Groundwater Working Group. The separation algorithm is:

$$Q_b(i) = \frac{k}{1+C} Q_b(i-1) + \frac{C}{1+C} Q(i) \quad \text{Subject to} \quad Q_b(i) \leqslant Q(i) \qquad \textit{Equation 1}$$

where Q_b is the baseflow contribution (interpreted as deep groundwater flow for this study), Q is the stream flow, and k and C are constants that can be altered to improve the fit of the separation. There is no physical basis for the value of the constants, so the methodology has been used as a tool to separate the deep groundwater component of flow from the hydrograph, rather than to quantify the proportion of deep groundwater in the river. Instead, recession analysis (see below) was used to quantify the proportion of deep groundwater flow to total flow for each of the selected catchments.

2.3.2.2 Recession Curves

The recession curve is the specific part of the flood hydrograph after the crest (and the rainfall event) where stream flow diminishes. The initial slope of the recession curve is steep, but decreases over time as the flood flow component passes and subsurface flow components become dominant. A recession period lasts until stream flow begins to increase again due to subsequent rainfall. Hence, recession curves are the parts of the hydrograph that are dominated by the release of water from natural underground storages.

Recession segments are selected from the hydrograph and can be individually or collectively analysed to gain an understanding of the discharge processes that make up the groundwater components of flow (intermediate, shallow and deep groundwater). Graphical approaches have traditionally been taken, but more recently analysis has focussed on defining an analytical solution or mathematical model that can adequately fit the recession segments.

Each recession segment is often considered as a classic exponential decay function (as applied in other fields such as heat flow, diffusion or radioactive decay), and is expressed as:

$$Q_t = Q_0 e^{-\alpha t} \quad \text{or} \quad Q_t = Q_0 e^{-\frac{t}{T_c}} \qquad \textit{Equation 2}$$

where Q_t is the stream flow at time t, Q_0 is the initial stream flow at the start of the recession segment, α is a constant and T_c is the residence time or turnover time of the groundwater system defined as the ratio of storage to flow.

The exponential term $e^{-\alpha}$ in this equation can be replaced by k, called the recession constant or depletion factor, which is commonly used as an indicator of the quantity of groundwater (Nathan and McMahon, 1990). Typical ranges of daily recession constants for stream flow components, namely runoff (0.2-0.8), interflow (0.7-0.94) and groundwater flow (0.93-0.995) do overlap (Nathan and McMahon, 1990). However, high recession constants (>0.9) tend to indicate dominance of deep groundwater in stream flow.

The recession constant can be determined by a correlation method, where the current flow (Q_t) is plotted on a natural scale against the flow (Q_{t-1}) at some previous fixed time step t (Langbein, 1938). By rearranging *Equation 1* the recession constant k can be derived from the slope of a linear trend line plotted through the curve. This value of k can then be used in *Equation 2* to plot a recession curve using the peak discharge (Q_o) from recorded data. However, a recession curve based on one exponential coefficient does not match recorded recessions well, since it implies only one store in the system. The derivation of the recession curve by this method for the pilot catchments is presented in Appendix 5 to demonstrate that it does not correlate well with the recorded recessions. The recession curve is based only one groundwater component.

2.3.2.3 Master Recession Curve Analysis

To overcome the limitations of the methods outlined in Sections 2.3.2.1 and 2.3.2.2, master recession curve analysis was employed in an attempt to determine the deep groundwater component of total stream flow. There were two main steps in the quantification of deep groundwater flow – or deep and shallow groundwater flow – for the pilot catchments:

- constructing a Master Recession Curve;
- determining the deep groundwater input (or deep and shallow groundwater) to total stream flow from the constructed curve.

There are many methodologies for constructing a master recession curve. Two commonly used methods are the Matching Strip method and the Tabulation method (Sujono *et. al.*, 2004). The Matching Strip method involves plotting multiple recession curves derived from the hydrograph on one semi-logarithmic plot in order of increasing minimum discharge. Each recession curve is superimposed and adjusted horizontally to produce an overlapping sequence. The master recession curve is determined by eye as the mean line through the latter part of the recessions.

In the Tabulation methodology, the starting value of the master recession is chosen as the highest of all the starting values of the recession segments. The other segments are then combined sequentially in descending order of starting value in each segment. The final value of the master recession is equal to the average of the segment values. The sequential combination of the individual recessions in this method becomes problematic where there are a significant number of recession segments available and the time step is large e.g. daily.

To overcome the deficiencies in the Tabulation methodology, the method was further developed by graphically sequencing the segments. The recession segments are sequenced in order of decreasing starting value by horizontally adjusting the individual segments on a graph.

In the Tabulation method, the master recession curve is defined by averaging the flow of all the segments at each time step. This approach works well for the earlier portions of the recession. As some recessions are shorter than others, the number of segments reduces at each time step. Many of the recessions which start at a higher stream flow are longer than the recessions at the low flow, which can lead to unsuitable results in the average recession curve.

The results of the graphical tabulation method show that the recession segments are evenly distributed between the highest and lowest recessions. This is a consequence of the changing response of the stream flow recession to changes in groundwater levels throughout the year (Figure 2.1).

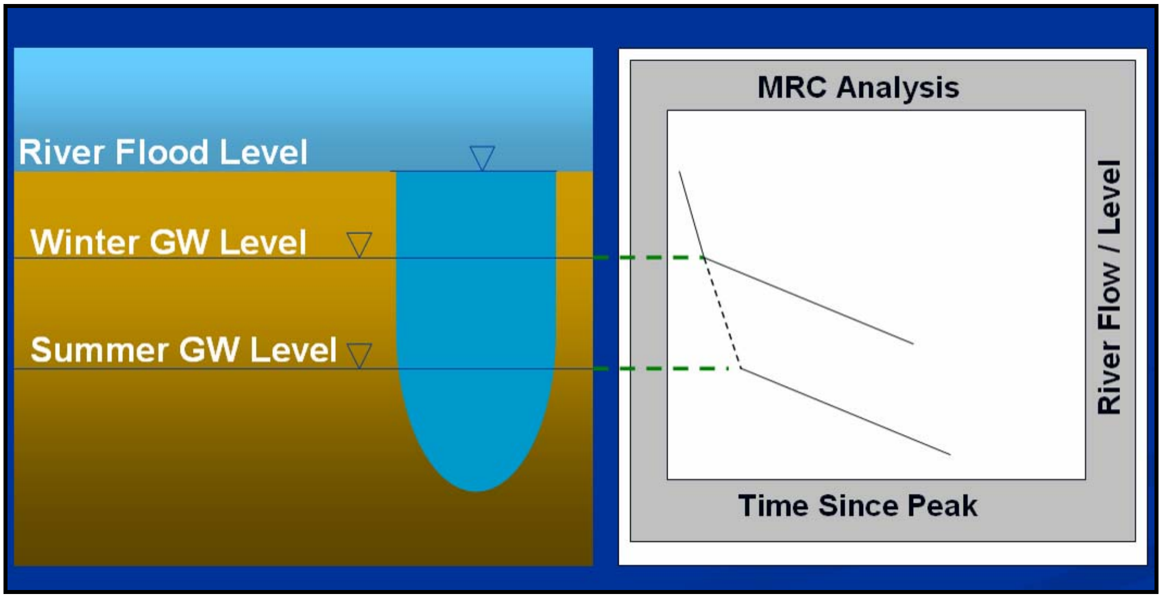

Figure 2.1 The relative response expected on a hydrograph for winter and summer recessions (Sujono *et. al.*, 2004).

The master recession curve is therefore taken as the average of the maximum and minimum recessions. The maximum recession from the tabulation method is comparable to the master recession curve derived from the Matching Strip method (Figure 2.2).

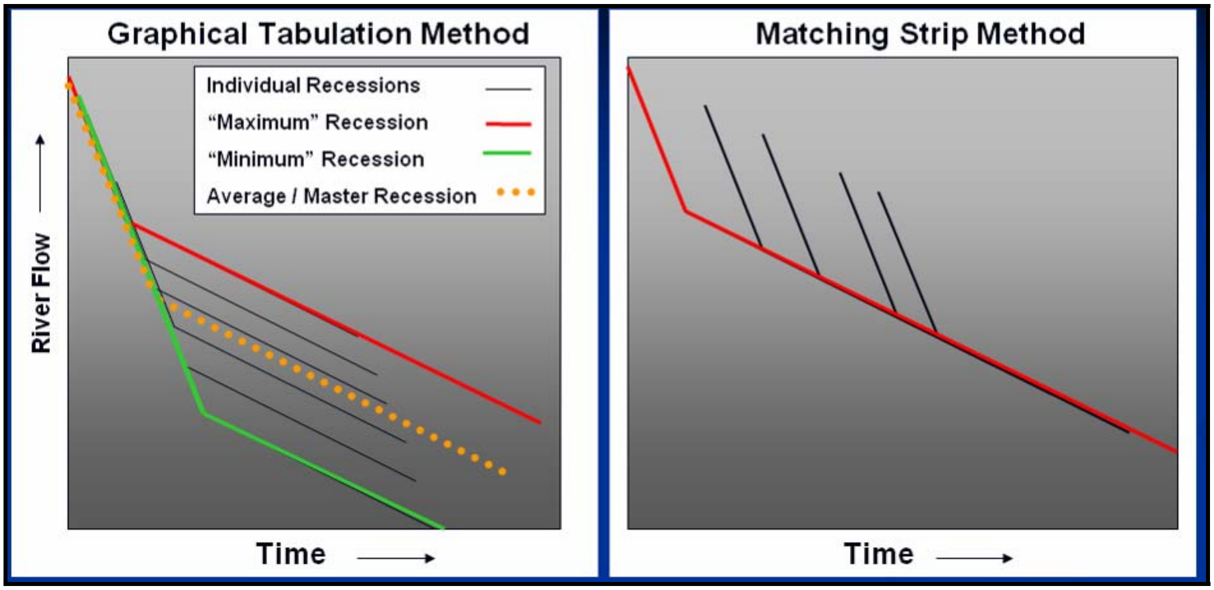

Figure 2.2. Two methods for constructing Master Recession Curve: Matching Strip and Tabulation methods (Sujono *et. al.*, 2004).

The second part of the analysis is to determine the baseflow portion of the master recession curve. The master recession curve can be approximated by a function that is the sum of several exponential segments of the total recession (Doctor and Alexander, 2005). Thus, the entire discharge time relationship of the recession is expressed as:

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

Equation 3

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 and α_i is the recession coefficient for each segment. In this model, each exponential segment is interpreted to represent the depletion of a reservoir, with the rate of depletion of that reservoir being represented by the recession coefficient (α_i) (Kiraly, 2003).

Accordingly, the segment with the greatest recession coefficient would represent the most rapid drainage (surface water runoff). The recession segment with the smallest coefficient would represent the slowest reservoir to drain, i.e. the aquifer. An intermediate segment is also defined and is considered here to represent interflow though soil and subsoil.

In reality it is not clear whether the above conceptual interpretation has any definitive physical validity. The relative volume of flow corresponding to each of the fitted exponential lines can be calculated by integration. The relative volume of the slowest store to the quickest and intermediate stores is considered to be equal to the proportion of deep groundwater flow – or deep and shallow groundwater flow where applicable. In some instances, it is necessary to use four exponential recessions to adequately represent the actual recession.

The proportion of deep groundwater flow is determined for the maximum and minimum master recession curves using this method. The average of the two is taken as the overall proportion of deep groundwater flow. The average proportion of deep groundwater flow calculated from this method is then used to determine the k and C coefficients (recession constants) in the Boughton method. This provides a useful reality check that the proportion of deep groundwater flow from the recession curve analysis suits the actual hydrograph. If the quantity of the deep groundwater component is too large, it will cause the stream flow to be exceeded by separation curve for deep groundwater flow during recessions.

2.3.2.4 Summary

In summary, the methodology adopted to quantify and separate the deep groundwater or combined deep and shallow groundwater components of flow from stream hydrographs uses the following steps:

1. Choose recession segments from river flow data. Only continuous recessions of greater than six days are used. Generally greater than 50 individual segments are used.

2. These recession segments are sequenced according to the Tabulation and Matching Strip master recession curve methodologies.
3. The minimum recession curve is constructed using 3-4 individual exponential recessions to represent the minimum recession in the graphical tabulation methodology.
4. The maximum recession curve is defined using 3-4 individual exponential recessions to represent the matching strip recession curve.
5. The relative volumes of the stores under both the maximum and minimum master recession curves are calculated.
6. The relative volume of the slowest store to the quickest and intermediate stores is taken as the average of the minimum and maximum proportion of deep groundwater flow.
7. The proportion of deep groundwater flow is then used to select suitable '*k*' and '*C*' coefficients for the Boughton two-parameter separation algorithm.
8. A visual check is made that the results are sensible. The proportion of deep groundwater flow – or combined deep and shallow groundwater flow – is taken as the result.

2.3.3 Groundwater throughput calculations

2.3.3.1 Overview

The groundwater throughput calculations made in this study estimate 'average', steady-state groundwater throughput volumes in poorly productive aquifers, specifically the 'deep groundwater flow' component described in the conceptual model in Section 1.2.

Estimates of groundwater throughput were made in order to provide reality checks against which results from the analytical hydrograph separation methods (Section 2.3.2) could be assessed. The results were also used to help constrain the 'deep groundwater' component modelled in NAM (Section 2.3.4).

In addition to estimating the 'deep' groundwater flow contribution to rivers, the calculations help to constrain maximum average groundwater recharge rates for different geological settings and aquifer properties.

2.3.3.2 Conceptual model

Figure 1.3 shows a cross-section through a generally poorly transmissive aquifer. Vertically, there are three zones with different amounts of fracturing, resulting in the variation of bulk aquifer hydraulic conductivity (permeability) with depth.

The 'broken and weathered rock' zone at the top of the bedrock aquifer corresponds to the 'shallow groundwater' pathway shown in Figure 1.1. This zone has high bulk permeability, but limited thickness. Due to seasonal groundwater level variations, this pathway may not contribute to groundwater flow year-round. It therefore does not constitute a sustainable groundwater resource.

The two zones below the weathered zone correspond to the ‘deep groundwater’ pathway in Figure 1.1. Groundwater flow volumes through the ‘deep groundwater’ pathway will, in general, be concentrated in the ‘zone of more interconnected fissuring’. This is because it forms a more connected network. Groundwater flows from the more isolated fissures can be significant if tapped by a borehole, but may contribute relatively little to overall groundwater through-flows under natural conditions.

The part of the aquifer of interest for this study is, therefore, the ‘zone of more interconnected fractures’ shown in Figure 1.3. The calculations and results described below relate to flow through this part of the groundwater system.

2.3.3.3 Methodology

The groundwater flux through a given volume of aquifer is a function of recharge rate and aquifer properties. The recharge rate varies through time and space; aquifer properties vary spatially, both laterally and vertically. To fully capture the spatial and temporal variability in the groundwater system, dynamic numerical modelling is required. A steady-state approach was adopted in this study, however. This was primarily to make the results as generic as possible (i.e. applicable over multiple catchments). Another reason is that there are insufficient readily-available data to allow characterisation of a complex dynamic model; it was outside the scope of this study to undertake detailed catchment-scale investigations to obtain these data. Using an analytical approach has the additional advantage of simplicity, allowing rapid re-calculations to be made.

Deep groundwater flow estimates were made using the following approach:

- Steady-state groundwater flux was calculated for a ‘flow tube’ in the aquifer using analytical groundwater flow equations.
- Parameter values for the analytical equations were derived from study catchments and GSI databases.
- Groundwater through-flow volumes were computed in an excel spreadsheet.
- Deep groundwater flux estimates were assessed in terms of groundwater recharge rates (mm/yr).
- Results obtained were compared qualitatively against analytical modelling reported in a different study (Fitzsimons, 2005), and also against a small number of vertical infiltration capacity calculations.

Two analytical methods for calculating groundwater through-flow were considered. The Darcy equation (*Equation 4*) is the simpler approach, but the Dupuit-Forchheimer equation (*Equation 5*) better represents the shape of the water table. Using both expressions requires certain assumptions (see equation definitions). A comparison of results from both methods was made and the results showed that there was approximately 5% difference between the two. The Darcy equation was therefore used for ease (5% is considered to be a small difference, given parameter value uncertainties, generalisations, etc.). The parameters of the equations are illustrated on Figure 2.3.

Darcy

$$\frac{Q}{A} = -Ki \qquad \textit{Equation 4}$$

where:

Q = groundwater flux (m^3/d);
A = cross-sectional area of aquifer (m^2);
K = aquifer hydraulic conductivity (m/d);
i = groundwater gradient (-).

Additionally:

A = effective thickness of deep groundwater flow zone (t, m) x unit width of aquifer (w, m);
L = maximum flow distance at the upstream end of the aquifer (m).

The unknowns in the equation are:

K, t and i.

An additional parameter, L (the length of the flow path) is required to relate groundwater flow volumes (Q_{out}) to the recharge amounts (q_{in}).

Assumptions:

Groundwater table is planar.
Groundwater flow is linear (horizontal).
hydraulic conductivity is isotropic

Dupuit-Forchheimer

$$\frac{Q}{A} = K\frac{h_1^2 - h_2^2}{L} \qquad \textit{Equation 5}$$

where:

Q = groundwater flux (m^3/d);
A = cross-sectional area of aquifer (m^2);
K = aquifer hydraulic conductivity (m/d);
h = water table elevation above impermeable base (m);
L = maximum flow distance at the upstream end of the aquifer (m).

The unknowns in the equation are:

K, h_1, h_2, and L.

Assumptions:

Groundwater flow is linear (horizontal)
Hydraulic conductivity is isotropic

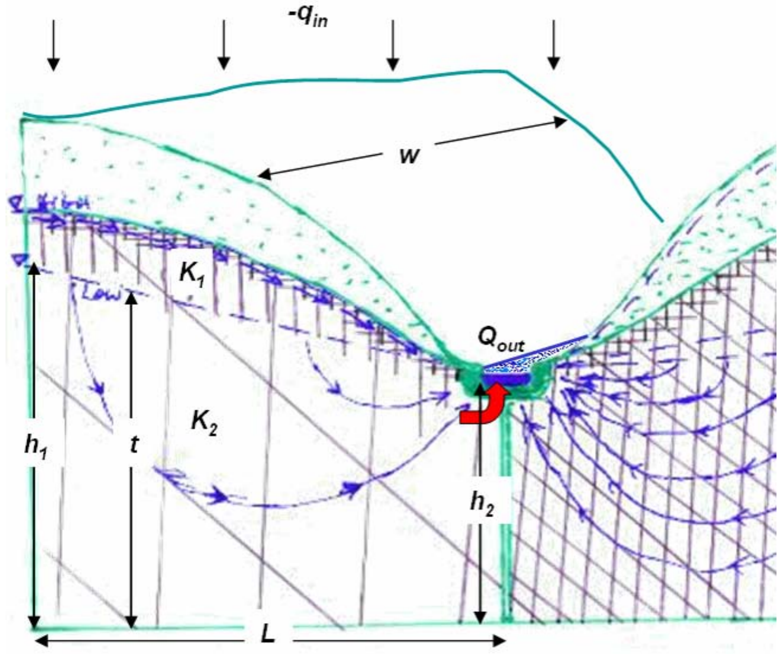

Figure 2.3. Conceptual model showing groundwater recharge, interflow, shallow groundwater flow, deep groundwater flow and outflow in poorly productive aquifer. The parameters of *Equations* 5 and 6 are indicated on the diagram.

2.3.3.4 Constraining equation unknowns

The equation unknowns were constrained by examining the pilot catchment physical characteristics, and by interrogating GSI databases and other source of information. Values for the equation parameters were derived in the following ways:

L – groundwater flow path length: In unconfined aquifers, groundwater divides coincide approximately with surface water divides. The length of the groundwater flow path between the groundwater divide and the discharge zone (stream or river) can therefore be estimated by assessing the average stream separation in a catchment.

Stream separation calculations were made for selected pilot catchments in a GIS environment, using a tool developed by Hogan (2003). The stream separations and estimated groundwater flow path lengths are summarised in Table 2.2. See Appendix 6 for more details.

Groundwater flow path lengths estimated from the catchment stream separations compare well with those estimated by Fitzsimons (2005) using an analytical approach. For typical groundwater recharge rates in Ireland of 250 mm/yr and an aquifer transmissivity of 40 m^2/d (which is significantly higher than those in the bulk of the poorly productive aquifers), he estimated the distance between groundwater divide and discharge zone to be approximately 600 m.

i – groundwater gradient: The groundwater gradient is typically a subdued reflection of topography in unconfined aquifers. In the absence of detailed groundwater level information, ground slopes were examined to constrain maximum groundwater gradients. Maximum groundwater gradients estimated for the pilot catchments and derived from other sources are summarised in Table 2.2. See Appendix 6 for more details.

t – effective thickness of 'zone of interconnected fractures': To ascertain the thicknesses of the of the upper, fractured weathered zone and the less-fractured 'deep' groundwater flow zone ('zone of interconnected fractures', see Section 2.3.3.2), packer test data in Upper Impure Limestones, well inflow data records from GSI's database, and outcrops were examined.

The weathered, fractured zone can be observed in exposed rock faces to range from approximately 1-10 m. Packer test data indicate decreasing hydraulic conductivity with depth in Upper Impure Limestones: 3-5m below rock head hydraulic conductivity is two orders of magnitude less. Estimating effective thicknesses for the rest of the aquifer is difficult, as existing data are limited. Inflow depth data from the GSI's well database were assessed. These data are useful in the absence of other information. However, there is no information on inflow volumes at the various depths, and recorded depths are probably estimates.

The estimated thicknesses of the 'zones of interconnected fractures' for bedrock types underlying the pilot catchments are summarised in Table 2.2. See Appendix 6 for more details.

K – aquifer hydraulic conductivity: Measured aquifer hydraulic conductivities were obtained from a limited number of packer test data in Impure Limestones. Transmissivities (the product of aquifer hydraulic conductivity and thickness) were obtained from the GSI's pumping test database. These sources provided limited data, however. In addition, the pumping test database tends to be biased to higher-yielding sources, since the well records are mainly of Public Water Supply Sources which would tend to be located on fault zones, only developed if sufficiently high-yielding, etc.

To augment the pumping test data, aquifer transmissivities were estimated by using Logan's rule (Logan, 1964). This allows specific capacity (borehole abstraction rate divided by the drawdown) to be used a proxy for transmissivity, according to the following relationship:

Transmissivity (Logan) = specific capacity ($m^3/d/m$) x 1.22 (m^2/d) *Equation 6*

Aquifer flow parameters (both hydraulic conductivity and transmissivity) for the bedrock types underlying the pilot catchments are summarised in Table 2.2. See Appendix 6 for more details.

Table 2.2: Summary of parameter values derived from pilot catchment characteristics and GSI databases.

	Owenduff *	**Shournagh**	**Bride****	**Deel/ Ryewater *****	**Typical values used in GSI******
Underlying bedrock aquifer	Pre-Cambrian (Pl)	Old Red Sandstones (ORS) (Ll)	ORS (Ll) (and pure unbedded limestones, Rk^d)	Upper Impure Limestones (Ll)	Poorly productive aquifers
Average stream separation (km)	0.311	0.410	0.23	0.45 to 0.52	-
Average groundwater flow path length (m)	156	205	115	225 to 255	-
Average ground surface gradients	0.15 to 0.33	0.04 (0.028 to 0.056)	-	-	0.025 to 0.05
Aquifer effective thickness ('zone of interconnected fractures') (m)	80% inflows <40 m	80% inflows <35 m		-	10-20
Aquifer flow properties *****	modal T values 0.1-1 m^2/d	modal T between 2-4 m^2/d (Ll) and 0.1-2 m^2/d (Pl)		modal T 0.5-3 m^2/d (Ll); typical K ranges from 0.002–0.1	-

** Upper catchment only.*
*** Values for Old Red Sandstone part of catchment only.*
**** Overestimate, since the smallest drainage streams could not be properly identified on the map to then be digitised. Figure also affected by subsoil properties in catchment.*
***** typical groundwater (not surface) gradients*
****** T = transmissivity (m^2/d); K = hydraulic conductivity (m/d); Ll, Pl – aquifer categories, see Section 1.3.2.*

2.3.3.5 Summary

- The ‘deep’ groundwater flow component through the different poorly productive aquifers underlying the pilot catchments are calculated using the Darcy groundwater flow equation.
- The shallow component of groundwater flow is estimated separately, since it is seasonal and does not constitute a groundwater resource. (It can, however, transmit pollutants).
- Typical values for the variables in the Darcy flow equation were obtained by analysis of pilot catchment data and assessment of pumping test and borehole data from GSI’s database.
- ‘Deep’ groundwater flow was computed in an Excel spreadsheet for different aquifer bedrock types. The flow was expressed in mm/yr equivalents and used to constrain hydrograph separation results and to condition numerical model parameter estimations.

2.3.4 NAM Rainfall-Runoff model

The NAM rainfall runoff is a module of DHI’s MIKE 11 modelling suite (DHI, 2000), and is a deterministic conceptual lumped sum model. It is not a groundwater flow model, but it can be used to simulate these components as a function of moisture content in three storage zones.

The NAM model (DHI, 2000) uses a conceptual representation of the hydrological cycle (Figure 2.4), and produces a time series of catchment runoff and subsurface contributions to stream flow. The simulated catchment runoff is split conceptually into three components: what the model terms surface runoff (overland flow), interflow and baseflow. The definition of the model’s baseflow component is groundwater flow beneath the groundwater table that interacts with the surface water system. The identification of the components of flow is subjective without constraining the model. It is the aim of the Surface Water-Groundwater Interaction Study to constrain the overland flow component using the Unit Hydrograph method and the model’s baseflow component to deep groundwater flow by the master recession curve analyses.

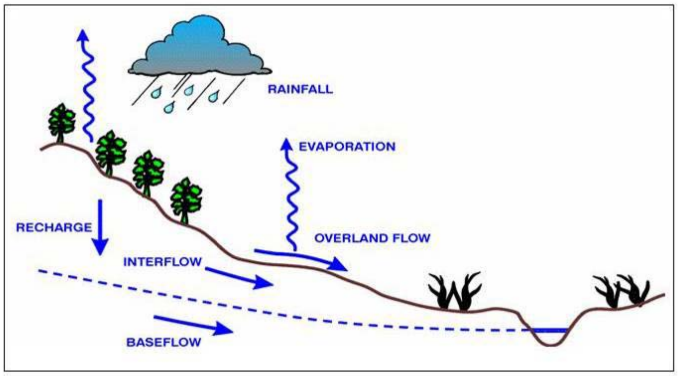

Figure 2.4. The conceptual representation of the hydrological cycle (DHI, 2000). The catchment runoff is separated into what the model terms overland flow, interflow and baseflow.

The basic requirements for the model are meteorological data, stream flow data for model calibration and verification, and the definition of physical catchment parameters. The meteorological data required includes rainfall timeseries, potential evapotranspiration timeseries, and also temperature and radiation timeseries if snowmelt is to be considered.

The MIKE 11 suite contains the NAM model which simulates rainfall-runoff processes on a catchment scale by continually accounting for water content in four inter-related storage zones (Figure 2.5). These storages are snow storage, surface storage, a lower or root zone storage and groundwater storage. The amount of water that recharges the groundwater storage depends on the soil moisture content in the root zone. The groundwater flow is estimated using a linear storage-discharge relationship.

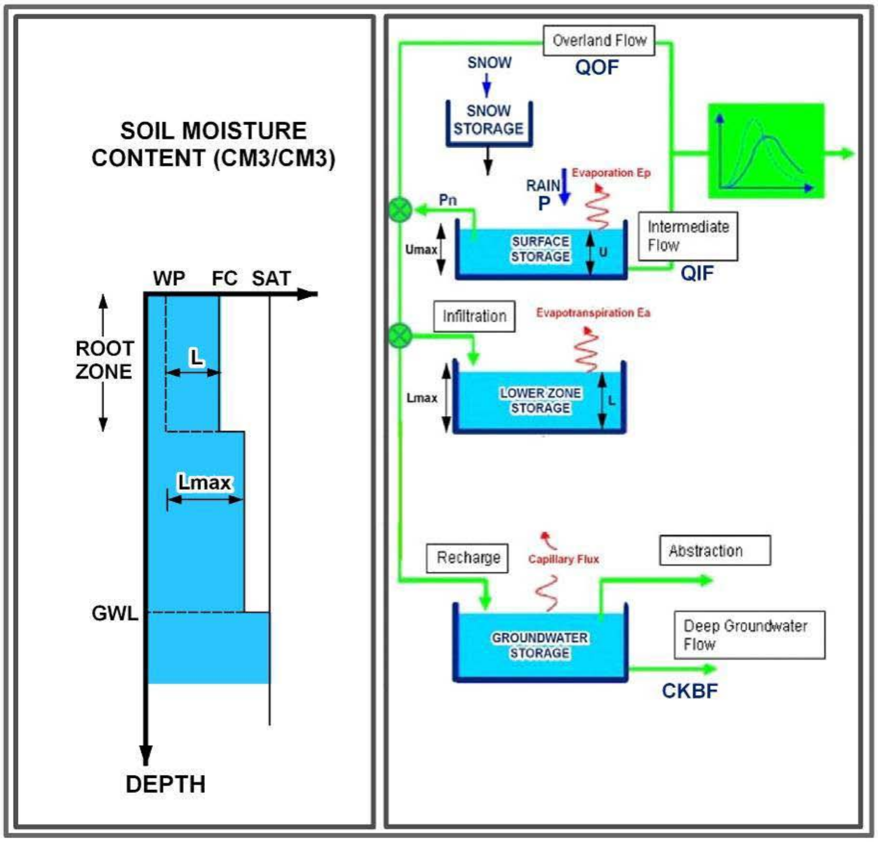

Figure 2.5. The structure of the NAM model. The abbreviated text are explained throughout the text concerning the model. Those that are not described are: WP, soil moisture content at wilting point; FC, soil moisture content at field capacity; SAT, soil moisture content at saturation level; GWL, groundwater level.

NAM is a lumped model, i.e. it considers each catchment to be a single unit and the physical parameters used to describe it are averages for the entire catchment. Consequently, the estimation of the final model parameters should be calibrated against known hydrological and hydrogeological observations.

The structure of NAM is presented in Figure 2.5. The model considers each of the storage zones to act as tanks. The surface storage zone is related to moisture trapped by vegetation and depressions, as well as the cultivated part of the ground. The maximum amount of water that can be stored in the surface storage zone is denoted by U_{MAX} (mm). The amount of water contained in the surface storage zone (U) continually decreases by the process of becoming intermediate flow and by potentaial evapotranspiration. When the maximum surface storage amount is reached ($U >= U_{MAX}$) then some of the excess water, P_N, contributes to stream flow by overland flow. The remainder of the excess water infiltrates to the soils and subsoils (lower zone storage), and the groundwater aquifer (groundwater storage). The typical values of U_{MAX} are in the range 10-20 mm

The soil moisture in the lower zone storage is diminished by the roots of vegetation taking water. The maximum amount of water that can be stored in the lower storage zone is denoted by L_{MAX} (mm), i.e. saturation of the lower storage zone. The moisture content (wetness) of the soil controls the amount of water that infiltrates the groundwater storage zone as recharge, and the intermediate flow and overland flow components. L_{MAX} represents an average value for the various soil types and root depths of vegetation over an entire catchment.

2.3.4.1 Evapotranspiration

Evapotranspiration affects the surface and lower zone storage (Figure 2.5). If the amount of water in the surface storage zone is less than the amount of potential evapotranspiration ($U < E_p$), then the remainder of the water is assumed to be taken up by the roots of vegetation in the lower zone storage as actual evapotranspiration (E_a). The rate of actual evapotranspiration is proportional to the potential evapotranspiration and the relative soil moisture content (L/ L_{MAX}) and is calculated by the equation:

$$E_a = (E_p - U).\ (L/ L_{MAX}). \qquad \textit{Equation 7}$$

2.3.4.2 Overland Flow

When $U > U_{MAX}$, then there is excess surface zone storage water (P_N) as well as infiltration to the lower zone storage. The amount of water that contributes to overland flow (Q_{OF}) is assumed to be proportional to P_N and the relative soil moisture content of the lower zone storage:

$$Q_{OF} \begin{cases} = CQ_{OF}\ .\dfrac{(L/ L_{MAX}) - T_{OF}}{1 - T_{OF}}\ .\ P_N & \text{for } L/\ L_{MAX} > T_{OF}, \quad \textit{Equation 8a} \\ = 0 & \text{for } L/\ L_{MAX} =< T_{OF}, \quad \textit{Equation 8b} \end{cases}$$

where CQ_{OF} is an overland flow runoff coefficient ($0 =< CQ_{OF} =< 1$), and T_{OF}[7] is a threshold value of L/ L_{MAX} for overland flow ($0 =< T_{OF} =< 1$). The overland flow runoff

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[7] T_{OF} is a threshold for overland flow in the sense that no overland flow is generated if the relative soil moisture content of the lower zone storage (l/L_{MAX}) is less than T_{OF}. The same is the case further in the document for the threshold for intermediate flow (T_{IF}) and threshold for deep groundwater flow (T_G).

coefficient (CQ_{OF}) determines the magnitude of infiltration and reflects the recharge conditions to the lower zone storage. Small values of CQ_{OF} would be expected for a relatively flat catchment with a high permeability substrate, whereas high values would be expected for the opposite extreme. CQ_{OF} values can range between 0.01 and 0.90.

The remainder of P_N that does not become overland flow ($P_N - Q_{OF}$) percolates into the lower zone storage (increasing the soil moisture content L) and deeper into the groundwater storage.

2.3.4.3 Intermediate Flow

The amount of intermediate flow (Q_{IF}) is assumed to be proportional to U and the relative soil moisture content of the lower zone storage:

$$Q_{IF} \begin{cases} = CK_{IF} \cdot \dfrac{(L/ L_{MAX}) - T_{IF}}{1 - T_{IF}} \cdot U & \text{for } L/ L_{MAX} > T_{IF}, \quad \textit{Equation 9a} \\ = 0 & \text{for } L/ L_{MAX} =< T_{IF}, \quad \textit{Equation 9b} \end{cases}$$

where CK_{IF} is a time constant for intermediate flow, and T_{IF} is a threshold value of L/ L_{MAX} for intermediate flow ($0 =< T_{IF} =< 1$). The time constant for intermediate flow (CK_{IF} measured in hours) is the average time for a droplet of rain to reach the stream in a catchment by intermediate flow. It is generally in the range of 500-1000 hours (20-40 days).

Intermediate flow occurs either directly as rainfall percolates the surface zone storage, or indirectly as overland flow occurs ($U > U_{MAX}$) and a portion of the overland percolates the surface zone storage. The time constant for routing the intermediate and overland flow ($CK_{1,2}$) determines the shape of the hydrograph peaks:

$$CK \begin{cases} = CK_{1,2} & \text{for } OF < OF_{min} \quad \textit{Equation 10a} \\ = CK_{1,2} \cdot (OF / OF_{min})^{-ß} & \text{for } OF >= OF_{min} \quad \textit{Equation 10b} \end{cases}$$

where OF is the overland flow (mm/hour), OF_{min} is the upper limit for the rate of overland flow (= 0.4 mm/hour), and ß = 0.4[8].

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[8] The constant ß = 0.4 corresponds to using the Manning formula for modelling overland flow (NAM reference manual, DHI, 2000).

2.3.4.4 Deep Groundwater Flow

The amount of water that contributes to recharging the model's groundwater storage (G) is assumed to be dependent on the relative soil moisture content of the lower zone storage:

$$G \begin{cases} = (P_N - Q_{OF}) \,.\, \dfrac{(L/ L_{MAX}) - T_G}{1 - T_G} & \text{for } L/ L_{MAX} > T_G, \qquad \textit{Equation 11a} \\[2ex] = 0 & \text{for } L/ L_{MAX} =< T_G, \qquad \textit{Equation 11b} \end{cases}$$

where T_G is a threshold value of L/ L_{MAX} for deep groundwater recharge ($0 =< T_G =< 1$).

The amount of water increasing the soil moisture of the lower zone storage (ΔL) is calculated as:

$$\Delta L = P_N - Q_{OF} - G. \qquad \textit{Equation 12}$$

The deep groundwater flow component is calculated as an outflow component from the groundwater storage with a time constant CK_{BF} (Figure 2.5). The deep groundwater flow component (DG) is given by:

$$DG \begin{cases} = (GWL_{BF0} - GWL) \,.\, S_Y \,.\, (CK_{BF})\text{-}1 & \text{for } GWL =< GWL_{BF0}, \qquad \textit{Equation 13a} \\[2ex] = 0 & \text{for } GWL > GWL_{BF0}, \qquad \textit{Equation 13b} \end{cases}$$

where S_Y is the specific yield of the aquifer, GWL is the groundwater table depth, and GWL_{BF0} is the maximum groundwater table depth at which deep groundwater flow will occur.

2.3.4.5 NAM Parameters

There are nine catchment parameters (seven surface water and two groundwater parameters) that can be adjusted according to physical and mathematical constraints in NAM:

(1) maximum water content in the surface storage (U_{MAX}) – affects overland flow, recharge, amounts of evapotranspiration and intermediate flow;
(2) maximum water in the lower zone/root zone storage (L_{MAX}) – affects overland flow, recharge, amounts of evapotranspiration and intermediate flow;
(3) overland flow coefficient (CQ_{OF}) – affects the volume of overland flow and recharge;

(4) intermediate flow drainage constant (CK_{IF}) – affects the amount of drainage from the surface storage zone as intermediate flow;
(5) overland flow threshold (T_{OF}) – affects the soil moisture content that must be satisfied for quick flow to occur;
(6) intermediate flow threshold (T_{IF}) - affects the soil moisture content that must be satisfied for intermediate flow to occur;
(7) time constant for overland flow ($CK_{1,2}$) – affects the routing of overland flow along catchment slopes and channels;
(8) deep groundwater recharge threshold (T_G) - affects the soil moisture content that must be satisfied for groundwater recharge to occur;
(9) time constant for deep groundwater flow (CK BFI) - affects the routing of groundwater recharge in the regional aquifers.

In some instances there may be reason to separate the groundwater storage zone into two components, an upper and lower component. Further parameters can be input for catchments that the groundwater storage has been separated into two components include:

(1) recharge to the lower groundwater storage zone (CQ_{LOW});

(2) time constant for routing a lower groundwater storage flow (CK_{BF2}, which is the time constant for routing deep groundwater flow).

In the instance that the groundwater storage zone is separated into two, then the flow from the lower groundwater storage zone represents deep groundwater flow. Consequently, the combination of the flows from the model's root zone and the upper groundwater storage zone represent intermediate flow.

2.3.4.6 NAM Output and calibration

The output of the model is tabular data (water balance, net rainfall, potential/actual evapotranspiration and groundwater recharge), and time series data of all discharge components and storage components.

For the calibration of the simulated rainfall-runoff model with the recorded hydrograph, the following objectives are usually considered: a good agreement of the average simulated and recorded catchment runoff volume i.e. a good water balance (F_1), a good overall agreement of the shape of the hydrograph (F_2), a good agreement of the flow peaks with respect to timing (F_3), rate and volume, and a good agreement of low flows (F_4). The NAM model has an automatic calibration scheme that aggregates the four objectives (F_1 to F_4) into a single objective function. The autocalibration tool does not focus on apportioning the correct contributions of flow to overland flow, intermediate flow and deep groundwater flow. The results of the Master Recession Curve analysis and deep groundwater permeability calculations for the pilot catchments must be used to inform the manual selection of NAM calibration parameters in order that the model constrains the contributions of flow. For catchments that include lakes, modelling should focus on a good water balance rather than the correlation of shape, or matching of peak and low flows.

2.3.5 Article V Characterisation Report

One of the assessments undertaken for the Article 5 Characterisation Report was the assessment of the impact of groundwater abstractions on bodies of groundwater and on groundwater dependent terrestrial ecosystems. The general approach to the impact assessment used a ‘source-pathway-receptor’ framework. The values of recharge for each of the catchments can be used to validate the numerical modelling of the regional catchments.

The WFD Groundwater Working Group in Ireland proposed infiltration coefficients that were used to estimate recharge of Irish bedrock aquifers nationally (Table 2.3) (WFD Groundwater Working Group, 2004). The dominant hydrogeological scenarios in Ireland were considered by combining full and interim vulnerability mapping with subsoils and soils mapping. Groundwater vulnerability is dependent on many factors, including the permeability and thickness of the subsoil, the thickness of the unsaturated zone (in sand and gravel aquifers only), and the type of aquifer. The infiltration coefficients were based on expert guidance of the Groundwater Working Group, as well as previous studies such as Wright *et al.* (1982) and Daly (1994).

Met Éireann’s annual average rainfall national dataset for 1961 to 1990 and the potential evapotranspiration (PE) for the same time period were available to estimate the effective rainfall. The Danish Aslyng scale (Aslyng, 1965) has been applied in a number of studies to calculate the actual evapotranspiration (e.g. Cawley, 1994; Daly, 1994). The calculations are normally performed on a catchment or sub-catchment scale. However, the groundwater abstraction risk assessment was carried out at a national level and it was agreed to simplify the calculation of actual evaporation (AE) based on expert judgement:

$$AE = 0.95 * PE. \qquad \textit{Equation 14}$$

The effective rainfall (measured in mm/yr) was determined by calculating the difference between the total rainfall and the AE:

$$ER = \text{Average Annual Rainfall} - AE. \qquad \textit{Equation 15}$$

The recharge of Irish aquifers was estimated by cross-multiplying the infiltration coefficients with the effective rainfall. A cap on the amount of recharge was included for the poorly productive aquifers (200 mm/yr for locally important aquifers and 100 mm/yr in poorly productive aquifers) to account for them not being capable of accepting the available recharge due to their low transmissivity. Where possible, the estimates of recharge were to be corroborated with any known assessments of baseflow.

Table 2.3. Potential groundwater recharge coefficients for different hydrogeological settings in the Republic of Ireland (WFD Groundwater Working Group, 2004). Due to their low transmissivity, poorly productive aquifers are typically not capable of accepting all available recharge, but instead require a cap on the amount of infiltration.

Vulnerability category		**Hydrogeological setting**	**Recharge coefficient (RC)**		
			Min (%)	Inner Range	Max (%)*
Extreme	1.i	Areas where rock is at ground surface	60	**80-90**	100
	1.ii	Sand/gravel overlain by 'well drained' soil	60	**80-90**	100
		Sand/gravel overlain by 'poorly drained' (gley) soil			
	1.iii	Till overlain by 'well drained' soil	45	**50-70**	80
	1.iv	Till overlain by 'poorly drained' (gley) soil	15	**25-40**	50
	1.v	Sand/ gravel aquifer where the water table is ≤ 3 m below surface	70	**80-90**	100
	1.vi	Peat	15	**25-40**	50
High	2.i	Sand/gravel aquifer, overlain by 'well drained' soil	60	**80-90**	100
	2.ii	High permeability subsoil (sand/gravel) overlain by 'well drained' soil	60	**80-90**	100
	2.iii	High permeability subsoil (sand/gravel) overlain by 'poorly drained' soil			
	2.iv	Moderate permeability subsoil overlain by 'well drained' soil	35	**50-70**	80
	2.v	Moderate permeability subsoil overlain by 'poorly drained' (gley) soil	15	**25-40**	50
	2.vi	Low permeability subsoil	10	**23-30**	40
	2.vii	Peat	0	**5-15**	20
Moderate	3.i	Moderate permeability subsoil and overlain by 'well drained' soil	25	**30-40**	60
	3.ii	Moderate permeability subsoil and overlain by 'poorly drained' (gley) soil	10	**20-40**	50
	3.iii	Low permeability subsoil	5	**10-20**	30
	3. iv	Basin peat	0	**3-5**	10
Low	4.i	Low permeability subsoil	2	**5-15**	20
	4.ii	Basin peat	0	**3-5**	10
High to Low	5.i	High Permeability Subsoils (Sand & Gravels)	60	**90**	100
	5.ii	Moderate Permeability Subsoil overlain by well drained soils	25	**60**	80
	5.iii	Moderate Permeability Subsoils overlain by poorly drained soils	10	**30**	50
	5.iv	Low Permeability Subsoil	2	**20**	40
	5.v	Peat	0	**5**	20

2.4 Summary

The methods described above are the techniques that have been selected by the sub-subcommittee of the Groundwater Working Group to undertake the Surface Water-Groundwater Interaction Study. The Unit Hydrograph method is a technique that considers storm events in recorded flow and rainfall data to estimate the quantity of overland flow. Master Recession Curve analysis uses recessions from recorded flow data plotted on a semi-logarithmic scale. The Matching Strip and Tabulation methods are considered to estimate the volume of the storage supplying the contribution to deep groundwater flow. Groundwater throughput calculations for different aquifer types in Ireland have also been used to estimate the contribution of flow from deep groundwater.

The NAM model is a lumped-sum conceptual rainfall-runoff model that can estimate the contributions of overland flow, intermediate flow and deep groundwater flow. The Unit Hydrograph method, Master Recession Curve Analysis and groundwater throughput calculations are used to constrain the contributions of overland flow and deep groundwater flow in the NAM model. The parameters from the numerical modelling combined with GIS analyses of catchment descriptors inform parameter selection in NAM for further catchments. The results of further NAM modelling of regional catchments are verified using the results of the Article V Charactisation results for the recharge of aquifers.