Appendix 8

Literature Review

Hydrograph Separation Techniques and Recharge in Ireland - Literature Review

1 Introduction

A subcommittee of the WFD Working Group on Groundwater (WGGW) has been formed to develop a methodology to estimate the groundwater contribution to Irish Rivers. The literature review aims to consider previous cacthment-scale water balance studies in Ireland and the most appropriate techniques to use for this study to separate components of streamflow.

Surface water flow in rivers, lakes and transitional waters is the result of discharge from groundwater and surface components. The number of components of discharge that can be identified depends on the conceptual model of flow. Some models consider two components of flow (e.g. overland and subsurface flow), whereas other models consider more than two components of flow. A complication with conceptual models can be that the terms for components of flow can be used inconsistently.

The term 'baseflow' can be used differently amongst hydrologists and hydrogeologists, generally depending on either the number of components the total volume of flow can be separated into, or the subjectiveness of the method used to apply the separation. In a two-component model (overland and subsurface flow), many scientists and engineers consider the entire subsurface contribution to streamflow to be baseflow (e.g. Gray 1973, Boughton 1988, Jakeman and Hornberger 1993). Some authors refer to the two components as "quick" response and "slow" response runoff (e.g. Jakeman and Hornberger 1993, Boorman *et al.* 1995). Jakeman and Hornberger (1993) define the "quick" response runoff as surface runoff (or overland flow) and the "slow" response flow as the sum of rapid subsurface, delayed subsurface and groundwater runoff). Authors can interchangeably use the term baseflow as "slow" response runoff.

Barnes (1939) was the first to consider interflow as an additional subsurface component of flow, as well as overland flow and baseflow. Interflow is defined by Barnes (1939) as part of the total runoff that moves laterally to surface runoff and finally enters a surface water body (as described in Nejadhashemi *et al.* 2003). Other researchers have applied Barne's model (e.g. Rodda *et al.* 1976, Nathan and McMahon 1990, Mugo and Sharma 1999). Rodda *et al.* (1976) define interflow as "that part of infiltration that moves through the 'soil zone' without penetrating to the underlying zone of saturation. Interflow may be 'thrown out' by impermeable soil layers as shallow springs or seepages; it may be augmented by tile drainage or controlled by the state of drainage ditches" (Rodda *et al.* 1976 p. 141). These authors comment that the term 'interflow' seems to be the same as 'throughflow' and explain that throughflow is defined by Kirkby and Chorley (1967) as "the slower *[compared to overland flow]* lateral movement of water through the soil layer." As such, it embraces all water discharged from the unsaturated zone including that from perched water tables. Baseflow in the three-component models is interpreted to be groundwater flow that is discharged to streamflow from beneath the groundwater table.

For the surface water - groundwater interaction study, five components of streamflow are considered in the conceptual model for a catchment. These are overland flow, interflow, shallow groundwater flow, 'discrete fault or conduit' flow (from karstic or productive fissured aquifers) and deep groundwater flow. The term baseflow is not used, although it strictly refers to deep groundwater flow. The components of flow are described in the main surface water/groundwater interaction study document. Since none of the hydrograph separation methodologies described below are able to distinguish between the interflow, shallow groundwater flow and/or 'discrete fault or conduit' flow components, the sum of them all is termed intermediate flow.

To have comparity between different conceptual models, it is important to state the definition of baseflow. The baseflow index (BFI) is a dimensionless variable that expresses the volume of baseflow as a fraction of the volume of total flow in a stream. Consequently, any discrepency in the use of the term baseflow can lead to confusion when considering recharge to bedrock aquifers and the outflow from them.

2 Hydrograph Separation

2.1 Overview

The response of streamflow at a gauged station is measured as unit flow (m^3/sec) and is recorded continually at regular time intervals. Flow measurements at selected equal time intervals (e.g. hourly, daily) can be extrapolated from the recorded time series of data and plotted against time. The curve that connects the points is known as a hydrograph. The shape of a hydrograph curve will have different characteristics depending on parameters such as topography, climate, seasonal variations, substrate composition, bedrock geology, land use, surface water storage such as lakes and any artificial controls on streamflow. For example, if the surface water drainage area is dominated by steep slopes, impermeable substrate and bedrock aquifer, and there are a number of heavy rainfalls, then the response of the hydrograph curve would be expected to show sharp peaks. This is because a large component of the rainfall would become surface runoff that flowed directly to the stream. An example of a daily flow hydrograph for a one-year period is shown in **Figure 1**. The response of the curve demonstrates the broad seasonal variation of streamflow - high streamflows during wet periods of the year and lower streamflows during dry periods (recessions) - as well as the peaky nature as a result of rainfall events. During wet seasons there will be relatively large contributions to streamflow from surface and the subsurface flow. During dry seasons, direct runoff (surface runoff, interflow and shallow groundwater components) will become less prevalent. A drought period occurs over an indefinite number of days without rain or snowfall. An absolute drought period in Ireland is considered to be 15 consecutive days, or more, without 0.2mm or more rainfall on each day. Any discharge to streamflow during a drought period is composed entirely from deep groundwater flow.

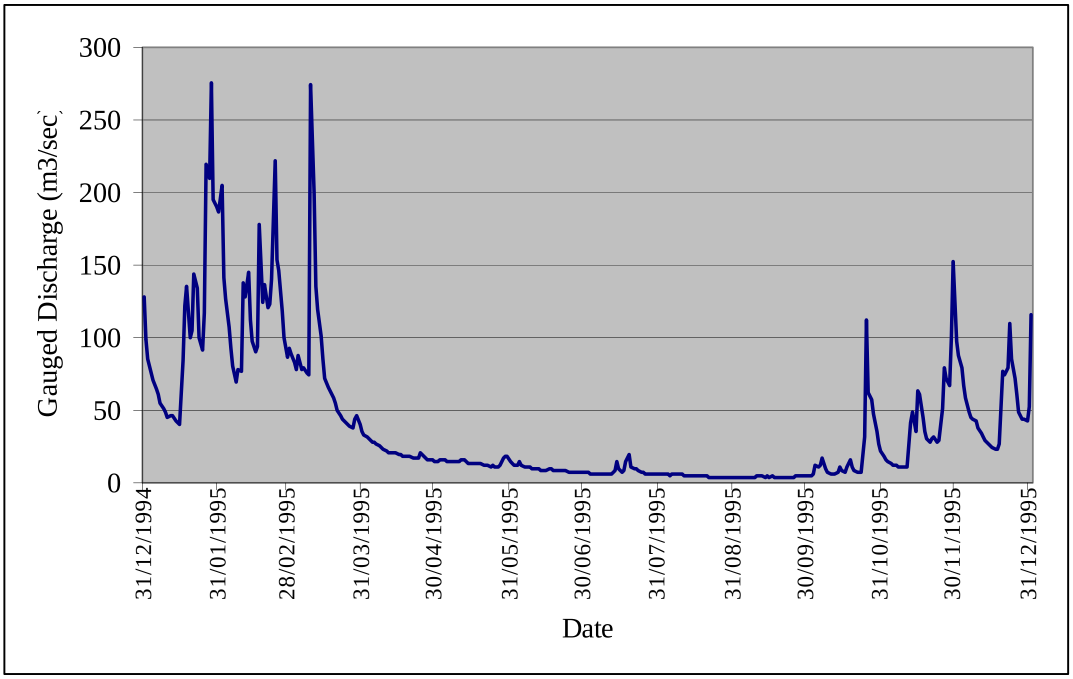

Figure 1. Daily flow hydrograph for the River Nore at Brownsbarn (15006) for 1995 (OPW data).

A hydrograph separation is the process whereby the hydrograph is separated into subsurface components and surface runoff. There are different techniques of hydrograph separation including graphical, analytical, geochemical and automated. Each of these types have there own advantages and disadvantages depending on the approach taken by hydrologists and hydrogeologists (e.g. considering physical parameters of drainage areas or pure analysis of the hydrograph), consistency of methodologies, ease and cost of use. None of the techniques are totally reliable. For this reason a number of methods need to be used in order to calibrate the partitioning of streamflow. A description of these types of separations are described below and summarized in **Tables 1** and **2** in order to select the most suitable separation techniques for this study.

Table 1. Different types of hydrograph separation techniques.

Type	Method	Descritption	Advantages	Disadvantages
Analytical	Mathematical algorithms Barnes (1939), Coutagne (1948), Chapman (1963), Lyne and Hollick (1979), Boughton (1993), Jake and Hornberger (1993)	Storage-discharge relationships for catchment areas (described in Table 2).	Easily converted to computer algorithms. Use fundamental theories of surface water and groundwater flow.	Pure mathematical procedures are not reality due to simplification and large number of known and not known factors (Nejadhashema *et al*. 2003). Effect of antecedent hydrological conditions within watershed not accounted for leading to differences between observed and modelled components.
Graphical	Nash (1960), Gray (1973), Subramanya (1994)	Methods involve drawing a line from the starting point of the rising limb on the total hydrograph to point on the recession limb.	Produces consistent results	Baseflow separated in an arbitrary fashion. Difficulty identifying end of direct runoff.
	USDA-ARS (1973) semi-analytical	Assumes that groundwater reservoir acts as a single linear reservoir during recharge and recession. Three equations developed for rising limb, crest and recession limb segments of the unit hydrograph, based during flow rates at those intervals.	Produces consistent results	Same disadvantages as analytical techniques.
	Nazeer (1989) semi-analytical	Firstly, any baseflow separation technique is used to draw an approximate baseflow curve. Then, an equation is used to determine a shape factor which is procedurally used to derive a new baseflow curve	Produces consistent results	Difficulty identifying end of direct runoff. Same disadvantages as analytical techniques.
Geochemical	Walling *et al*. (1975), Sklash and Farvolden (1979)	Use of chemical characteristics such as conservative natural isotopes and chemical tracers. Requires long-term sampling from thesurface and subsurface flow in different seasons during wet and dry years.	Discharge curves correlate well with response of flow components. Provide valuable information on the hydrological cycle.	Requires addition of many other types of measurements e.g. pH, turbidity and concentration of major ions (Winston and Criss, 2002). Can be effected by external water chemistry factors. Expensive.

Type	Method	Descritption	Advantages	Disadvantages
Automated	Wittenberg and Sivaplan (1999)	Model describes a non-linear storage-discharge relationship for baseflow.	Ability to imply and compare different approaches easily. Same advantages as all of the other techniques because of origin of methods used.	Suffer same disadvantages as all of the other techniques because of origin of methods used. Arbitrary, non-physical technique. Smootehed Minima Technique can lead to unusually high estimations of baseflow where turning points are close together (Nathan and McMahon, 1990).
	Mugo and Sharma (1999)	Uses recursive digital filter to separate streamflow into three components, purely by Fourier analysis of wavelets.		
	Boughton (1988)	Developed two automated models: difference between baseflow and total flow is surface flow comsidering increments of time; baseflow is a portion of total runoff and increases as total runoff increases.		
	Smootehed Minima Technique	Streamflow hydrograph is separated by using a simple smoothing rule. Minimum amount of 5 day non-overlapping data required. The timeseries of data are searched for values that are less than 0.9 times the two values of neighbouring measurements. This point is called a turning point. Turning points are connected to each other to draw the baseflow hydrograph.		
	WISKI Institute of Hydrology (1980)	Method 1. Uses the Smoothed Minima Technique.		
		Method 2. Manual baseflow line can be drawn considering a daily mean flow time series.		
		Method 3. Baseflow line drawn considering non-equidistant daily mean flow values i.e. do not need a continuous time series.		

Table 1 continued.

Table 2. Summary of analytical baseflow separation techniques.

Method	Equation	Components	Comments
Boussinesq (1877)	$Q(t) = Q(t_0).e^{-t/\tau} = Q(t_0)k^t$ Linear storage – discharge (S-D) relationship	$Q(t_0)$ and $Q(t)$ are flows at times 0 and t, and τ is the time for stored water to be fully discharged.	The Boussinesesq and Barnes methods provide reasonable approximations of baseflow in a stream from a confined aquifer or unconconfined aquifer well below the stream bed. (Werner and Sundquist, 1951). The Coutagne and Chapman methods are vertical plane analyses for the case where the stream bed intersects impermeable bedrock. The assumption for all of these equations is that groundwater storage is released as streamflow.
Barnes (1939)	$Q = S / \tau = a.S$ Linear S-D relationship	$a = 1 / \tau$. The constant 'a' depends on catchment properties which are primarily area, shape of catchment, pore volume and transmissivity.	
Coutagne (1948)	$Q = a.S^n$ Non-linear S-D relationship	'n' is a constant and varies between 0 and 1	
Chapman (1963)	$Q = a.S^2$ Non-linear S-D relationship		
Boughton (1995)	$Q(t) + q = [Q(t_0) + q].e^{-t/\tau*}$ where $q = S_d / [\tau s + \tau d]$ and $\tau* = \tau_{s.}\tau_d / [\tau_s + \tau_d]$ Non-linear S-D relationship	S_s and S_d refer to shallow and deep storage, q is the loss of flow from evapo-transpiration. The suffxes s and d refer to shallow and deep.	The Boughton equation is a model for leaky catchments i.e. catchments where the deep groundwater storage component feeding the stream overlies a storage with outflow outside the catchment. It is a recession equation that states that under the conditions of $Q(t) = Q_s$, that the upper storage Ss > 0 and that the lower storage S_d is constant while there is baseflow.

Lyne and Hollick (1979)	$Q_b(i) = k.Q_b(i-1) + (1-k).Q_d(i)$ and $Q_b(i) = [k / (2-k)].Q_b[i-1] + [(1-k)/(2-k)].Q(i)$ 'One-parameter' baseflow separation algorithm	$Q_b(i)$ and $Q_d(i)$ are the baseflow and direct runoff at time interval i and k is a recession constant during periods of no direct runoff.	The separation of baseflow from a stream hydrograph begins with determining when streamflow from direct runoff starts and ends. The start point can be identified as the time when flow increases and the end point is the time at which the plot of 'logQ' against time becomes a straight line (Chapman, 1999). Once the end point has been determined a number of digital filter methods are available for streamflow partitioning. The digital filter methods presented have been generated by the mathematical assessment of observed and modelled streamflow that have been supplied during periods of direct runoff and recession periods. Lyne and Hollick (1979) were the first to use a digital filter. Their method indicates that baseflow will be constant when there is no direct runoff (Chapman and Maxwell, 1996).
Method	**Equation**	**Components**	**Comments**
Boughton (1993)	$Q_b(i) = [k / (1+C)].Q_b(i-1) + [C / (1+C].Q(i-1)$ 'Two-parameter' baseflow separation algorithm	C = 1-k	The Boughton (1993) algorithm includes an additional parameter , C = 1-k. This method is also known as the Australian Water Balance Model (AWBM). The Jake and Hornberger

Jakeman and Hornberger (1993)	$Q_b(i) = [k / (1+C)].Q_b(i-1) + [C / (1+C].[Q(i) + \alpha_q.Q(i-1)]$ where $Q_b(i) = \beta_s u(i) - \alpha_s Q_b(i-1)$ $Q_b(i) = \beta_q u(i) - \alpha_d Q_d(i-1)$ 'Three-parameter' baseflow separation algorithm (IHACRES)	'α' and 'β' are constants, 'u' is the effective rainfall, the suffixes 's' and 'd' refer to quick and slow flow respectively, and $Q_b(t)$ and $Q_d(t)$ and the baseflow and direct runoff at time t respectively.	(1993) algorithm partitions the effective rainfall into quick and slow components to determine the baseflow separation. The limitations with the one- and three-parameter algorithms is that they can generate sharp peaks on the hydrograph during recessions and that the baseflow component can intersect the total runoff component. The two-parameter algorithm is considered to be the most satisfactory streamflow separation method of the three algorithms, although the parameter selection is subjective (Chapman 1999). However, it is important to note that mathematical procedures are far from reality because of the complexity of catchments and the large number of known and unknown factors.

Table 2 continued.

2.2 Recession Curve Analysis

The period of the hydrograph showing a decreasing rate of total streamflow following a period of rain or snowmelt is known as a recession curve (also known as the 'recession limb'). Recession curve analysis is the study of the relationship between groundwater storage and the discharge to stream channels during dry periods i.e. no rainfall. The start of a recession can be identified as the inflexion point at which peak flow in a stream has been reached a maximum and is about to decline.

It is difficult to determine the point on the recession curve that defines when direct runoff ends and deep groundwater is the sole contribution to streamflow. There is no single method which identifies this point. Many graphical techniques for baseflow separation use Linsley's (1958) empirical equation:

$$N = A^{0.2},$$

where N is the time interval from peak of the hydrograph to end of direct runoff and A is the drainage area in square miles. An analytical approach is suggested by Chapman (1999) and considers that direct flow ends when a plot of log of the flow versus time becomes linear.

For periods of non-recharge, Boussinesq (1877) and Barnes (1939) described the relationship between groundwater storage and baseflow discharge as being linear (see **Table 2** for algorithms), assuming that all groundwaters are stored within the drainage area do not escape outside. Werner and Sundquist (1951) regarded their algorithms as providing a reasonable approximation of baseflow (contribution from all groundwaters) for confined aquifers or unconfined flow when the underlying impermeable layer is well below the stream bed. The linear storage-discharge relationship is related to the small variation in the flow depth from the drainage divide to the stream channel (**Figure 2a**).

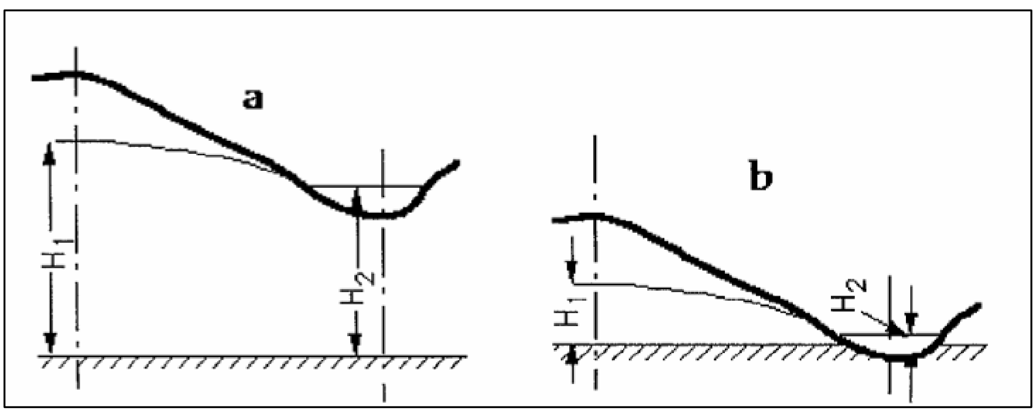

Figure 2. Schematic cross-sections from drainage divide to stream channel: (a) little variation in flow depth H; (b) significant variation in flow depth (Chapman 1999).

Coutagne (1948) and Chapman (1963) have demonstrated that for conditions of shallower bedrock, or where an impermeable layer intersects the stream channel, the storage-discharge relationship is non-linear (**Table 2**). This is because the relative change in the flow depth is relatively greater from the drainage divide to the stream channel (**Figure 2b**). Boughton (1995) further developed the analytical analysis of recession curves by considering the scenario where a shallow groundwater storage feeds a stream above a deep groundwater storage that has outflow outside the catchment (**Table 2**).

2.3 Graphical

Graphical methods for hydrograph separation are useful for partitioning baseflow from individual storm events as against continual records of data. The technique does not consider physical parameters within catchments and so is arbitrary in nature i.e. it is difficult to understand what the baseflow component represents. Two methods of graphical hydrograph separation are presented in **Figure 3** (Gray 1973, Subramanya 1994). For Gray's (1973) method a line is drawn backwards on the recession limb from the point at which direct runoff ends (point B, calculated using Linsley's method described above) until it reaches under the peak of the hydrograph, and is then connected to the event marking the beginning of surface water runoff (point A). Subramanya's (1994) method is applied in a similar fashion except that the line drawn backwards from the recession limb until it reaches the point of inflexion on the hydrograph.

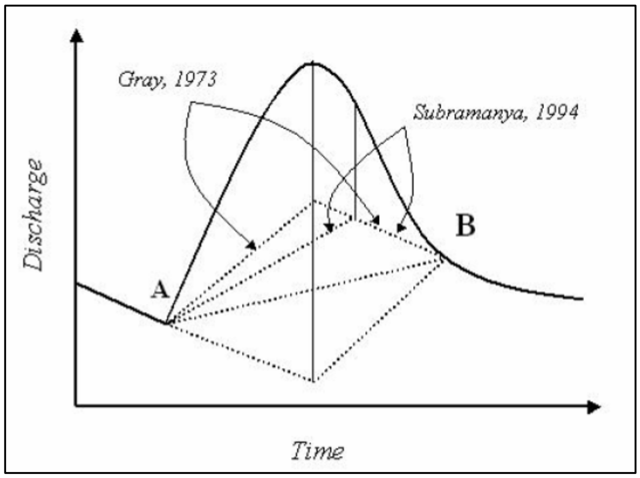

Figure 3. Exampkes of graphical baseflow separations by Gray (1973) and Subramanya (1994) (Nejadhashemi *et al.* 2003).

Graphical techniques that use analytical algorithms include one proposed by the United States Department of Agriculuture – Agricultural Research Service (USDA-ARS, 1973) and Nazeer (1989).

The USDA-ARS method uses a mass balance approach and assumes a two-component model (groundwater is a single component). Three equations are used to separate baseflow (as they define it) into periods of recharge of soil moisture, recharge of groundwater and recession. These periods correlate with the rising limb, crest segment and recession limb of the hydrograph, respectively. The equations used to describe the separation curve assume a linear storage-discharge relationship during recharge as well as recession.

In the first step of the technique by Nazeer (1989), any baseflow separation technique can be used to draw an approximation of the baseflow curve. In the second step, the shape factor of the baseflow curve is calculated (using an algorithm which is related to the time to peak streamflow). The shape of the approximated baseflow curve is procedurally altered until the shape factor correlates with the shape factor of the hydrograph curve.

2.4 Analytical methods

Chapman (1999) categorised the analytical approach to baseflow separation into three classes (one-, two- and three-parameter algorithms). Lyne and Hollick (1979) first introduced the one-parameter algorithm which uses a recession constant, 'k'. The results from using the algorithm indicate that the baseflow element in a stream will be constant when there is no direct runoff. The algorithm was simplified to its present form by Maxwell and Chapman (1996) (**Table 2**), the baseflow being a weighted average of the total streamflow and the baseflow at the previous time interval. Boughton's two-parameter algorithm is the same as the one-parameter algorithm, only 'C' is a second parameter which is equal to '1-k' (**Table 2**). It is also known as the Australian Water Balance Model (AWBM). The three-parameter algorithm (IHACRES) was introduced by Jakeman and Hornberger (1993) and was developed by distinguishing the components of rainfall that become "quick" and "slow" runoff (quick runoff: surface runoff; slow runoff: the sum of rapid subsurface, delayed subsurface, and groundwater runoffs). Rainfall is eliminated from the equations by expressing them in terms of total rainfall and baseflow (**Table 2**).

Baseflow separation techniques that use algorithms have the advantage that they can be translated into computer codes easily and they have a consistent approach when working with long continuous records of streamflow data. The disadvantage of using these methods is that even though the recession constants 'k' and 'C' are related to physical entities within the catchment, the choice of values when attempting a baseflow separation is very subjective. Expert judgement is required to decide that what is separated as baseflow from a hydrograph is comparable with the expected recharge of the substrate and bedrock geology of a catchment.

2.5 Master Recession Curve Analysis

Master Recession Curves (MRCs) can be used to estimate the recession constant 'k' for the analytical methods discussed above (Doctor and Alexander 2005, Fenicia 2005). 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) (**Figure 4**). The Matching Strip method involves plotting multiple recession curves derived from the hydrograph on the 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.

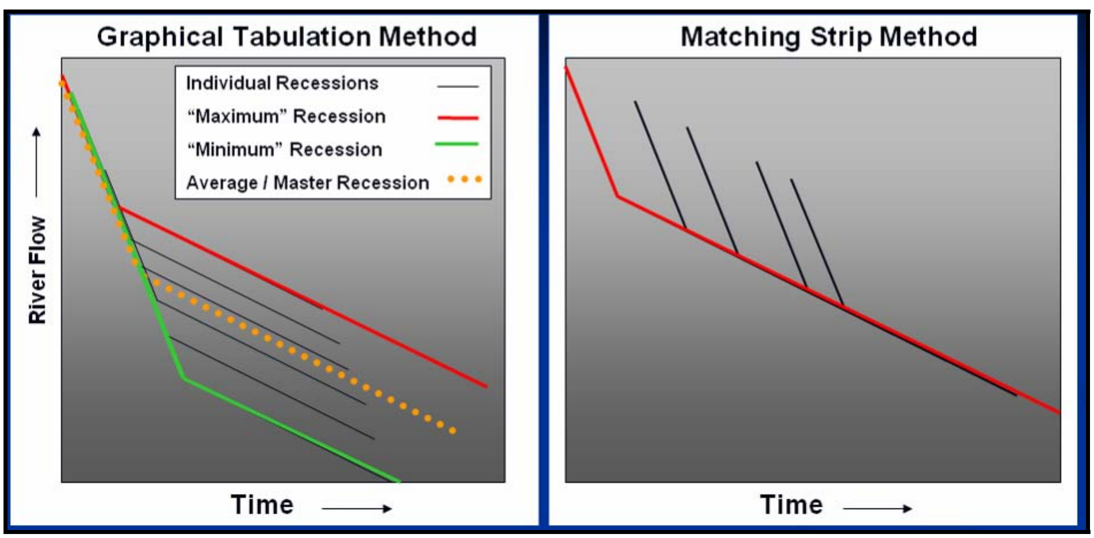

Figure 4. Two methods for constructing Master Recession Curve: Matching Strip and Tabulation methods (Sujono *et. al.* 2004).

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 overall starting value of the master recession is equal to the average of the segment values.

Once the Master Recession Curve has been constructed 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& Alexander 2005).

Thus the entire discharge time relationship of the recession is expressed as

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

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 a 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 each of the fitted exponential line 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 Baseflow Index.

2.6 Flood Studies Report Method

The Flood Studies Report (FSR) Method was published in 1975 and can be used to calculate the percentage of surface runoff from a hydrograph based on collated rainfall and flow data (NERC, 1975).

In this method the time lag between the centroid of an observed rainfall event and the peak flow is derived and the end point of the surface runoff is taken as four times this lag after the end of rainfall (**Figure 5**). In the case of multi-peaked flow events then the centroid of the flow peaks is used. The separation is derived manually and is done by continuing to draw the recession of the previous flow event until it is located beneath the peak flow of the event that is being focused on. A straight line is then drawn from beneath the peak flow to the point identified as the end of surface runoff. The surface runoff is the portion of flow above this separation.

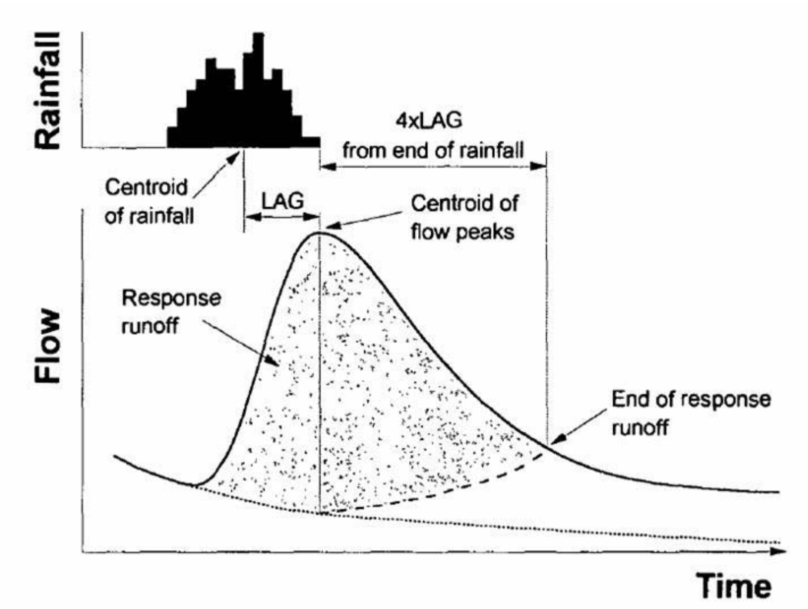

Figure 5. The Flood Study Report method of separation (NERC 1975).

The Flood Study found that this method was a robust procedure that could be reliably applied to individual events.

2.7 Unit hydrograph Separation

The Unit Hydrograph Model simulates runoff from single storm events and derives a resulting hydrograph from any amount of excess rainfall. It treats the rainfall as a pulse response within a linear hydrological system.

The basic assumptions that are used by the Unit Hydrograph Model include that:

(1) excess rainfall has a constant intensity for the effective duration;
(2) rainfall is distributed uniformly over a catchment;
(3) the time taken for surface runoff to occur from a unit of excess rainfall is constant;
(4) the principle of superposition applies to hydrographs resulting from continuous or isolated periods of excess rainfall;
(5) the physical characteristics of a catchment area remain constant.

Hydrological conditions within catchments are met by these assumptions in many cases although they may not be wholly correct.

The amount of excess rainfall from a rainfall event is calculated assuming that some of the rainfall infiltrates the subsurface. The amount of rainfall that infiltrates the subsurface can be calculated by either considering it to be a fixed initial and constant loss, a proportional loss or calculated by using a method developed by the U.S. Soil Conservation Service (SCS) (U.S. SCS 1972).

The fixed and constant loss model dictates that there is no overland flow from rainfall until an initial loss demand is met by infiltration. Once the specified constant infiltration rate is exceeded then there is excess rainfall. The equation for this model, assuming that a specified constant loss rate is exceeded, is given by:

$$P_{excess} = A_f \,.\, P \,.\, I_c,$$

where P_{excess} is the excess rainfall (direct runoff mm/hr), A_f is an aerial adjustment factor, P is the rate of rainfall (mm/hr), and I_c is a user defined constant loss rate (mm/hr).

The proportional loss model considers that the infiltration of rain into the subsurface is proportional to rate of rainfall. The equation for this model is given by:

$$P_{excess} = a \,.\, A_f \,.\, P,$$

where P_{excess} is the excess rainfall (direct runoff mm/hr), a is a constant and can vary between 0 and 1, A_f is an aerial adjustment factor and P is the rate of rainfall (mm/hr).

The SCS model for loss states that the depth of direct runoff (excess rainfall P_{excess}) is always less or equal to the depth of precipitated rainfall (P). Also, after runoff begins, the additional depth of water retained in the subsurface, Fa, is less than or equal to the potential maximum depth of storage, S. There is also some amount of the rainfall will pond (a depth Ia) and for which no runoff will occur. So the maximum potential runoff is equal to 'P – Ia'.

The SCS hypothesis considers that the ratios of the actual surface and subsurface quantities of water from rainfall compared to their maximum potential quantities are equal:

$$Fa / S = P_{excess} / P - Ia$$

Since '$P = P_{excess} + Ia + Fa$' then the basic equation to calculate direct runoff from rainfall is:

$$P_{excess} = (P - Ia)^2 / (P - Ia + S)$$

The U.S. SCS developed an empirical relation that for many small catchments:

$$Ia = 0.2S$$

Consequently, by combing the above equations the depth of direct runoff can be expressed in terms of the depth of rainfall and storage of the subsurface:

$$P_{excess} = (P - 0.2S)^2 / (P + 0.8S).$$

The Unit Hydrograph is characterised by the duration of unit rainfall (tr) resulting in a hydrograph and the lag time (Tlag), which is defined as the difference between the centre of the unit rainfall and the peak runoff (**Figure 6**). The time to peak runoff (Tp) is expressed as:

$$Tp = (tr / 2) + Tlag.$$

Synthetic hydrographs that use the Unit Hydrograph method are the SCS triangular UH and the SCS dimensionless hydrograph (**Figure 6**). The lag time (tl) can be calculated from catchment area statistics. The standard SCS formula is:

$$Tlag = ((L \,.\, 3.28 \,.\, 10^3)^{0.8} \,.\, (1000 / (CN - 9))^{0.7}) / (1900 \,.\, Y)^{0.5}$$

where Tlag is lag time in hours, L is the hydraulic length of the catchment in km, CN is the SCS curve number (a constant), and Y is the average slope of the catchment as a percentage.

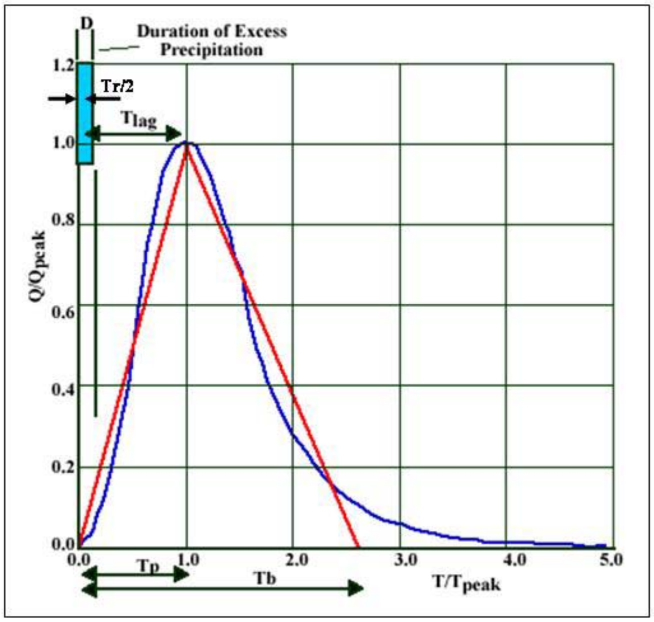

Figure 6. Soil Conservation Service Synthetic Hydrographs: dimensionless hydrograph (blue curve); triangular hydrograph (red curve).

By considering single storm events, the unit hydrograph model can be used to filter the element of surface runoff from streamflow recorded on a hydrograph.

2.8 Automated

In 1980, the Institute of Hydrology developed the Smoothed Minima Technique. The technique uses stream gauge measurements for five day non overlapping periods. The first step of the model is to select the first three groups of five days (days one to fifteen) and calculate the lowest flow value from each of them. If the low flow value of the middle group is less than 0.9 of the two neighbouring low flow values, what is termed a turning point is plotted. The automated model rolls onto the next five day groups (days six to twenty) and follows the same procedure, and so on. By connecting the turning points together a baseflow curve is generated. Three points to note for this method are that: (1) the physical parameters of the catchment area are not considered; (2) the closeness of turning points can lead to higher estimations of baseflow compared to total streamflow; (3) it is sensitive as to where in the timeseries data the model is run.

WISKI is a time series hydrological management package that uses the Smoothed Minima Technique as its standard method. Two other methods are also available with the WISKI package. They allow the user to manually draw a baseflow curve using: (1) a middle group continual daily mean flow time series; (2) a daily mean flow time series that is irregular.

Boughton (1988) developed two automated methods which use simple techniques. The first method (Method 1) assumes that the change in baseflow (including all groundwater components) is constant over equal time increments from the beginning of rainfall in a catchment until the end of surface water runoff. Consequently, the method draws a linear baseflow curve under a hydrograph curve until it reaches the time that surface water runoff ceases i.e. this is a two component model that uses the assumption that all groundwaters are baseflow.

Boughton's second method (Method 2) is also a two-component model and assumes that from the beginning of rainfall in a catchment until the end of surface water runoff the component of baseflow on a hydrograph is a fraction of the total flow at the previous time step, i.e the fraction is the baseflow index (BFI). The value of BFI remains constant for the timeseries dataset and its value is estimated by considering the volume of streamflow at the end of surface water runoff events.

The recursive digital filter is a conceptual technique that separates flow into three components by using a computer program to analyse the response on a hydrograph from streamflow (e.g. Nathan and McMahon 1990, Mugo and Sharma 1999). A schematic representation of the concept is presented in **Figure 7**. Any hydrograph response can be separated into a number of high and low frequency wavelets (by Fourier Analysis). The 'baseflow runoff filter' distinguishes the lower frequency wavelets (considered to represent baseflow) from the higher frequency wavelets (direct runoff – surface runoff and interflow). The 'direct runoff filter' distinguishes the highest frequency wavelets (surface runoff) from those wavelets that have passed through the 'baseflow runoff filter'.

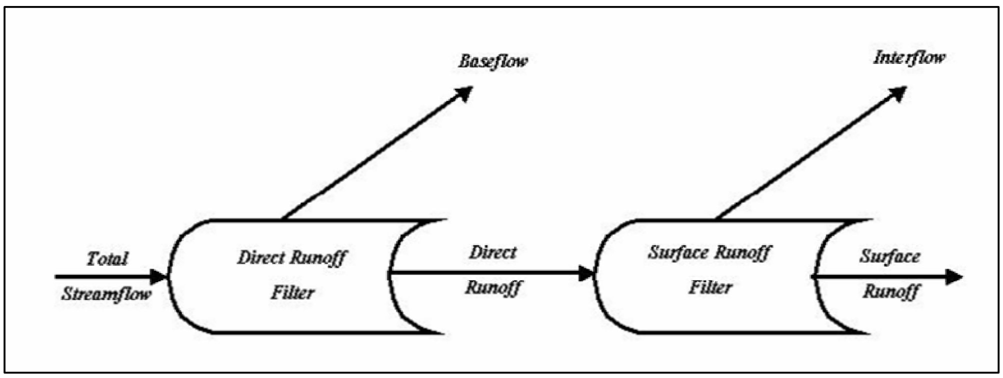

Figure 7. Schematic representation of Nathan and McMahon's automated digital filter method (Nejadhashemi *et al.* 2003).

The 'baseflow runoff filter' uses a linear algorithm and takes the form:

$$f_k = \alpha . f_{k-1} + [(1+ \alpha) / 2] . [y_k - y_{k-1}], \text{ where}$$

f_k is the filtrated quick response at k^{th} sampling instant, y_k is the original streamflow, α is a constant and $y_k - f_k$ is the filtrated baseflow. The filter is applied by repetitively passing the hydrograph response through the filter which attentuates it, narrowing the response and separating the lower frequency element. An important part of the use of the digital filter technique is that it is calibrated using graphical methods.

The method considers purely the response of the hydrograph and not any of the physical parameters of a studied river system, which is a disadvantage. It has been compared to other empirical methods (Nathan and McMahon 1990) and is considered to give more detailed results than the 'Smoothed Minima Technique' when simulating large catchments with relatively flashy peak conditions. However, it has been found to be less suitable when considering catchments that have long lag times (greater than 24 hours).

The Wittenberg and Sivaplan automated method was proposed by Wittenberg (1999) and Wittenberg and Sivapalan (1999). These authors describe a non linear storage-baseflow relationship to derive a recession curve:

$$Q_{t-\Delta t} = [Q_t^{1-b} + [t.(b-1) / a.b] . t]^{1/(b-1)},$$

where '$Q_{t'}$' is the baseflow discharge at time t, 'Q'_0' in the initial discharge value, 'a' depends on catchment properties (primarily area, shape of the basin, pore volume and transmissivity), and 'b' varies between 0 and 1. An iterative least squares method is applied to calibrate both 'a' and 'b' for each series of flow recession data. The parameters 'a' and 'b' are altered until the equation describes a curve that fits the baseflow portion of the measured hydrograph curve (on the recession limb). The automated model then works backwards through the timeseries of flow data from the recession limb to generate a baseflow curve i.e. if Q_t is known then $Q_{t-\Delta t}$ can be determined.

2.9 Geochemical

One widely employed separation method involves identifying different chemical components (natural isotopes and/or chemical tracers), before, during and after rainfall events.

Many tracer based separation techniques have demonstrated that groundwater stored before a rainfall event is a major contributor to streamflow during and shortly after a rainfall event, for a variety of different geological settings (Fritz *et al.* 1976, Turner *et al.* 1991, Sklash 1990, Jones *et al.* 2005). Consequently, these techniques attempt to separate surface runoff from pre-rainfall event (pre-event) components in the un-saturated and saturated zones that contribute to streamflow. This is done by estimating the changing proportions of chemically dilute rainfall compared to more enriched pre-event waters. If there is no chemical or isotopic contrast between the rainfall and the pre-event groundwater, then a hydrograph separation using geochemical models is not possible.

Many of the hydrograph separation models use a mass balance approach to separate flow into two-, three- or more components. Early studies were based on the assumption that only two major components contribute to streamflow (Fritz *et al.* 1976): the groundwater (termed baseflow at the time) and surface water runoff including flow in the permeable upper few centimeters of the soil (termed storm runoff). Hinton (1994) recognized there was more than one subsurface component.

The three-component model can be written as:

$$Q_t = Q_p + Q_u + Q_s,$$

where Q is discharge, C is concentration, and the subscripts 't', 'p', 'u' and 's' refers to total measured streamflow, the surface runoff component, the pre-event unsaturated zone portion and pre-event saturated zone portion, respectively (Jones *et al.* 2005). If the initial concentrations of a tracer originating from precipitation, the unsaturated and saturated zones (C_{pi}, C_{ui}, and C_{si}) are known and their values are measured over time in the stream (C_{ti}) then the following tracer mass balance equation can be used to estimate the unknown source zone contributions (Q_p, Q_u, Q_s) to the total discharge (Q_t):

$$C_{ti}.Q_t = C_{pi}.Q_p + C_{ui}.Q_u + C_{si}.Q_s.$$

The value Q is assumed to be discharge driven by a hydraulic gradient such as Darcian-type subsurface flow. The hydraulically driven estimate of discharge is calculated by eliminating the effects of dispersion driven by concentration.

The components of water chemistry can change due to variety of different physical characteristics of a catchment area e.g. geomorphology of the area, intensity of rainfall, water temperature, soil composition and depth, pathways by which water contributes to stream. For this reason the technique requires long-term sampling and should be combined with the analysis of other parameters such as conductivity, pH, turbidity and the concentration of major ions to make final conclusions (Winston 2002).

2.10 Comparison of models

Chapman (1999) compared estimated BFI values from the three analytical digital filter techniques described above ('one-', 'two-' and 'three-parameter' algorithms, Table 2) the for thirteen catchments within Queensland and New South Wales, Australia, with eight to sixteen years worth of daily mean flow records. There were large differences in the estimated BFIs between the different methods. There was a similarity in the range of BFI values between the 'one-' and 'two-parameter' algorithms, but not between the 'three-parameter' algorithm and the others. Expert judgement on some of the separations suggests that the 'one-parameter' algorithm can result in unrealistically low BFI values. In contrast, expert judgement of the 'three-parameter' algorithm suggests that it can give unrealistically high BFI values (the baseflow curve can be higher than the total runoff curve and has unrealistic sharp peaks). The Boughton 'two-parameter' algorithm is considered to give the most reliable analytical baseflow separations from total streamflow hydrographs (Chapman 1999).

Nejadhashemi *et al*. (2004) tested the automated methods against twelve years of separately-measured surface runoff and baseflow data from a small catchment area (0.34 ha) in the southern US Coastal Plain physiographic region of the southern United States. Statistical analysis demonstrated that the average baseflow and surface flow estimation from Boughton's Method 1 consistently produced the best predictive results when compared to observed data. It was also among the easier methods to use for incorporation into large-scale natural resource and environmental models. Nejadhashemi *et al*. (2004) further considers that the use of this method could be improved by relating the slope of the baseflow curve to physical and hydrological conditions of catchment areas.

Nejadhashemi *et al*. (2003) have evaluated most of the streamflow partitioning techniques described above. The authors conclude that graphical methods use an arbitrary approach to hydrograph separations and should only be used to roughly estimate the contributions to streamflow. The authors also consider that geochemical methods are one of the most powerful techniques and that they can help develop a strong understanding of the groundwater and surface water flow mechanisms. However, they are expensive and highly dependent on external factors that affect water chemistry components. The authors also consider analytical techniques are reliable because they use fundamental theories of surface water and groundwater flow and can be easily translated to computer algorithms, even though pure mathematical procedures are far from reality.

2.11 Selected methods

The components of streamflow in the surface water-groundwater interaction study's conceptual model that can be identified, using the techniques of streamflow separation that are available, are overland flow and deep groundwater flow. One of the largest challenges for the hydrograph separation methods outlined is that without real measured data, the true nature of the different components is inherently arbitrary in nature. Consequently, the chosen technique needs to be flexible enough to allow for expert judgement to be considered. Also, many years worth of flow data is available for this study and so methods that manually assess individual storm events (e.g. many of the graphical methods) are not suitable. The use of geochemical methods is not possible because there is a lack of understanding of the water chemistry in our selected catchments, although surface water physical-chemistry data is available. For the reasons stated, the techniques of hydrograph separation that have been chosen for this study include:

(1) Boughton's 'two-parameter' algorithm method to separate deep groundwater component, using Master Recession Curves to estimate the volume of the storage zone; and
(2) the Unit Hydrograph Separation method to separate the overland flow component, using the Flood Studies Report method to calculate the time lag between the centroid of an observed rainfall event and peak flow.

These methods of hydrograph separation will allow the components of overland flow, intermediate flow and deep groundwater flow to be quantified.

3 Rainfall-Runoff Modelling

3.1 Overview

In general there are two types of numerical modeling techniques: 'stioichistic' that use statistical measurements and 'physical' that are based on representing actual physical processes. Physical models can be further subdivided into conceptual models and distributed models (finite element models). The finite element models are data intensive whereas the 'conceptual models are lumped conceptual models i.e. a catchment is considered to have overall average values for physical characteristics. Lumped conceptual models have the advantage that they have relatively low data requirements. NAM is a lumped conceptual rainfall-runoff model that has been used for Northern Ireland and is considered to be reliable (DHI 2000).

3.2 MIKE 11 Rainfall-Runoff Framework

The MIKE 11 Rainfall-Runoff model (DHI 2000) uses a conceptual representation of the hydrological cycle (**Figure 8**) 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 and Flood Studies Report methodologies and the model's baseflow component to deep groundwater flow by the Master Recession Curve analysis and bedrock aquifer transmissivity calculations.

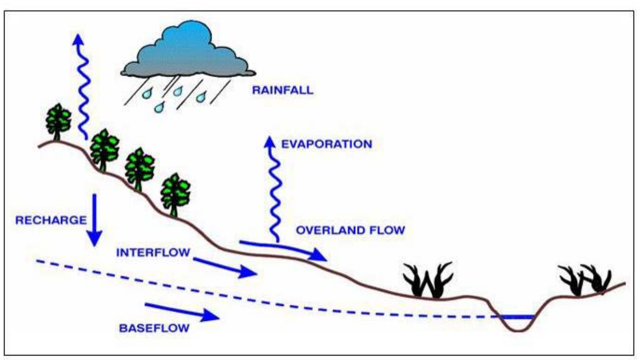

Figure 8. The conceptual representation of the hydrological cycle (DHI 2000). The catchment runoff is separated into what the model terms overland flow, interflow and baseflow.

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 snow melt is to be considered.

3.3 NAM concept and parameters

The NAM rainfall runoff is a module of DHIs MIKE 11 modelling suite (DHI 2000) and is a deterministic conceptual lumped sum model. The model continuously accounts for water in three interconnected storage zones: surface, lower zone and groundwater storages (Figure 2). The water discharged from the model is released through three linear reservoirs, which has been constrained by the hydrograph separation techniques and transmissivity calculations to overland, intermediate and deep groundwater flow.

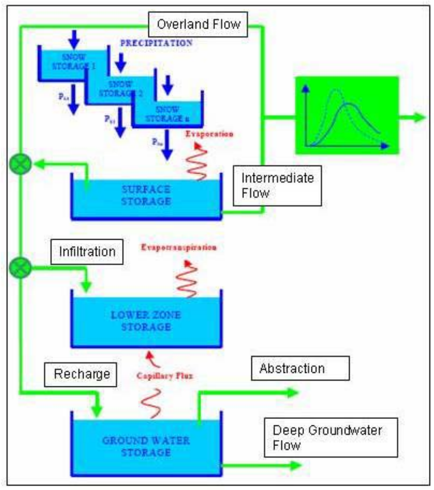

Figure 9. The inter-relationship of the storage zones that are considered by the MIKE 11 NAM model.

The key part of the modelling system 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 the 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 is released with an independent time constant.

The NAM model has nine catchment parameters (seven surface water and two groundwater parameters) that can be adjusted to control the contributions of flow:

(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 storage (L_{MAX}) – affects overland flow, recharge, amounts of evapotranspiration and intermediate flow;
(3) overland flow coefficient (CQOF) – affects the volume of overland flow and recharge;
(4) intermediate flow drainage constant (CKIF) – affects the amount of drainage from the surface storage zone as intermediate flow;
(5) overland flow threshold (TOF) – affects the soil moisture content that must be satisfied for quick flow to occur;
(6) intermediate flow threshold (TIF) - 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 (TG) - affects the soil moisture content that must be satisfied for groundwater recharge to occur;
(9) time constant for deep groundwater flow (CKBF) - affects the routing of groundwater recharge in the regional aquifers.

There isan option in the NAM model to split the groundwater storage zone (upper and lower groundwater storages). This option was used for the Bride, Boro and Deel catchments because the NAM model overpredicted the deep groundwater contribution. Two further parameters were required for these catchments.

(10) recharge to the lower groundwater storage zone (CQLOW);
(11) time constant for routing a lower groundwater storage flow (CKBF2, which is the time constant for routing deep groundwater flow).

The lower groundwater storage zone contributes to deep groundwater flow in the instance of the groundwater zone being split. The contribution from the upper groundwater storage zone is part of intermediate flow and is probably related to slow flow from low permeability subsoils, and/or top of the bedrock aquifer shallow groundwater.

3.4 Conclusions

The NAM model is a capable of estimating three components of water contributing to streamflow: surface runoff, intermediate flow and deep groundwater flow. The results of the Master Recession Curve Analysis and Unit Hydrograph Method analysis will be used to calibrate the NAM model.

For the surface water - groundwater interaction study there are recorded timeseries of streamflow for a selection of catchments, and it would be advantageous to be able to establish relationships between physical catchment attributes and runoff model parameters in order to model ungauged stations.

4 Recharge Estimates in Ireland

4.1 Introduction

Previous recharge estimates in Ireland have been based on soil moisture defecit calculations and river baseflow separations (Misstear 2000). They have mainly focused on the influence of glacial tills (which cover approximately 55% of the country) above regionally important aquifers. Consequently, there is little understood of the flow mechanisms of groundwaters in poorly productive aquifers. Below is a consideration of recharge estimates that have been documented for Ireland.

4.2 Estimations of recharge through tills

Fitzsimons and Misstear (2005) have tabulated previous recharge and baseflow studies for Ireland, Northern Ireland and the UK, in which aquifers are overlain by glacial tills (**Table 3**). The authors table has been edited in this document to include the ERTDI study being undertaken by Misstear *et al.* (2006).

Table 3. Selected examples of previous recharge and baseflow studies in aquifers overlain by glacial tills (edited Fitzsimons and Misstear 2006[9]).

Authors	Recharge estimation method and location	Description of bedrock aquifer	Description of till	Actual recharge (mm/yr)	BFI[10] or recharge co-efficient
Examples of studies where tills are assumed to be thick or low permeability[11]					
McConville and Kalin (1999)	Field measurement using environmental tracers	Triassic sandstone	> 1.5m thick. Surface water gley soils overlie tills[12]	22	4%
Soley and Heathcote (1998)	Numerical modeling on a catchment in the U.K.	Cretaceous chalk and Quaternary gravel	Silty clay till[3] up to 60m thick	10 to 36	5 to 20%
Daly (1994)	Baseflows and monthly soil moisture budgets within the Nore catchment (2,388 km^2)	Carboniferous limestone / dolomite Devonian sandstone	Thick till or gley soils[3]	-	30%
MacCarthaigh (1994)	Baseflow analyses within the Monaghan Blackwater catchment (126 km^2)	Fissured and karstified Carboniferous limestone	Thick, moderate to low permeability subsoils[13]	-	27%
Jackson and Rushton (1987)	Numerical modeling on a catchment in the U.K.	Cretaceous chalk	'Boulder Clay' > 10m thick Permeability > $1.2*10^{-9}$ m/s[5]	24	13%[h]
Senerath and Rushton (1984)	Routing model for river flow prediction on a catchment in the U.K.	Cretaceous chalk and Quaternary gravel	'Boulder Clay' Permeability > $1.2*10^{-8}$ m/s to $1.2*10^{-11}$ m/s[14]	-	10 to 17%
Misstear *et al.* (2006)	Baseflow separations, Nore catchment at Bennettsbridge	Carboniferous limestone / dolomite Devonian sandstone	Thick till or gley soils[3]	138 to 184	30 to 40%
Misstear *et al.* (2005)	Baseflow separations, uplands of NW County Monaghan, Tydavnet catchment	Carboniferous limestone	Low permeability subsoils	<24	12 to 16%
Examples of studies where tills are assumed to be thin or permeable					
Daly (1994)	Baseflows and monthly soil moisture budgets within the Nore catchment (2,388 km^2)	Fissured and karstified Carboniferous limestone	Thin tills	-	60%
		Karstified Carboniferous limestone	Thin tills	-	90%
Soley and Heathcote (1998)	Numerical modeling on a catchment in the U.K.	Cretaceous chalk and Quaternary gravel	Silty clay till[3] up to 60m thick	160	88%
Brown (Pers Comm., 2006)	Catchment water balance, groundwater hydrograph analysis	Quaternary gravel	Thin tills	280-310	87 to 94%

[9] Table used courtesy of Fitzsimons and Misstear (2006) and edited to include research by Misstear *et al.* (2006).
[10] Baseflow index.
[11] The authors provide an estimate of actual recharge but no specific estimate of effective precipitation.
[12] No specific permeability information provided by the authors. However, in Ireland, these soil and till descriptions are typically associated with low permeability parent material (Lee 1999).
[13] Description taken from Geological Survey mapping (Swartz and Daly 2002).
[14] Using the classification scheme proposed by Swartz *et al.* (2003), this recharge rate would be classed as "low" permeability.

The Nore Basin (2,388km^2) encompasses a range of hydrogeological environments in both upland and lowland settings. Daly (1994) considered that the basin is representative of the hydrology of the southeast. All aquifer classes are represented, and many of the rock unit groups occurring in Ireland are found within the basin.

The Quaternary geology is diverse, with subsoils ranging from gravels to peats. Quaternary deposits are generally less than 10m thick, and very thin or absent on elevated ground. There are over ten 'relatively large' deposits where thicknesses are greater than 10m, and can often exceed 20m. These thicker deposits tend to be dominated by sands/gravels.

Most of the bedrock topography and drainage system developed during the Tertiary. This topography was subsequently modified by at least two glacial episodes. The depth and degree of karstification is largely determined by the older drainage systems, and the length of time that deep groundwater circulation could have operated below the current base level. Most karstification probably took place in the late Tertiary, with more occurring during the last two glacial episodes.

Daly (1994) used graphical baseflow separation techniques to quantify the main components of the hydrologic cycle in the river basin, and to calculate the groundwater resources in each aquifer in the Nore basin. The author estimated infiltration coefficients of 30% for thick tills or gley soils, 60% for thin permeable tills and 90% for thin tills overlying karstified limestones.

Baseflow separations were undertaken by MacCarthaigh (1994) for the Blackwater catchment area in Monaghan. The catchment area is dominated by thick, moderate to low permeability tills. The author estimated the infiltration coefficient through the tills to be 27%, which is consistent with the estimates of Daly (1994).

McConville and Kalin (1999) undertook a tracer study involving O^{18} isotopes for the Enler catchment area, County Down in Northern Ireland. The authors used δO^{18} profiles to estimate the recharge rate of soil types. The recharge rates were area averaged according to the percentage of soil types over the entire catchment area to estimate an average recharge rate for the Enler catchment. Triassic sandstones are the main bedrock unit in the catchment. Results were presented for tills overlain by gley soils (recharge rate = 22mm/yr) and brown earth soils (recharge rate = 60mm/yr). It was inferred by Fitzsimons and Misstear (2005) that the potential recharge for the catchment area lies between 380mm/yr and 600mm/yr, suggesting that the BFI was 4% to 6% for tills overlain by gley soils and 10% to 15% for tills overlain by brown earth soils.

Mistear and Brown (2007[1]) have estimated recharge coeficients for four hydrogeological scenarios in Ireland to study different subsoil characteristics (**Table 4**). They used a variety of techniques depending on the availability of data and site suitability. These included soil moisture balance, catchment water balance, water level hydrograph analysis. The river baseflow separations were undertaken using the Boughton 'two parameter algorithm'.

The recharge coefficients they obtained are:

(1) the Curragh Aquifer (gravel), Kildare. The gravel aquifer is overlain by tills with a maximum thickness of 60m. The estimate of recharge through the tills is 81% to 85%.
(2) a catchment in the Nore Basin (a catchment with its outflow at Bennettsbridge, 1,605km2). The estimate of recharge through the moderate permeability tills within the Callan-Bennetsbridge lowlands was 41% to 54%, (or 36% to 60% for the entire subcatchment areas, including high, moderate and low permeability tills). Theestimates of recharge through the low permeability tills is consistent with the findings of Daly (1994).
(3) the Galmoy area. The estimate of recharge was 55% to 65% for the moderate permeability subsoils.
(4) The Knocktallon Aquifer in the NW of County Monaghan. The estimate of recharge through low permeability subsoils is less than 17% (and probably less than 5%).

Table 4. Summary table of the main project results from the Recharge and groundwater vulnerability, Project 2002-W-MS16, ERTDI Programme 2000-2006, Phase 3 Water Framework Directive (Misstear and Brown, 2007[2]).

Study area	Main aquifer, subsoil and topographic setting	Methodology	Recharge Coefficient
Curragh Aquifer County Kildare	Regionally important gravel aquifer. Thin (<3m), moderate to low permeability till cover; high vulnerability. Lowland setting.	Soil moisture budget (SMB), hydrograph analysis, numerical modelling, natural tracers and catchment water balance	81-85%
Bennettsbridge lowlands	Two subcatchments studied. Mixed aquifer, including regionally important limestone. Variable thickness of moderate permeability till and high permeability gravel cover. Mainly lowland topography.	SMB, baseflow analysis	41-54% (for Mod perm. subsoils) [36-60% for entire subcatchments]
Galmoy Mine, County Kilkenny	Regionally important limestone aquifer. Till cover generally 5-10m thick and of moderate to high permeability. Lowland setting	SMB, natural tracers and water balance using dewatering discharges	55-65%
Knockatallon Aquifer County Monaghan	Locally important aquifer. Thick, low permeability till cover. Upland and lowland topography	SMB, dewatering discharges, baseflow analysis and natural tracers	<17% (and probably <5%)

The paper by Fitzsimons and Misstear (2006) includes the estimated infiltration coefficients for studies from catchment areas in the UK. The estimations of infiltration coefficients from studies by Senerath and Rushton (1984), Jackson and Rushton (1987) and Soley and Heathcote (1998), compare well with the estimations from Irish studies (**Table 4**).

Fitzsimons and Misstear (2006) highlighted the parameters that influence recharge in the Nore Basin. These include soil moisture budgeting parameters (root constant and soil moisture budgeting time-step) and the physical parameters of tills (thickness, permeability). Using the Penman-Grindley and Aslyng models to calculate actual evapotranspiration from meteorological data from Kilkenny for 1994 to 1998, the variation in recharge from the baseline value was 121% to 91% for pasturelands. However, by just considering grasslands (64% of vegetation across Ireland) and discounting rough grazing land use and woodlands this variation was 101% to 95%. The authors concluded that the soil moisture parameters do not have major affect on the recharge of tills in Ireland because of the wet climate and the dominance of grassland. The permeability of tills has the most influence on recharge of aquifers, as well as till thickness.

Misstear and Fitzsimons (2007) have considered the sensitivity of baseflow estimates where there is a lack of understanding of the conceptual model of the groundwater system. The authors used the Institute of Hydrology's automated Smoothed Minima technique to undertake baseflow separations for three catchments: the Scart, the Dinin and a hybrid catchment along the Nore River, derived from upstream and downstream gauges (**Figure 10**). They represent a range of hydrogeological regimes, from locally important fractured sandstones overlain by thin glacial deposits, to locally important fractured sandstones overlain by valley gravels and low permeability glacial deposits, to regionally mportant karst limestone and dolomite aquifers overlain by valley gravels and moderately permeable glacial deposits.

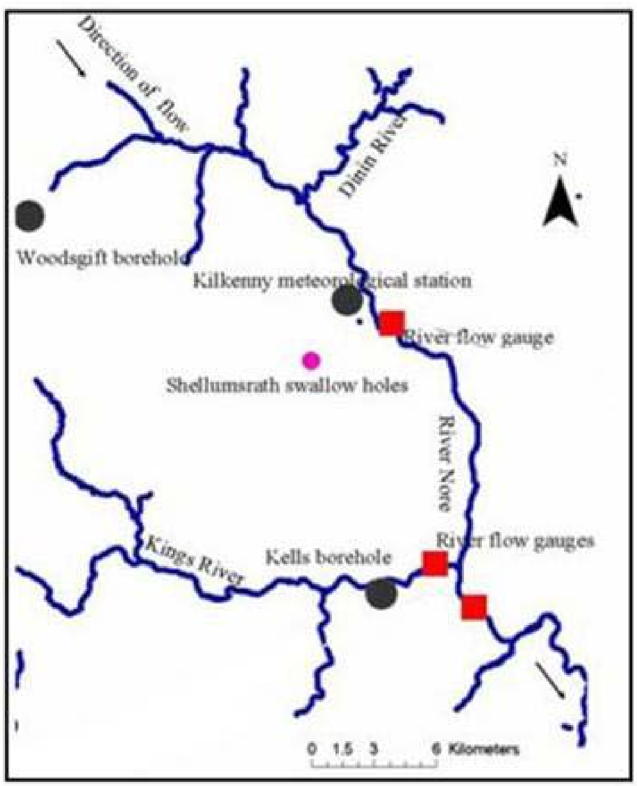

Figure 10. Nore River catchment between upstream and downstream gauges.(Misstear and Fitzsimons 2007).

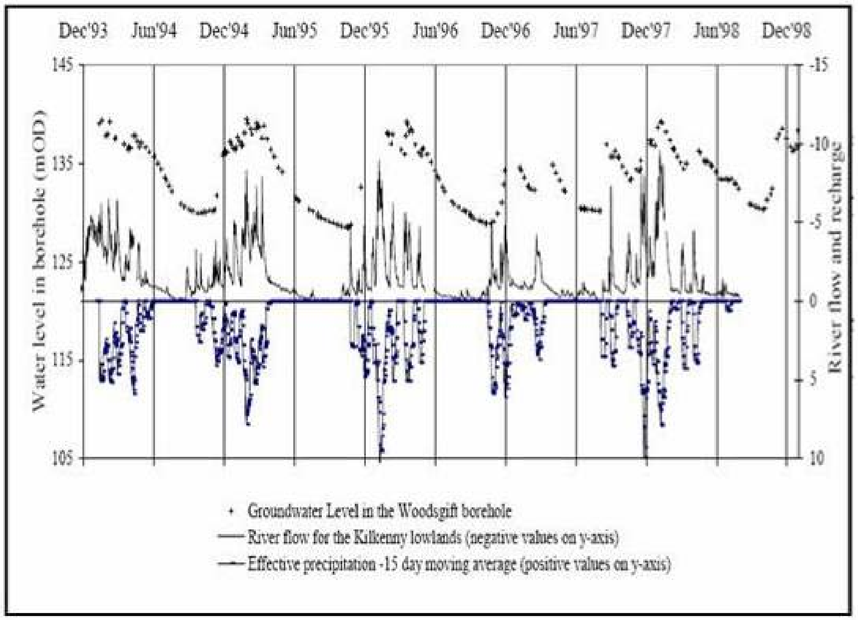

Figure 11. A comparison between the upstream and downstream gauges of the response of surface water and groundwater to effective precipitation .(Misstear and Fitzsimons 2007).

The five days overlapping period in the Smoothed Minima Technique represents the time interval from the peak in a hydrograph to the end of direct flow (known as the time base) in the model. The authors did not use the standard five days overlapping period. Misstear and Fitzsimons (2007) calculated the actual time base (N) using Linsley's equation: $N = A^{0.2}$ (1958) (p. 9), where A is the catchment area. To assess the sensitivity of the automated technique they allowed the time base to vary up to two days.

Table 5. Examples of the sensitivity of groundwater baseflow to the time base parameter (Misstear and Fitzsimons 2007).

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

[1]Note: Baseflow index (BFI) is the ratio of average annual baseflow to average annual runoff. Baseflow was estimated by the IOH method (IOH, 1989).

During storm events the response of river flow and groundwater levels can be similar to the effective precipitation (Figure 11**). For the Kilkenny catchment a suitable borehole hydrograph was used to judge the suitability of various time bases. The results of the sensitivity analysis (**Table 5**) suggest that even when one technique is used to undertake baseflow separation that there can be a significant variation in predicted baseflow indices. The authors do qualify that the baseflow index estimates attained from this technique are higher than those values expected for the catchments.**

4.3 Article V Characterisation Report

One of the assessments undertaken for the Article V 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 WFD 'Groundwater Working Group' in Ireland proposed infiltration coefficients that were used to estimate recharge of Irish bedrock aquifers nationally (**Table 6**) (WFD Groundwater Working Group, 2004). The dominant hydrogeological scenarios in Ireland were considered by combining the Geological Survey of Ireland's (GSI's) vulnerability and subsoil mapping with Teagasc's subsoil and soil mapping[15]. Teagasc's soil dataset was used to distinguish between 'poorly drained' and 'well drained' soils, and GSI's/Teagasc's subsoils mapping was used to distinguish between low, moderate and high permeability subsoils. The GSI's vulnerability of the bedrock aquifers is dependent on many factors including the permeability and thickness of the subsoil, the presence of an unsaturated zone, and the type of aquifer. The infiltration coefficients were based on expert guidance as well as previous baseflow separation studies such as Wright *et al.* (1982) and Daly (1994).

Table 6. Recharge Coefficients for different hydrogeological settings in the Republic of Ireland (WFD Groundwater Working Group, 2004).

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

[15] Teagasc's subsoil mapping was used where the GSI's subsoil permeability was unavailable.

	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

Met Éireann’s annual average rainfall national dataset for 1961 to 1990 and the potential evapotranspiration (PE) for the same time period were available as a spatial dataset in order 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 scale and it was agreed to simplify the calculation of actual evaporation (AE) based on expert judgement:

$$AE = 0.95 * PE.$$

The effective rainfall (ER, mm/yr) was determined by calculating the difference between the total rainfall and the AE

$$ER = \text{Average Annual Rainfall} - AE.$$

The recharge of Irish aquifers in groundwater bodies 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 (200mm/yr for locally important aquifers and 100mm/yr in poor 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.

Although the dataset of existing abstractions in Ireland is not comprehensive, a comparison could be made between the abstraction pressure in each groundwater body with the recharge to that groundwater body. The degree of risk posed by an abstraction pressure was represented by a threshold that is intended to leave sufficient recharge to meet ecological needs.

4.4 HOST

The Hydrology of Soil Types (HOST) is a hydrologically based classification of soils and substrate for Northern Ireland (as well as the United Kingdom) that was published by the Institute of Hydrology (Boorman *et al.* 1995).

The HOST classified soils into twenty nine different types based on conceptual models of the dominant pathways of water movement in the soil and substrate. Baseflow Indices (BFIs) were estimated for each of the HOST types which can be applied to ungauged catchment areas.

The HOST is not available for the Republic of Ireland. The dataset suffers from the limitation that as well as bedrock geology not being taken into consideration in the flow pathways, low permeability substrates with a gleyed layer within 40cm (Class 24) are dominant in Northern Ireland, resulting in generalised estimates of BFIs in ungauged catchment areas.

4.5 Conclusions

Recharge studies that have been documented for Ireland have been focused on baseflow separations and soil moisture deficits budgeting. The infiltration rate through thick, low permeability tills can vary between 4% and 40%. The infiltration rate through thin, permeable tills can vary between 60% and 94%. The Irish landscape is dominated by grassland. Fitzsimons and Misstear (2005) have observed that the soil moisture budgeting parameters have less of an affect on recharge through tills than their physical parameters (permeability and thickness) in areas overlain by this land use type.

Estimates of recharge to aquifers have been determined for Irish groundwater bodies nationally (WFD Groundwater Working Group, 2004). These have been based on dominant hydrogeological scenarios observed in Ireland. The limitations of these recharge studies is that soil, subsoil and bedrock aquifer types have been generalised and some of the calculations have been simplified (e.g. recharge values for caps in poorly productive aquifers, calculations of actual evapotranspiration).

In the Northern Ireland, baseflow estimates for rivers use their HOST dataset which has categorized various soil types into twenty nine classes. The disadvantage of this dataset is it does not consider bedrock geology. The work of Fitzsimons and Misstear (2005) highlights the importance of developing a conceptual model of the geology in order to understand the recharge mechanisms and recharge rates.

5 Rainfall Runoff Modelling in Northern Ireland (MIKE 11 NAM)

Due to the size and shallowness of Lough Neagh, Northern Ireland, strong winds can cause significant surges resulting in periodic fluctuations of the water level in the lake (up to 0.5m). The lake's water level is currently managed on a reactionary basis (using limited hydrolocal and meteorological information) by venting flows through sluices into the Lower Bann River. A hydrological model was developed to assess the behaviour of the Lough Neagh catchment to investigate ways of improving control and operation of water levels in Lough Neagh and the Lower Bann system (Bell *et al.* 2005).

The hydrological model MIKE 11 NAM was used to describe the runoff pattern in ten gauged sub-catchments flowing into Lough Neagh . Daily rainfall and evaporation data were used for a period between 1993 and 2002. The rainfall runoff model was calibrated with the observed runoff by adjusting the response parameters. Bedrock geology, land use and HOST provided information on groundwater, root zone and surface storage characteristics. Based on these range of information, the runoff model parameters were selected and checked against water balance considerations.

Lough Neagh itself was modelled as a full two-dimensional model (MIKE 21 HD) in order to describe the depth and velocities. The two-dimensional model made it possible to simulate variations in water level under different meteorological conditions. The overall model improved significantly the understanding of surface flows in the Lough Neagh catchment and resulted in alternatives for the management of water levels in the lake.

6 Other studies of interest

6.1 Introduction

The literature review has focused on the methodology of hydrograph separations and recharge studies in Ireland. The following is a summary of the findings of other studies that may be of relevance to further applications of the GW/SW Interaction Study.

6.2 Soulsby *et al.* (2003)

Soulsby *et al.* (2003) were able to distinguish between three components of stream flow based on observed Si and NO_3-N concentrations in sampled soil water, groundwater and streams in a Scottish agricultural catchment, Newmills Burn (14.5km^2). The components included overland flow (low NO_3-N concentrations), subsurface storm flow (high Si and NO3-N concentrations) and groundwater flow (high Si and intermediate NO_3-N).

From sampled soil waters, the overland flow component was characterised by dilute concentrations of Si, NO_3-N and Ca, largely reflecting the short amount time to reach stream channels. However, the samples exhibited variability reflecting the different origins of overland flow (e.g. compaction of soil by machinery, affected by excrement where animals gain access to streams for drinking). The subsurface component of flow sampled from drains also exhibited variable chemistry, but was much more enriched in Si and NO_3-N than the overland flow. The groundwater component was characterised by intermediate to high NO_3-N values and high Si values. The authors suggest that the high NO_3-N values may reflect leaching from subsoils whilst high Si values result from the relatively long periods that waters are in the subsurface.

The chemical composition of the stream waters is temporally variable although they are generally enriched in N and P. However, the authors were able to identify patterns of chemical changes in Si and NO_3-N during storm events. Si is a weathering related element and exhibited dilution with increased flow. NO_3-N concentrations diluted during the initial phase of the rising limb of the hydrograph and rose again prior to maximum discharge, before peaking on the recession limb.

By considering the end member chemistries of Si and NO_3-N (related to their mean and standard deviation chemistries) and the mathematical modeling of them, the authors were able to determine the proportion of each of the three components of streamflow. The authors observed that high groundwater contributions during storm events were abnormally high after prolonged dry periods when soils were dry with extensive cracking and also during prolonged, low intensity rainfall.

6.3 Jarvie *et al.* (2001)

Jarvie *et al.* (2001) examined the temporal variability and extremes in river water quality in the upland River Dee at Mar Lodge, Scotland. The River Dee at Mar Lodge has a catchment area of 289km^2, is dominated by mountainous terrain and is composed mainly of granites and Dalradian metamorphic rocks. At high altitudes there is poor soil cover and abundant coarse gravel debris and fractured bedrock. The shallow groundwater draining the drift deposits is acidic. Peat dominates the lower altitudes of the upper River Dee catchment.

In the study the pH and conductivity of streamflow were measured every fifteen minutes between 6th December 1995 and 31st July 1997. The authors observed that low pHs correlated with low flows in the River Dee. They also observed a loose relationship between a decrease in conductivity with high flows, although there were occasional short-lived peaks probably related to displacement of peat soils from upper Dee catchment, or the input of ions from an atmospheric source (sea-salt). Jarvie *et al.* (2001) also calculated continuous levels of dissolved carbon dioxide in the stream water to estimate partial pressures of carbon dioxide ($EpCO_2$), which is related to the uptake of carbon dioxide by aquatic species.

The authors used end-member mixing techniques to separate the hydrograph into two components; a rapid surface water runoff component corresponding to runoff from glacial drift and soil water, and a deeper groundwater component that occurred during dry-weather conditions. A relationship was established between alkalinity, flow and conductivity from stream water samples.

It was observed that there were diurnal variations of pH and $EpCO_2$ under baseflow conditions, and that the pH variations were most pronounced in summer months. These variations are a direct response to carbonic acid concentrations in the stream water and are related to the uptake of CO_2 in aquatic plants at night. It was also observed that the highest $EpCO_2$ concentrations occurred during winter periods when the soils were saturated. During these conditions large proportion of flow was derived from peat-rich soil horizons.

The authors work suggests that an understanding of how chemical components react in complex catchments during the hydrological cycle can improve the implementation of a water quality monitoring programme. Fortnightly sampling and sampling only during the day would not capture the range of extremes in chemistry of the River Dee catchment, and catchments like it, and so would be biased.

6.4 Conclusions

The two papers discussed above relate to chemical and geochemical approaches to understanding components of streamflow. Whilst it is not within the realm of our further characterisation study to undertake such detailed geochemical analysis, it may be worth noting the findings of Soulsby *et al.* (2003) and Jarvie *et al.* (2001) since some physical-chemical monitoring data of groundwaters and surface waters will be available to the analyses of further studies.

7 Summary

The conceptual components of flow that this study is interested in are surface flow, interflow, shallow groundwater flow, deep groundwater flow and discrete fault or conduit flow. From the hydrograph separation techniques that have been considered in the literature review we are likely to be able to quantify three components: overland flow, deep groundwater flow and the subsurface component of flow between them (intermediate flow).

A number of hydrograph separation techniques are available: analytical, graphical, geochemical, automated. The Boughton 'two parameter' algorithm method has been documented to be the most reliable of the analytical techniques to separate baseflow and is easy to use with continuous streamflow data. The choice of parameters to use for the Boughton method can be guided by the application of the results from Master Recession Curves. The Unit Hydrograph separation method has been used in Ireland and been found to provide reliable results for overland flow from storm events.

The NAM model is a lumped sum conceptual rainfall-runoff model. The results from techniques that separate overland flow and deep groundwater can be used to calibrate parameters within the rainfall-runoff model.
The recharge estimates in Ireland are based largely on soil moisture budgeting and baseflow separations of streamflow. The results have focused on regionally important aquifers overlain by tills. The work of Fitzsimons and Misstear (2005) indicates that the sensitivity of recharge through tills is affected by physical parameters of the tills as against soil moisture budgeting parameters.

A national study to estimate the recharge of aquifers across Ireland was undertaken in consideration of the risk from groundwater abstraction (WFD Groundwater Working Group, 2004). The study along with other previous recharge studies demonstrate that a conceptual model of physical parameters in a catchment need to be understood in order to estimate separate components of streamflow. The results from previous studies, such as the Article V Characterisation Report, should be used as a reality check to verify the methods of separations that are applied during the study.

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Appendix 9

National Hydrology Conference Paper November 2007

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[16] 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[17] 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[18] was selected gauged at Bellagill (26007);

[16] "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.
[17] 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.
[18] 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.

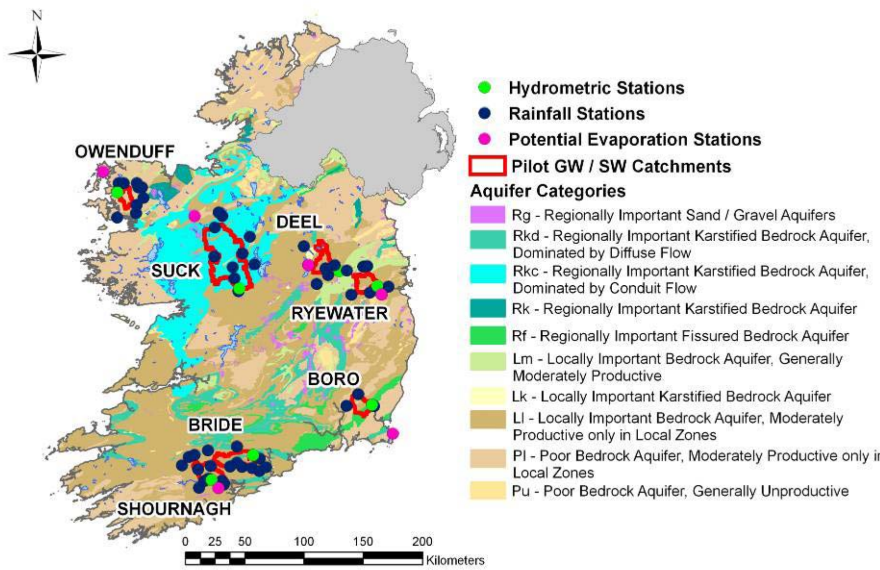

Figure 1. Pilot catchments selected for the surface water-groundwater interaction study, shown on map of Irish bedrock and gravel aquifers

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.

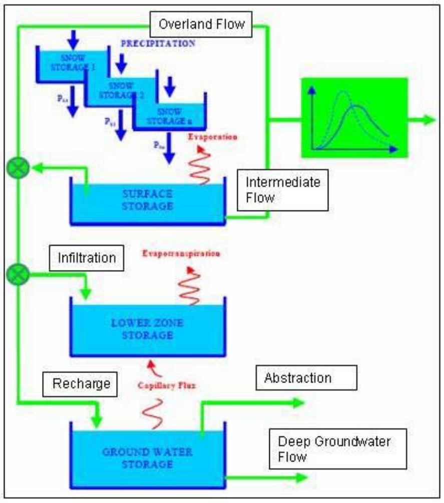

Figure 2. The inter-relationship of the storage zones that are considered by the MIKE 11 NAM model.

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**

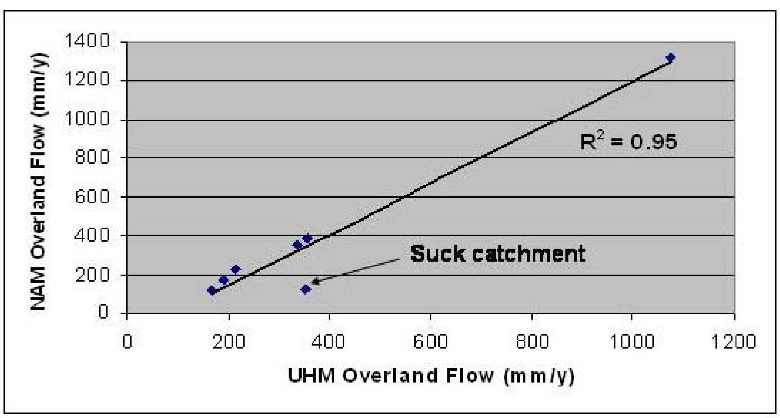

Figure 3. Correlation between the simulated contributions of overland flow from the Unit Hydrograph (UH) method and NAM model.

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.

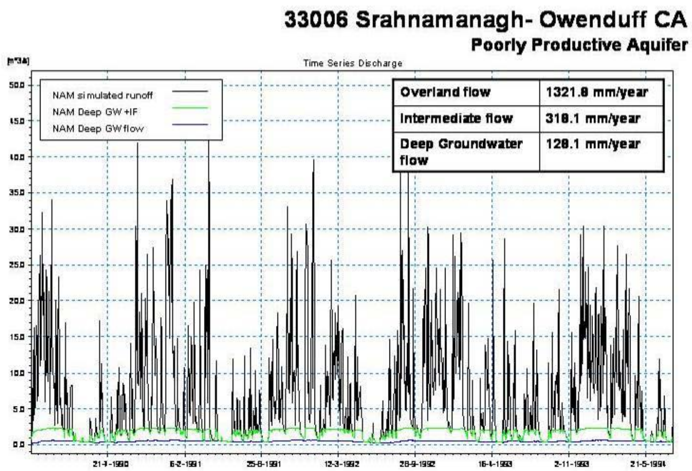

Figure 4. An example of the hydrograph separation from the NAM model for the Owenduff catchment at the Srahnamanagh hydrometric station (33006) for the period 1990 to 1994.

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)*.

<table>
<tr><th>NAM Parameter</th><th>Regional Aquifers</th><th>Broad range of NAM parameter value</th><th colspan="2">Characteristics of vulnerability, suboils, soils and slope datasets</th><th>Refinement of NAM parameter value</th></tr>
<tr><td rowspan="11">CQOF</td><td rowspan="5">Pl / Pu / Ll</td><td rowspan="5">0.5 – 0.9</td><td colspan="2" rowspan="2">High % of poorly drained soils (>30%)</td><td>0.9 if poorly drained soils >50%</td></tr>
<tr><td>0.8 – 0.9</td></tr>
<tr><td rowspan="3">Low % of poorly drained soils (<30%)</td><td>High % of low permeability subsoils (>50%) or slope >5%</td><td>0.8</td></tr>
<tr><td>Low % of extreme vulnerability (<30%)</td><td>0.7 – 0.85 Tend towards 0.85 if slope >5%</td></tr>
<tr><td>Otherwise</td><td>0.5 – 0.7</td></tr>
<tr><td rowspan="2">Rkd / Rkc</td><td rowspan="2">0.5 – 0.7</td><td colspan="2">High % of extreme vulnerability (>30%) or low % of low permeability subsoils (<30%)</td><td>< 0.5</td></tr>
<tr><td colspan="2">Otherwise</td><td>> 0.5</td></tr>
<tr><td rowspan="2">Rf / Lm</td><td rowspan="2">0.5 – 0.8</td><td colspan="2">High % of poorly drained soils (>30%)</td><td>0.7 – 0.8</td></tr>
<tr><td colspan="2">Low % of poorly drained soils (<30%)</td><td>0.5 – 0.7</td></tr>
<tr><td rowspan="2">Rg / Lg</td><td rowspan="2">0.2 – 0.6</td><td rowspan="2">Proximity to river</td><td>Gravels close to river</td><td>0.6</td></tr>
<tr><td>Gravels not close to river</td><td>0.2</td></tr>
</table>

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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