Section 3: Pilot Catchments

3.1 Introduction

The main hydrogeological scenarios relevant to Ireland were identified by a subcommittee of the Groundwater Working Group (Figure 1.1 and Appendix 2). The catchment characteristics of the seven pilot catchments have been determined from the relevant GIS datasets and are presented in Table 3.1. These characteristics have had a significant influence in the respective hydrographs. Five of the pilot catchments are composed of primarily one aquifer type (Owenduff, Shournagh, Deel, Ryewater, and Suck). The Boro and the Bride catchments contain mixed aquifer scenarios.

Table 3.1. Catchment descriptors used for estimating the contributions to stream flow for the groundwater components in the pilot catchments.

Catchment Descriptor	Poorly Productive Aquifer				Productive Aquifer (Rkc)	Mixed aquifer Prod. / Poorly Productive Aquifers	
	Owenduff	**Shournagh**	**Deel**	**Ryewater**	**Suck**	**Bride**	**Boro**
Hydrometric Station	Srahmanragh 33006	Healys Bridge 19015	Killyon 7002	Leixlip 9001	Bellagill 26007	Mogeely 18001	Dunanore 12016
Area (km^2)	119	205	285	209	1207	334	174
% Extremely Vulnerable Areas	38.4	34.5	12.5	16.0	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
% Rkc	0.0	0.0	0.0	0.0	86.8	0.0	0.0
% Rkd	0.0	0.0	0.0	0.0	0.0	12.6	0.0
% Rf	0.0	0.0	0.0	0.0	0.0	0.0	36.2
% Lm	0.0	0.0	0.5	1.6	1.6	0.0	0.0
% Ll	0.1	98.7	88.1	79.4	11.6	86.5	46.0
% Lk	0.0	1.0	9.5	0.2	0.0	0.0	0.0
% Pl	99.9	0.0	1.6	18.8	0.0	1.0	17.7
% Pu	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Channelisation	0.0	7.5	100.0	19.2	0.0	0.0	0.0
% 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

The following sections describe the modelling undertaken to separate and quantify the components of deep groundwater, intermediate and overland flow using the selected hydrograph separation techniques. Since the range in effective rainfall values across the country are between 1600 mm/yr and 300 mm/yr, it is unsuitable to compare the relative stores between catchments in percentages of total river flow. For this reason, the flows are expressed volumetrically in millimetres per year (mm/yr).

It is not possible for NAM to model all of the components of flow from the variety of pathways (e.g. interflow, shallow groundwater flow). Consequently, the NAM model has been constrained by the other techniques described in Section 2 to identify overland, intermediate and deep groundwater flow. At present there is no methodology to quantify the quantities of interflow and shallow groundwater flow from the intermediate flow component.

3.2 Unit Hydrograph Results

3.2.1 Overview

A minimum of five flood events, some with multiple peaks, were examined on each of the pilot catchments, all as described earlier in Section 2.

The initial set of floods comprised well-defined isolated events. In the case of multiple peaks, a trial separation method was analysed to provide a unit hydrograph that fitted the first peak and the surface runoff prediction was extended on to the second peak, using its rainfall. This provided an extension of the separation line, which was checked for consistency across the complete flood event.

This unit hydrograph approach represents the simplest possible model for Quick Response Runoff. The unit hydrograph was allowed to vary from one event to another.

The common consistent features of the separation among the flood events were identified and the chosen system applied to full length of record. In some cases the method was rolled out across the record as a separation line with a constant rising slope. The slope was derived as described above. The method allowed a different slope of the separation line in wet conditions as against dry conditions.

It is recognised that this simplistic method may not be realistic for each time interval in the record, but it provides a useful representation for the average separation of surface runoff across a flood event.

The method of separation of the Flood Studies Report (IH Wallingford, 1975) was applied initially. This is illustrated in Figure 3.1 below. It was found in all catchments that the end point of the surface runoff extended significantly longer than that indicated in the figure, i.e., more than four times the time lag. This is consistent with similar studies in Ireland (Flood Studies Report, Five Years On, ICE, 1980). It is likely that the extended surface runoff is due to the flatter catchment slopes in Ireland and to the extensive areas of poorly drained soils and subsoils.

Furthermore, the Nash Cascade model of the Unit Hydrograph was applied, rather than the triangular model of the Flood Studies Report, as it also provides for an extended surface water recession. It allows the time base of the unit hydrograph to continue for a longer period after the peak than the triangular shape, when this becomes evident, while at the same time retaining the ability to represent a short time base.

From the period of record, the total rainfall, total runoff and surface water runoff was derived in mm on the catchment and the results are presented in Section 3.2.3.

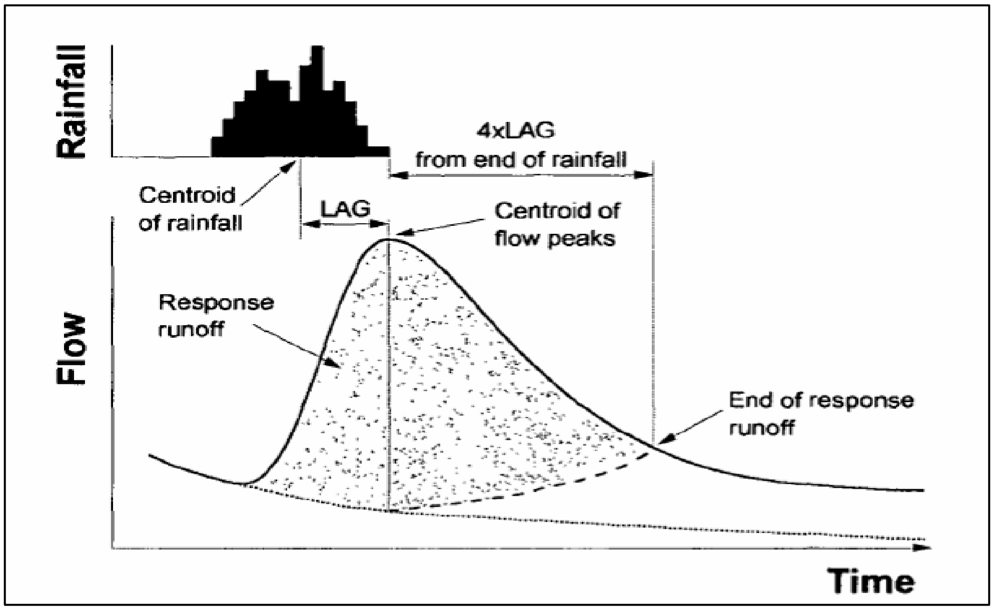

Figure 3.1 Flood Studies Report method of separation.

3.2.2 Sample Hydrograph Plots for Flood Events and for Selected Periods of Record

3.2.2.1 River Shournagh

The fitted separation line for an isolated event is shown in Figure 3.2 (a). The light blue line represents a chosen cutoff point for the end of the event. Figure 3.2 (b) shows the roll-out of the resulting separation line to a period of record.

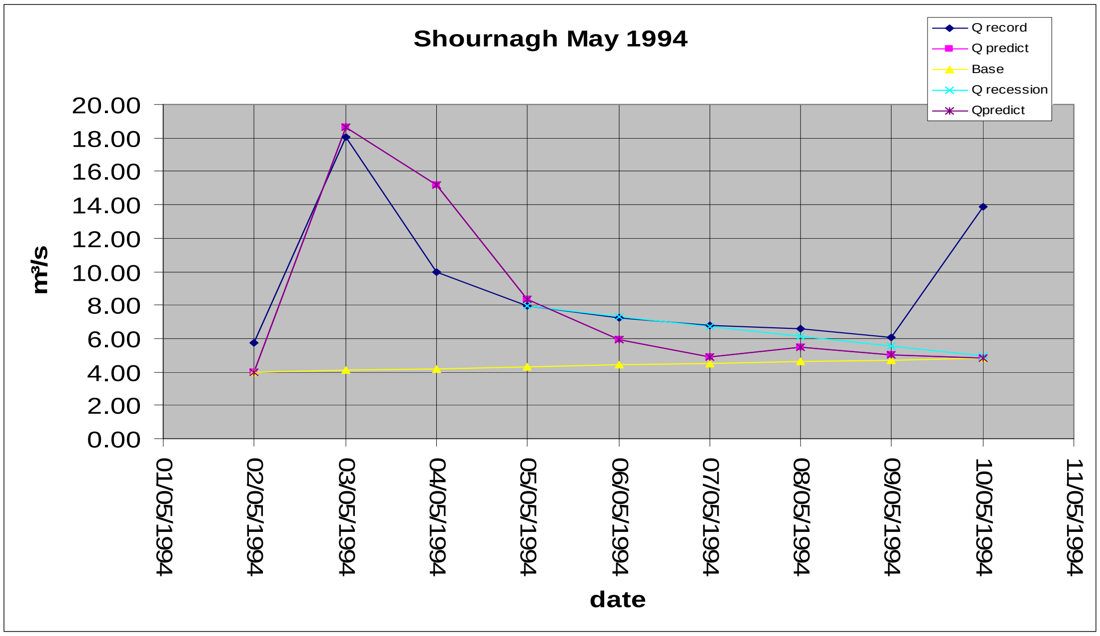

Figure 3.2 (a) Isolated flood event on the River Shournagh

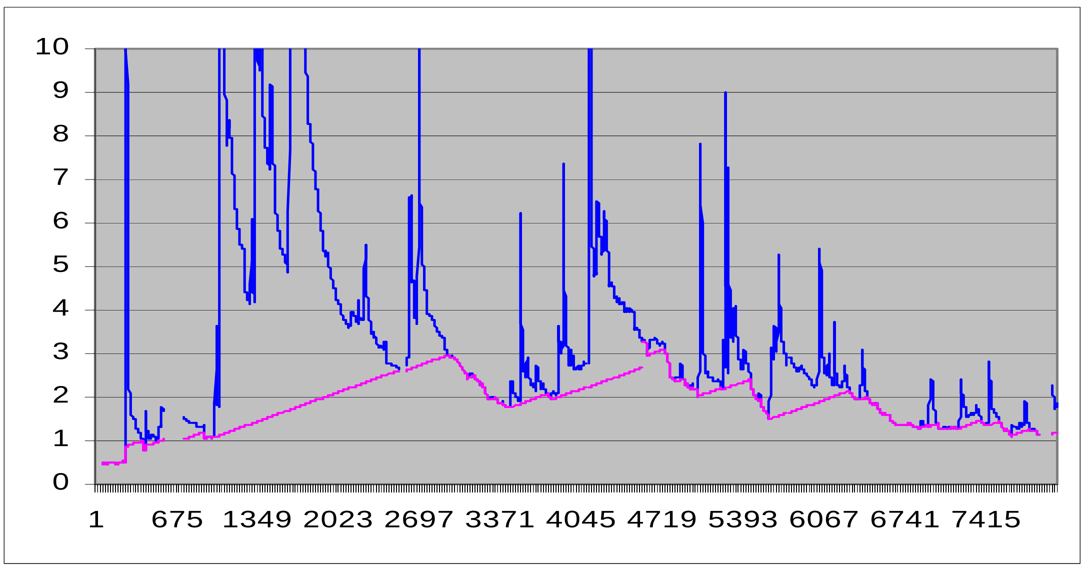

Figure 3.2 (b) Representative average slope of separation line for River Shournagh from series of Unit Hydrograph analyses (hourly interval)

3.2.2.2 Owenduff Catchment

In this catchment, there are very few multi-peak flood events. Figure 3.3 (a) illustrates two isolated flood events and Figure 3.3 (b) shows the roll-out of the resulting separation line to a period of record.

During both summer and winter, the results indicated that a constant straight line slope was appropriate. The slope is very small; it is a constant rising rate of 0.003 m^3/s per hour. In certain catchments the slope was not constant.

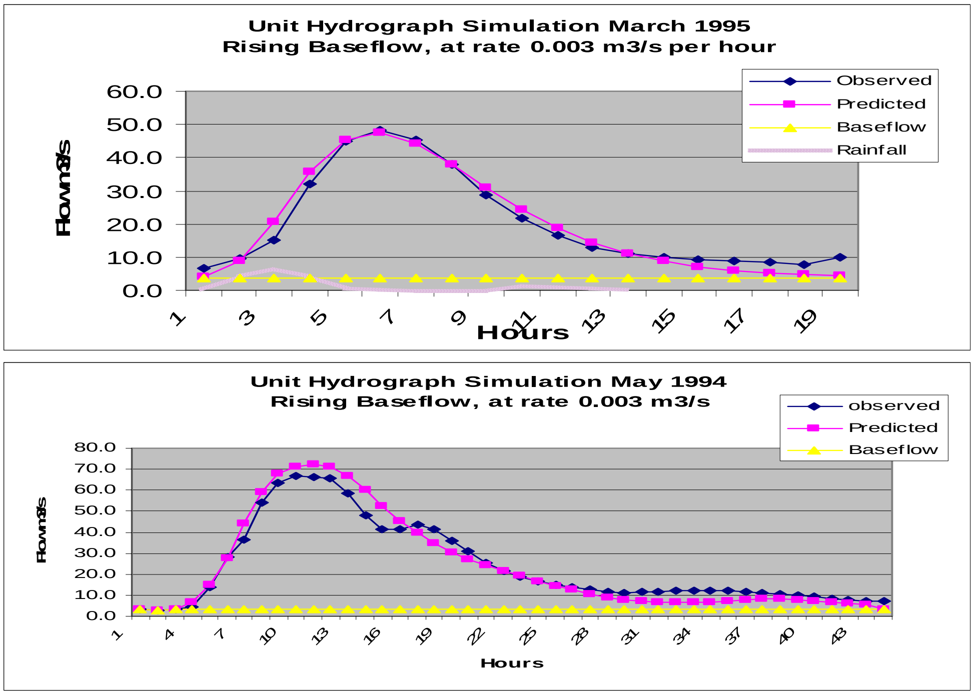

Figure 3.3 (a) Owenduff flood events

The March 1995 flood event shown above occurs within the hydrograph of Figure 3.3 (b). A check was made on the baseflow separation at the beginning of the flood event, so that it was consistent with the previous event. This was a time-consuming process in catchments where the slope is not constant.

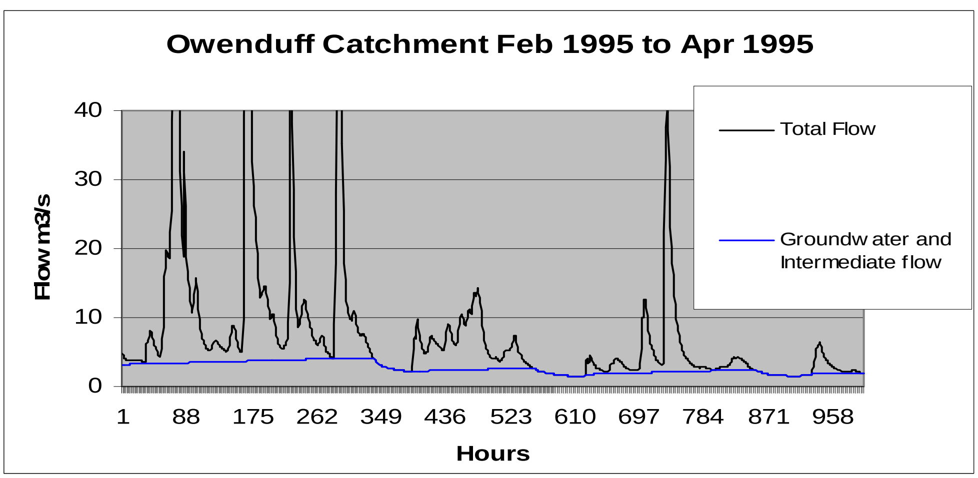

Figure 3.3 (b) Hydrograph for period of record in 1995.

3.2.2.3 Deel Catchment

A double peak flood is shown for the Deel Catchment in Figure 3.4 (a). The separation under the second peak was tested and chosen to fit the prediction to the observed hydrograph.

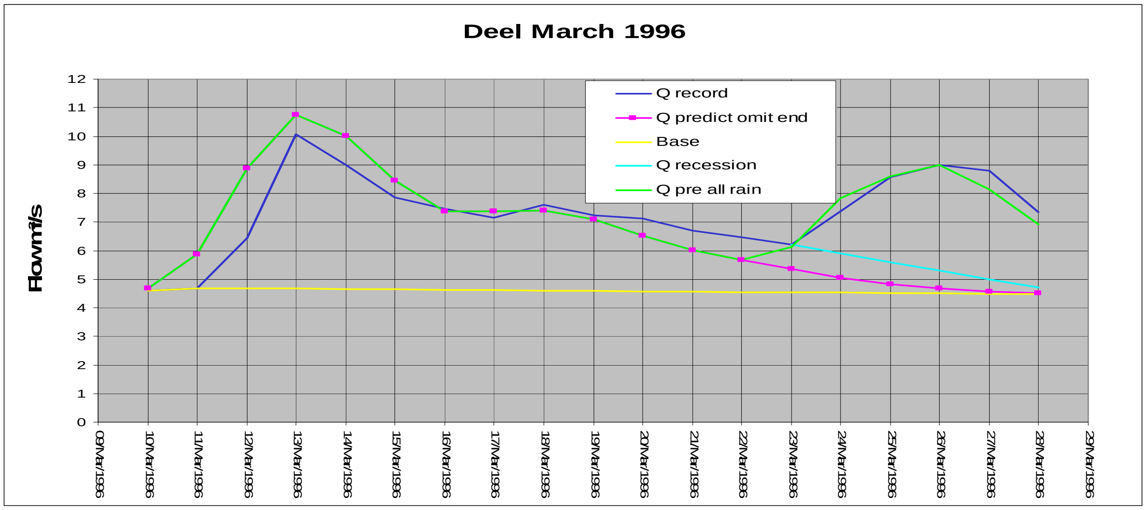

Figure 3.4 (a) Deel Catchment double peak flood.

This procedure resulted in the separation as shown for a period of record in Figure 3.4 (b), where the slope is not constant. There are short periods between some events where there is no surface runoff.

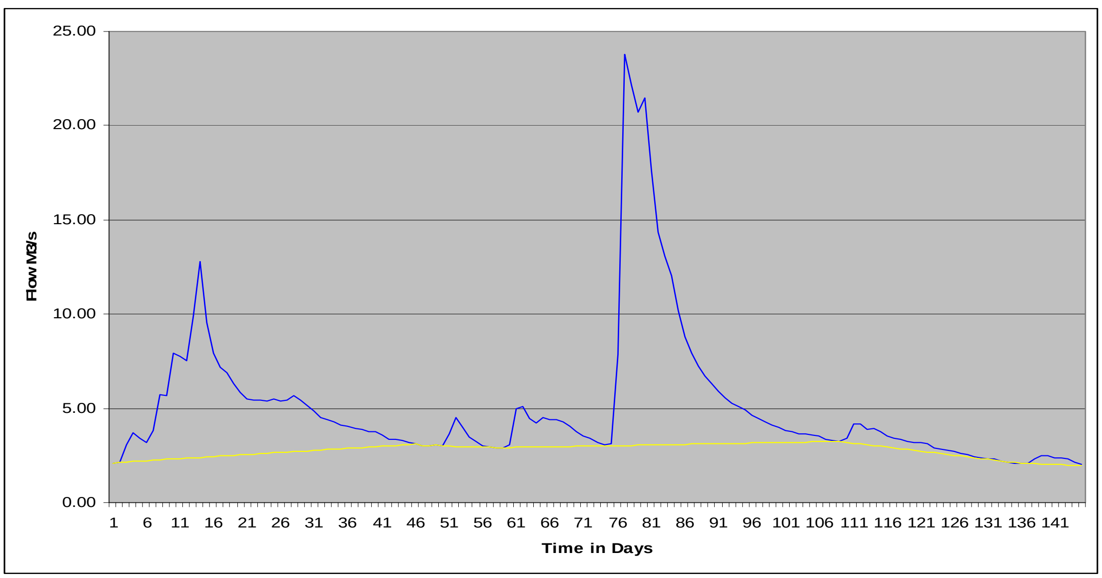

Figure 3.4 (b) River Deel – period of record with varying slope

3.2.2.4 Ryewater Catchment

The sample event shown for the Ryewater is a complex flood event with three peaks (Figure 3.5 (a)). The unit hydrograph and the separation were chosen to fit the peaks, and to provide consistency across the period.

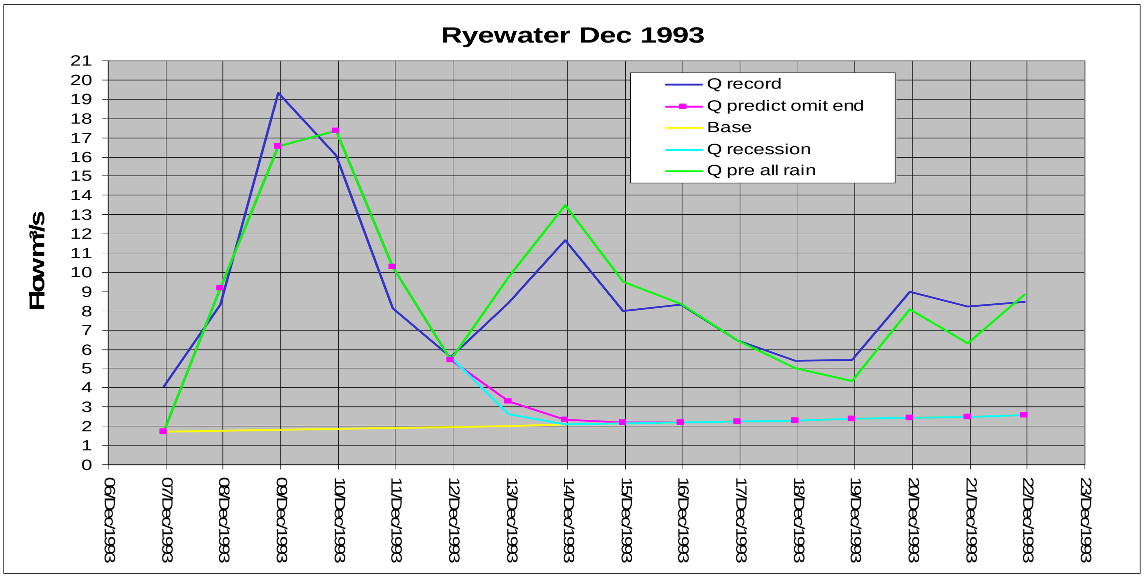

Figure 3.5 (a) Complex flood on the Ryewater River.

When rolled out across a long period of record, the separation process appears as indicated in Figure 3.5 (b) below.

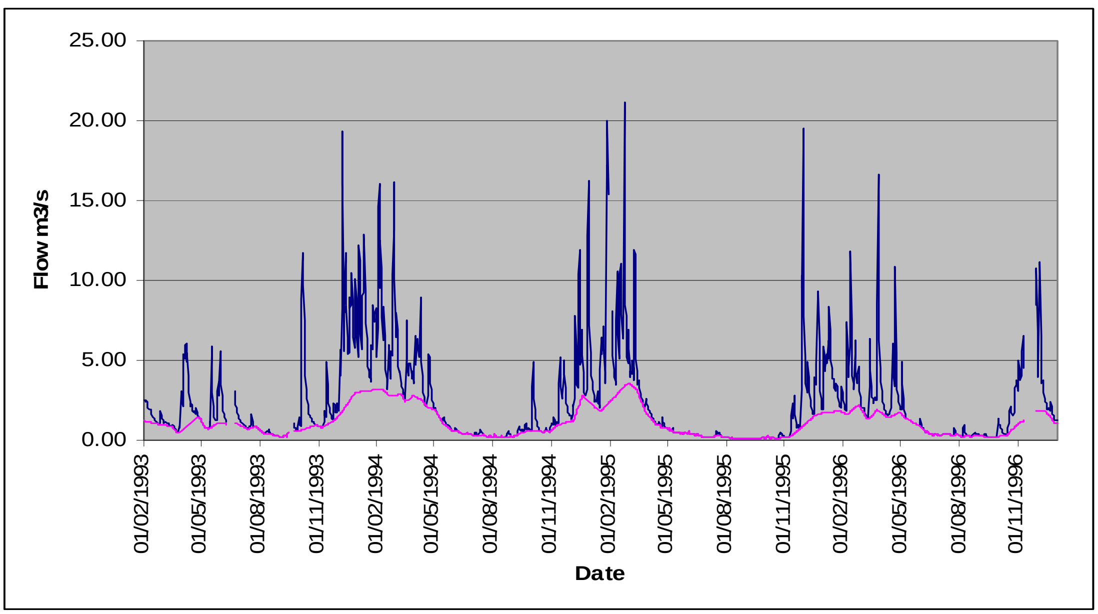

Figure 3.5 (b) Four years of record for the Ryewater.

3.2.2.5 River Suck

The Suck River is illustrated below (Figure 3.6). It presented a difficult scenario in which to model a separation line. Some individual events were fine, and a double peak event shown below provides some consistency. The variation overall in the separation line across a long period of record varied considerably, perhaps due to activation of different flow conduits within the karst in the catchment at different groundwater levels.

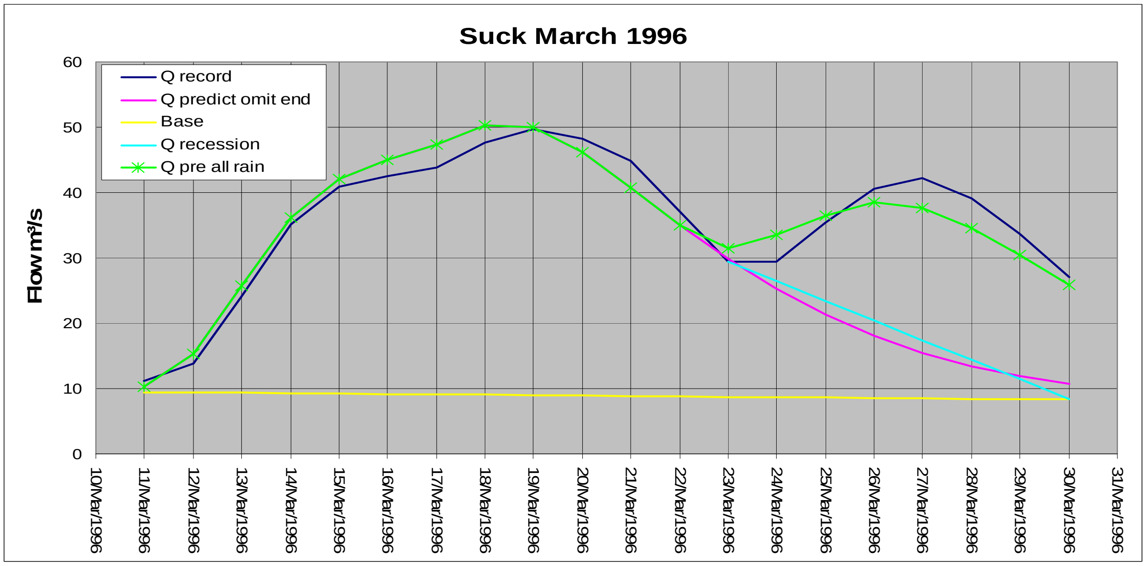

Figure 3.6 (a) River Suck double peak event.

A constant rising separation was finally chosen for most of the period of record.

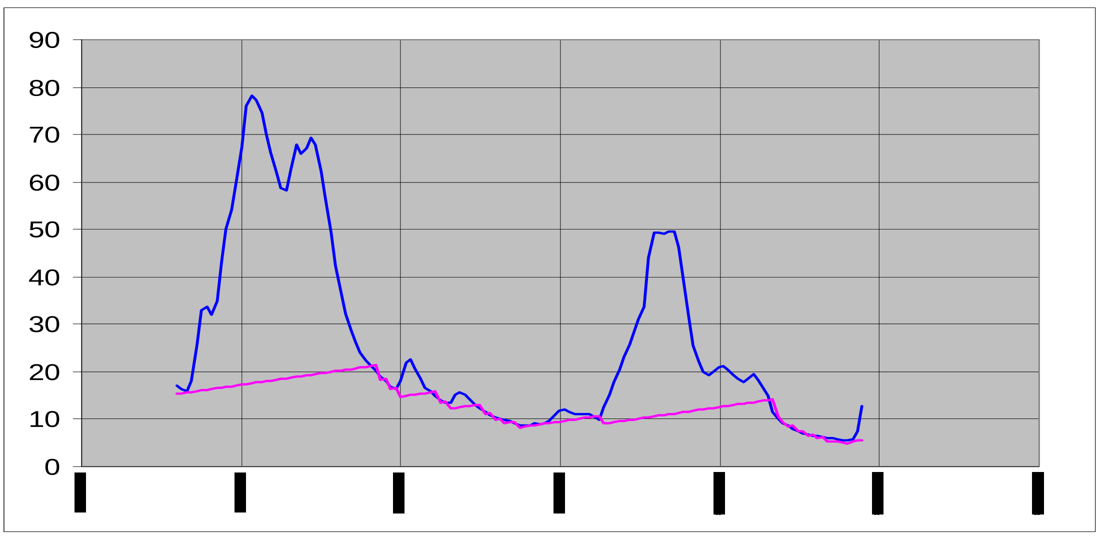

Figure 3.6 (b) River Suck period of record with constant slope.

3.2.2.6 Boro Catchment

The Boro proved difficult to analyse due to the lack of hourly rainfall data in or near the catchment. One successful event occurred and this is shown below (Figure 3.7). As an overall approach, a trial system was applied based on results from other catchments. This is not illustrated, but the overall separation result in mm/year on the catchment is included in the table of results below.

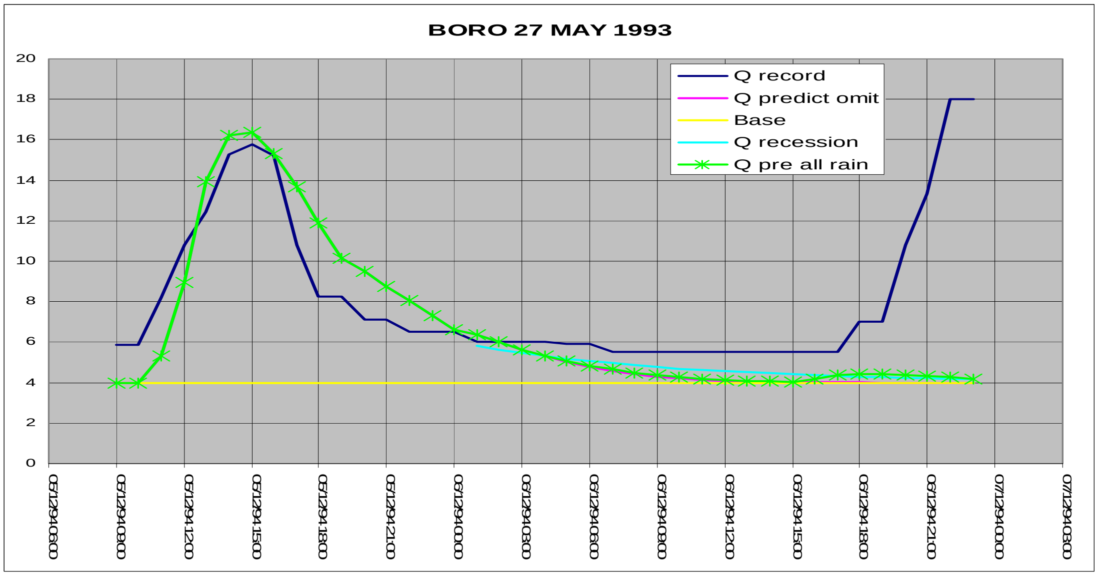

Figure 3.7 Flood event on the Boro catchment.

3.2.2.7 Bride

The Bride River provided a good match from one event to the next, as shown in Figure 3.8 (a).

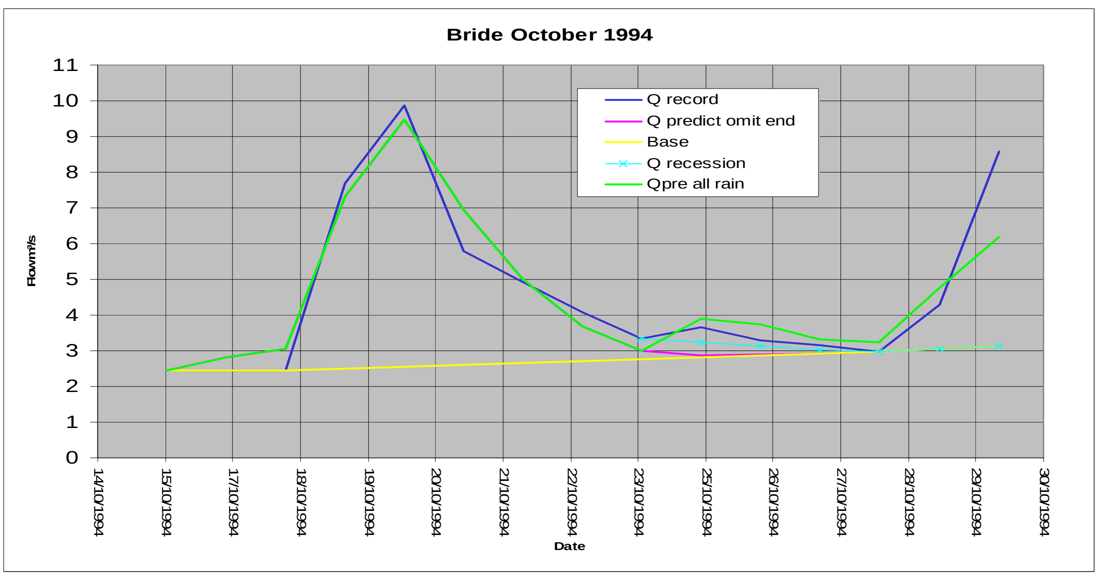

Figure 3.8 (a) Double peak on the River Bride.

The resulting separation varied from summer to winter, and also to some extent within these seasons. A plot of a period of record from March to July 1993 is shown in Figure 3.8 (b).

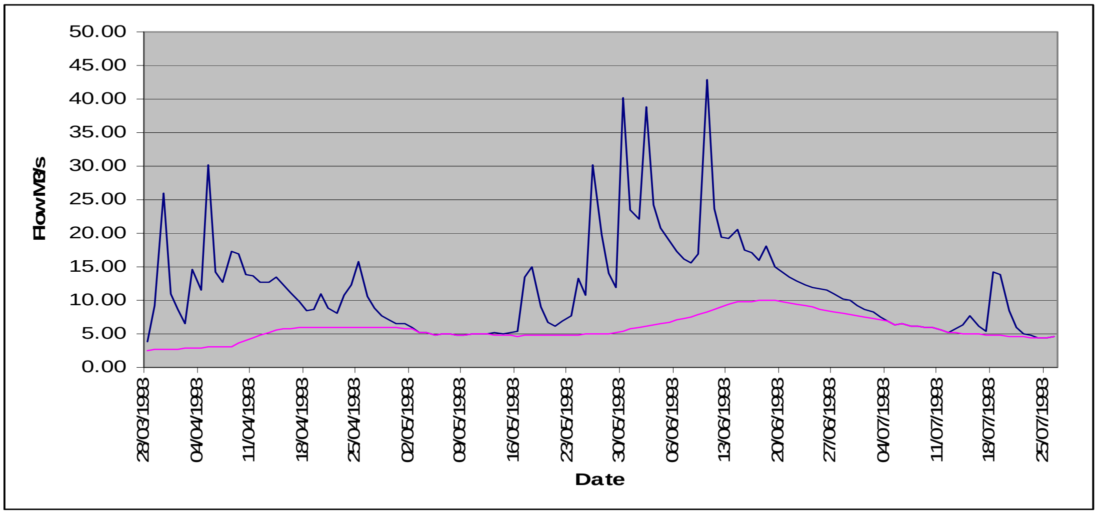

Figure 3.8 (b) Period of record on the River Bride.

3.2.3 Results

The average separation was derived for a selected period of record of the hydrograph in each catchment – in most cases this was three years, and it included the dry year 1995.

Average flows were expressed as mm/yr on the catchment. The results are shown in Table 3.2.

Table 3.20. Summary of results for the quantification of deep groundwater flow (red), intermediate flow (green) and overland flow (blue) for the pilot catchments. Abbreviations: NAM (numerical model); MRC (Master Recession Curve); UH (Unit Hydrograph method).

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 throughput 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**	**232**	**330**	**388** (includes another component)	**240**
Bride	**'Southern Synclines' (Ll and Karst)**	0.81	-0.7	**336**	**352**	**269**	**153**	**170**	**537** (includes another component)	**200**
Deel	**Ll Limestone**	0.90	-0.1	**168**	**120**	**210**	**158**	**232**	**323** (includes another component)	**159**
Owenduff	**Pl Poorly Productive**	0.75	0.3	**1074**	**1322**	**318**	**73**	**183**	**441** (includes another component)	**128**
Ryewater	**Ll Limestone**	0.82	0.0	**191**	**171**	**85**	**158**	**232**	**110**	**121**
Shournagh	**Ll Old Red Sandstone**	0.72	-0.7	**357**	**383**	**205**	**153**	**170**	**321** (includes another component)	**220**
Suck	**Karstic limestone**	0.91	0.1	**354**	**124**	**362**	No calc.	No calc.	**234**	**171**

3.3 Groundwater throughput calculations

Steady-state groundwater throughput estimates were made using the Darcy groundwater flow equation. The analytical equation was evaluated in an Excel spreadsheet. The derivation of values for equation variables was assisted by analysing pilot catchment characteristics such as stream separation and ground slope, and also by using GSI database records of pumping test transmissivities, specific capacities, and groundwater inflow depths (see Section 2.3.3.4 for details).

The results of groundwater throughput calculations are summarised in Table 3.3 below. Note that the groundwater throughput estimates

Table 3.3 Results of spreadsheet modelling of groundwater throughput, expressed as mm/yr.
See Figure 2.4 in Section 2.3.3 for a schematic illustration of the parameters t, K, T, i and L.

Type of bedrock aquifer		*Granite/ Pre-cambrian*	*Namurian/ Lower Palaeozoic**		*Impure limestone*	*Impure limestone*	
Typical aquifer category		*Pl*	*Pl(-Ll)*	*Ll*	*Ll (lower end)*	*Ll (upper end)*	
Represented in pilot catchment		*Owenduff*	*Bride, Shournagh*		*Deel, Ryewater*		
Weathered zone 1 thickness	**t (m)**	0.25	0.5	0.5	0.5	0.5	
Weathered zone 2 thickness		0.5	0.5	0.5	1.5	2.5	
Interconnected fractured zone thickness		5	6	8	10	12	
Weathered zone 1 permeability	**K (m/d)**	1	1	1	1	1	
Weathered zone 2 permeability		1	1	1	1	1	
Interconnected fractured zone permeability		0.1	0.2	0.3	0.35	0.6	
Weathered zone 1 transmissivity	**T (m^2/d)**	0.25	0.5	0.5	0.5	0.5	
Weathered zone 2 transmissivity		0.5	0.5	0.5	1.5	2.5	
Interconnected fractured zone transmissivity		0.5	1.25	2.25	3.25	7	
Groundwater gradient	**i**	0.06	0.045	0.04	0.03	0.025	
Groundwater flow path length	**L (m)**	150	185	215	225	275	
			Groundwater throughput				
Interconnected fractured zone only	**(as mm/ yr)**	73	111	153	158	232	**MIN**
+ Weathered zone 2		146	155	187	231	315	
+ Weathered zone 1		183	200	221	256	332	**MAX**

Where: *t* = effective thickness of deep groundwater flow zone; *K* = aquifer hydraulic conductivity (m/d);	T = aquifer transmissivity (m^2/d); *i* = groundwater gradient (-); *L* = maximum flow distance at the upstream end of the aquifer (m).

* Lower Palaeozoic rocks include Silurian and Ordovician bedded sandstones and mudstones, and Devonian Old Red Sandstones.

3.4 Master Recession Curve Results

The results of the Master Recession Curve analysis are described below for the seven pilot catchments.

3.4.1 Shournagh – Gauge No. 19015 at Healys Bridge

The Master Recession Curve analysis at the River Shournagh contained 66 recession segments over a period of 13 years (1990 – 2003). Figure 3.9 shows a clear distinction between summer and winter recessions. The graphical tabulation method suggests a deep groundwater storage of 0.23 and the matching strip methodology suggests a deep groundwater storage of 0.57. The average (0.40) implies a recharge value of 321 mm/yr for the catchment of the gauge. Three exponential recessions were combined to define the Master Recession Curve in both methods.

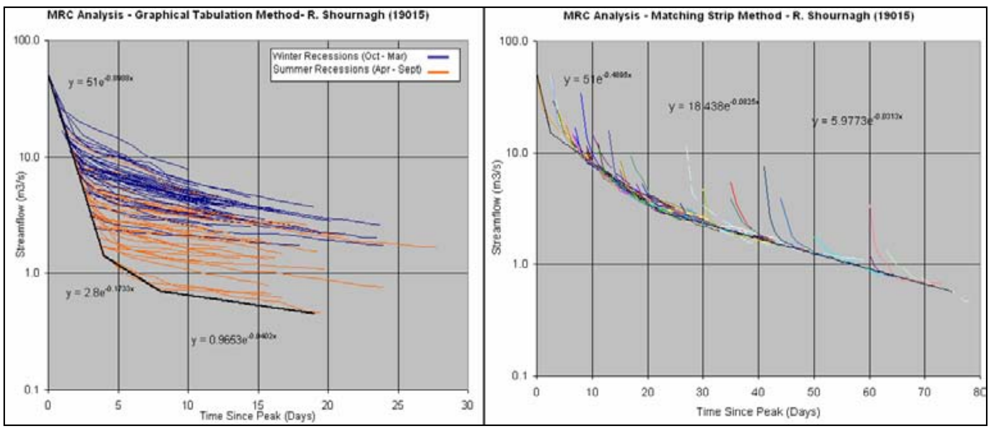

Figure 3.9. Master Recession Curves derived from the tabulation and matching strip methods for the Shournagh River.

The resulting hydrograph separation using the average deep groundwater storage derived from the recession curve analysis is presented in Figure 3.10. The groundwater level data from EPA monitoring point CON076, located 10 km north of the catchment and measured monthly, is also shown for comparison.

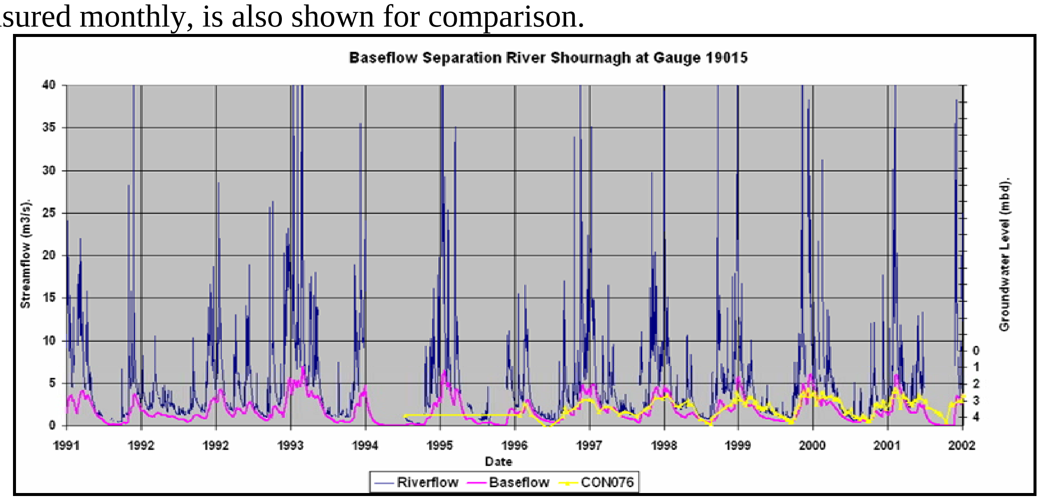

Figure 3.10 Application of the Boughton two-parameter algorithm hydrograph separation to the results of the Master Recession Curve for the Shournagh River.

3.4.2 Owenduff – Gauge No. 33006 at Srahnamanragh

The Master Recession Curve analysis at Srahnamanragh on the River Owenduff contained 70 recession segments over a period of 26 years (1979 – 2005). Figure 3.11 shows a clear distinction between summer and winter recessions. The graphical tabulation method suggests a deep groundwater storage of 0.18 and the matching strip methodology suggests a deep groundwater storage of 0.37. The average (0.28) implies a recharge value of 441 mm/yr for the catchment of the gauge. Three exponential recessions were combined to define the maximum recession curve where as four were used to define the minimum recession curves.

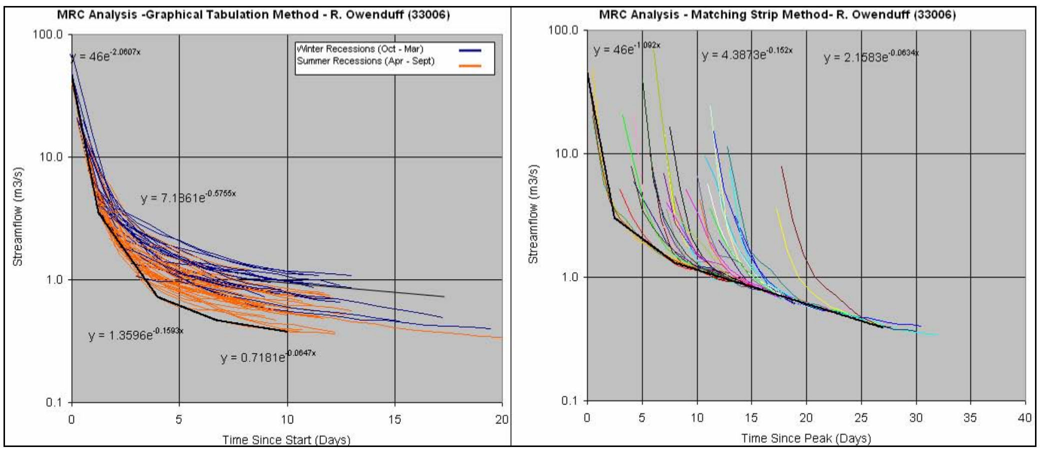

Figure 3.11. Master Recession Curves derived from the tabulation and matching strip methods for the Owenduff River.

The resulting hydrograph separation using the deep groundwater storage derived from the recession curve analysis is presented in Figure 3.12. The groundwater level data from EPA monitoring point MAY067, located 1.5 km north of the catchment and measured monthly, is also shown here for comparison.

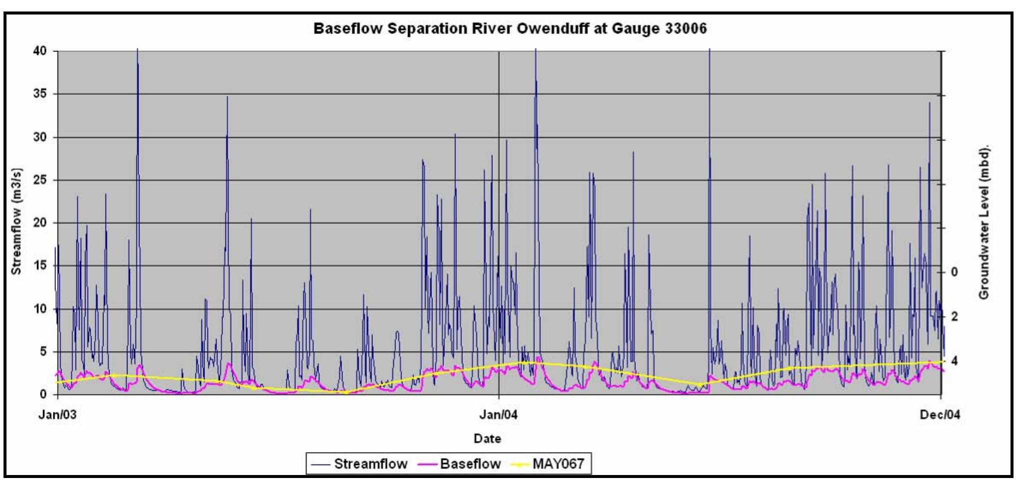

Figure 3.12 Application of the Boughton two-parameter algorithm hydrograph separation to the results of the Master Recession Curve for the Owenduff River.

3.4.3 Deel – Gauge No. 07002 at Killyon

The master recession curve analysis at the Deel River contained 184 recession segments over a period of 33 years (1971 – 2004). Figure 3.13 shows a clear distinction between summer and winter recessions. The graphical tabulation method suggests a deep groundwater storage of 0.44 and the matching strip methodology suggests a deep groundwater storage of 0.82. The average (0.63) implies a recharge value of 323 mm/yr for the catchment of the gauge. Three exponential recessions were combined to define the Master Recession Curve in both methods.

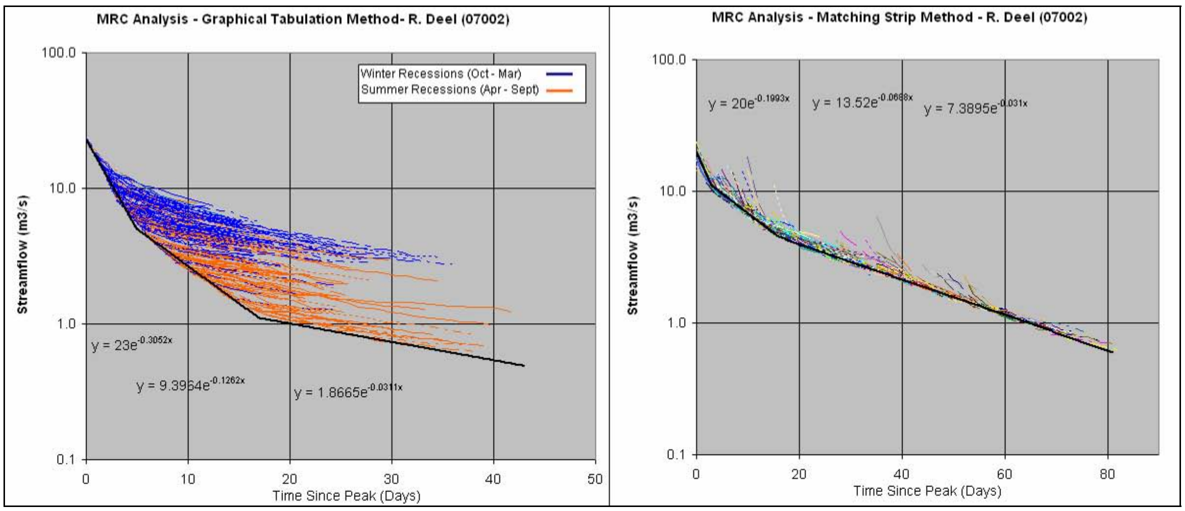

Figure 3.13. Master Recession Curves derived from the tabulation and matching strip methods for the Deel River.

The resulting hydrograph separation using the average deep groundwater storage derived from the recession curve analysis is presented in Figure 3.14. The groundwater level data from EPA monitoring points WES027, WES031 & WES032, which are located within the catchment and are measured monthly, are also shown here for comparison.

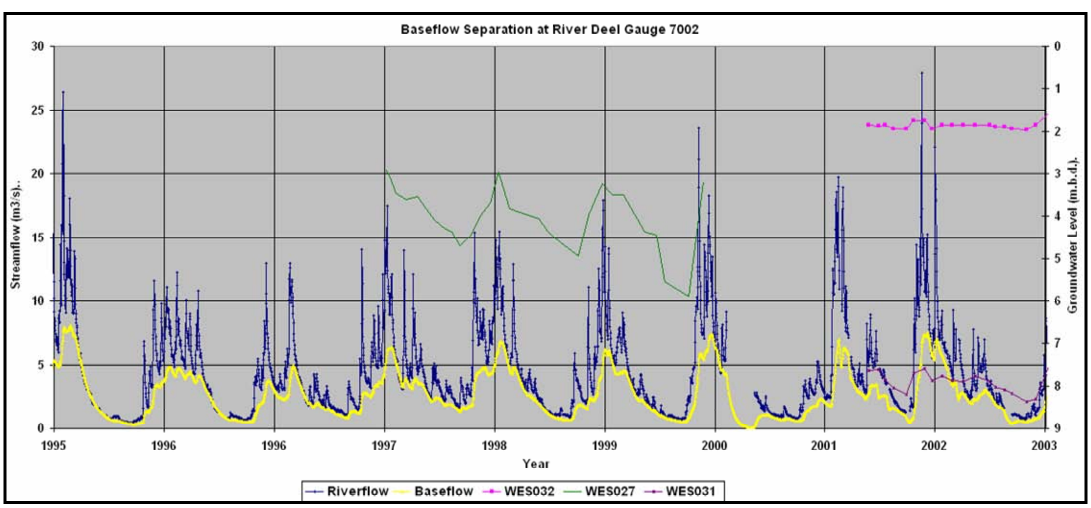

Figure 3.14 Application of the Boughton two-parameter algorithm hydrograph separation to the results of the Master Recession Curve for the Deel River.

3.4.4 Ryewater – Gauge No. 09001 at Leixlip

The Master Recession Curve analysis for the River Ryewater contained 147 recession segments over a period of 34 years (1970 – 2004). Figure 3.15 shows a clear distinction between summer and winter recessions. The graphical tabulation method suggests a deep groundwater storage of 0.11 and the matching strip methodology suggests a deep groundwater storage of 0.43. The average (0.27) implies a recharge value of 105 mm/yr for the catchment of the gauge. Three exponential recessions were combined to define the maximum recession curve whereas four were used or the minimum recession curve.

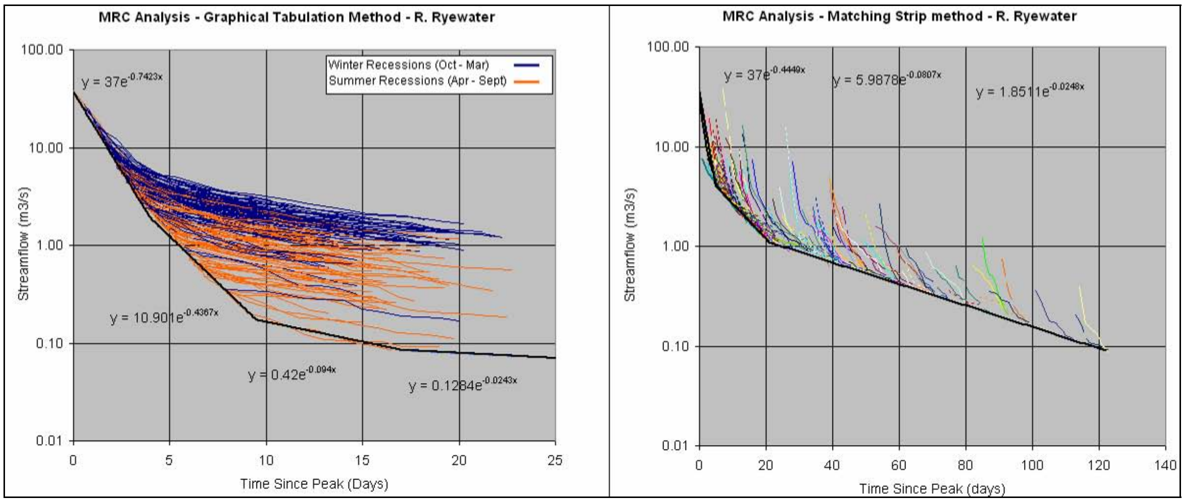

Figure 3.15. Master Recession Curves derived from the tabulation and matching strip methods for the Ryewater River.

The resulting hydrograph separation using the average deep groundwater storage derived from the recession curve analysis is presented in Figure 3.16. The groundwater level data from EPA Monitoring Points KID063, which is located 10 km southwest of the catchment and is measured monthly, is also shown here for comparison.

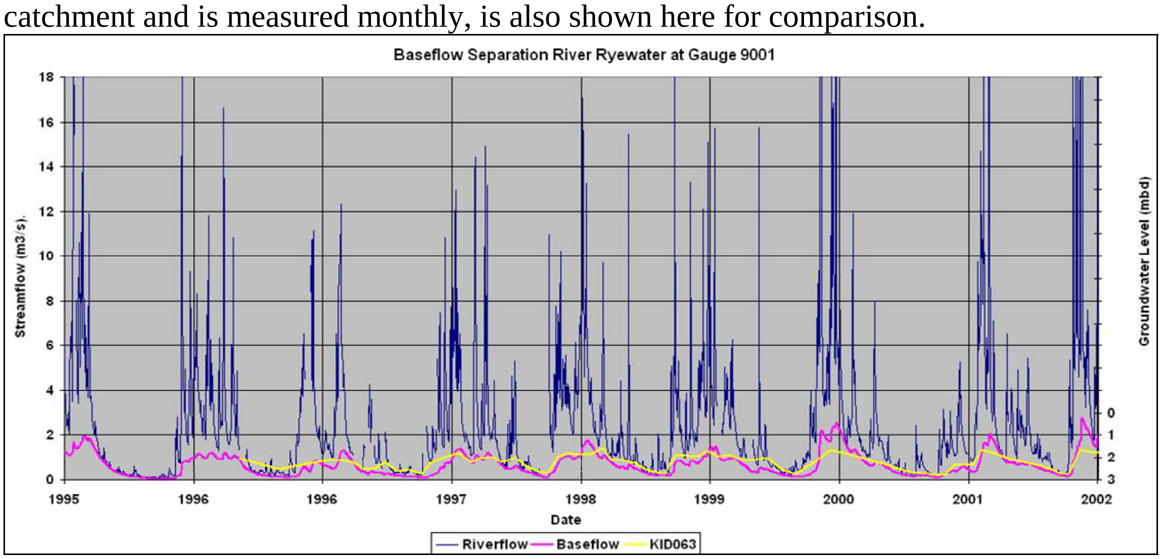

Figure 3.16 Application of the Boughton two-parameter algorithm hydrograph separation to the results of the Master Recession Curve for the Ryewater River.

3.4.5 Suck – Gauge No. 26007 at Bellagill

The master recession curve analysis at Belagill on the River Suck contained 192 recession segments over a period of 28 years (1975 – 2003). Figure 3.17 shows a clear distinction between summer and winter recessions. The graphical tabulation method suggests a deep groundwater storage of 0.18 and the matching strip methodology suggests a deep groundwater storage of 0.53. The average (0.35) implies a recharge value of 234 mm/yr for the catchment of the gauge. Three exponential recessions were combined to define the MRC in both methods.

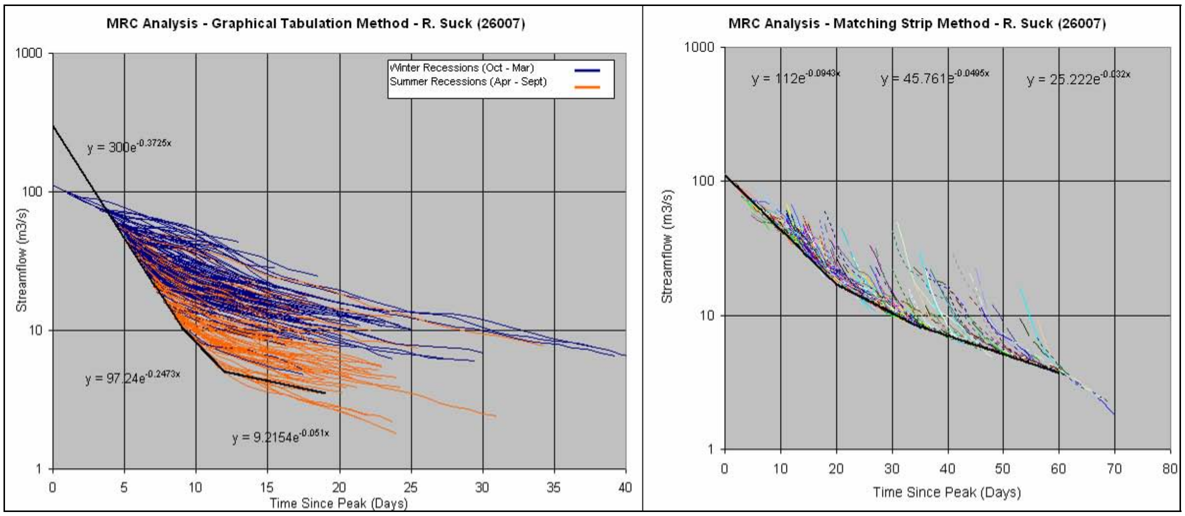

Figure 3.17. Master Recession Curves derived from the tabulation and matching strip methods for the Suck River.

The resulting baseflow separation using the average deep groundwater storage derived from the recession curve analysis is presented in Figure 3.18. The groundwater level data from EPA Monitoring Point ROS082, located in the catchment of the gauge and measured monthly, is also shown here for comparison.

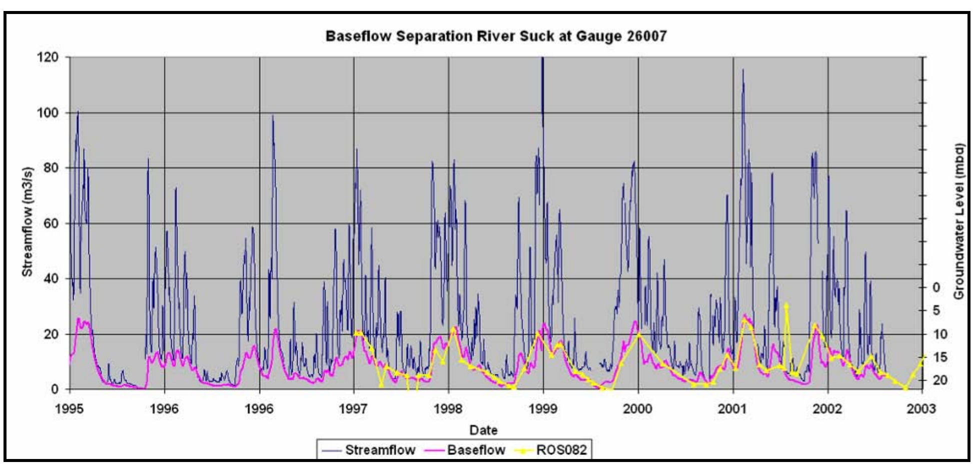

Figure 3.18 Application of the Boughton two-parameter algorithm hydrograph separation to the results of the Master Recession Curve for the Suck River.

3.5.6 Boro – Gauge No. 12016 at Dunanore

The Master Recession Curve analysis at the River Boro contained 100 recession segments over a period of 26 years (1979 – 2005). Figure 3.19 shows a clear distinction between summer and winter recessions. The graphical tabulation method suggests a deep groundwater storage of 0.38 and the matching strip methodology suggests a a deep groundwater storage of 0.78. The average (0.58) implies a recharge value of 388 mm/yr for the catchment of the gauge. Three exponential recessions were combined to define the Master Recession Curve in both methods.

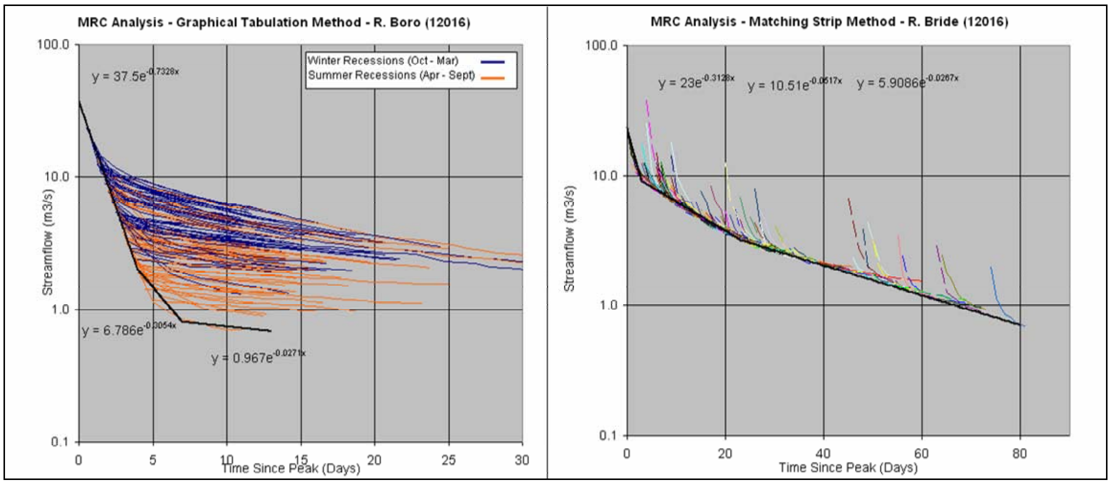

Figure 3.19 Master Recession Curves derived from the tabulation and matching strip methods for the Boro River.

The resulting hydrograph separation using the average BFI derived from the recession curve analysis is presented in Figure 3.20. The groundwater level data from EPA monitoring point KIK121, which is located 22 km southwest of the catchment, and WEX140 located is 3 km south of the catchment are also shown for comparison. The monitoring at the boreholes is not frequent enough to pick out the detail of water level changes in the aquifer.

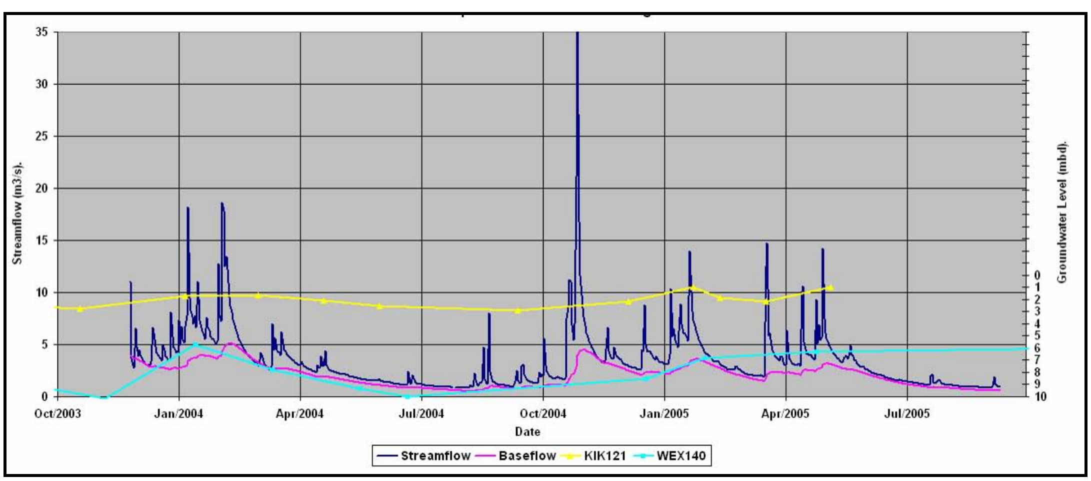

Figure 3.20 Application of the Boughton two-parameter algorithm hydrograph separation to the results of the Master Recession Curve for the Boro River.

3.4.7 Bride – Gauge No. 18001 at Mogeely

The Master Recession Curve analysis at the River Bride contained 63 recession segments over a period of 28 years (1972 – 2000). Figure 3.21 shows a clear distinction between summer and winter recessions. The graphical tabulation method suggests a deep groundwater storage of 0.45 and the matching strip methodology suggests a deep groundwater storage of 0.85. The average (0.65) implies a recharge value of 537 mm/yr for the catchment of the gauge. Three exponential recessions were combined to define the MRC in both methods.

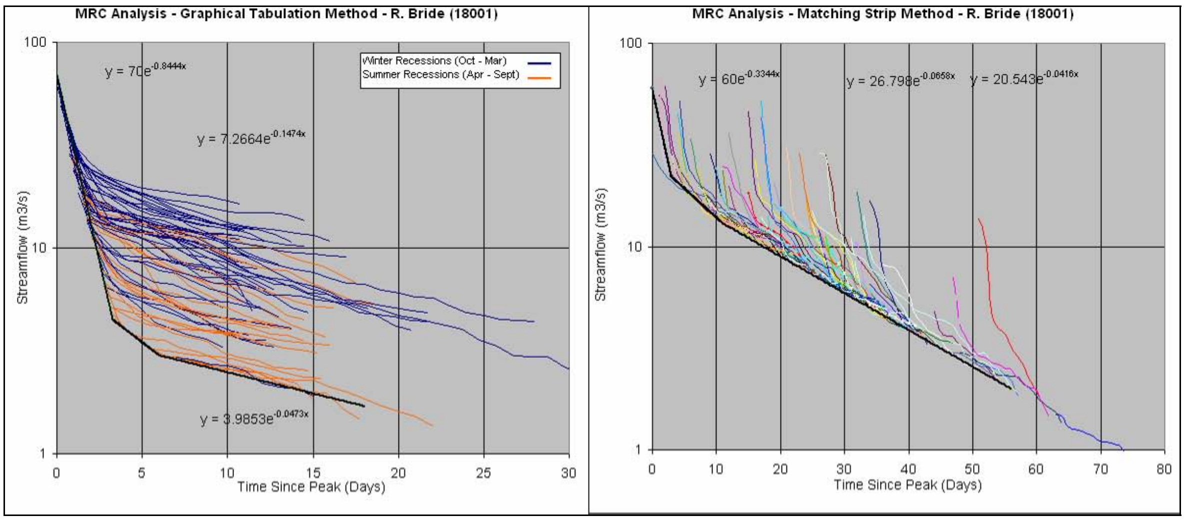

Figure 3.21. Master Recession Curves derived from the tabulation and matching strip methods for the Bride River.

The resulting hydrograph separation using the average deep groundwater storage derived from the recession curve analysis is presented in Figure 3.22. The groundwater level data from EPA monitoring point CON098, which is located in the Waulsortian Limestone aquifer within the catchment and measured monthly, is also shown here for comparison.

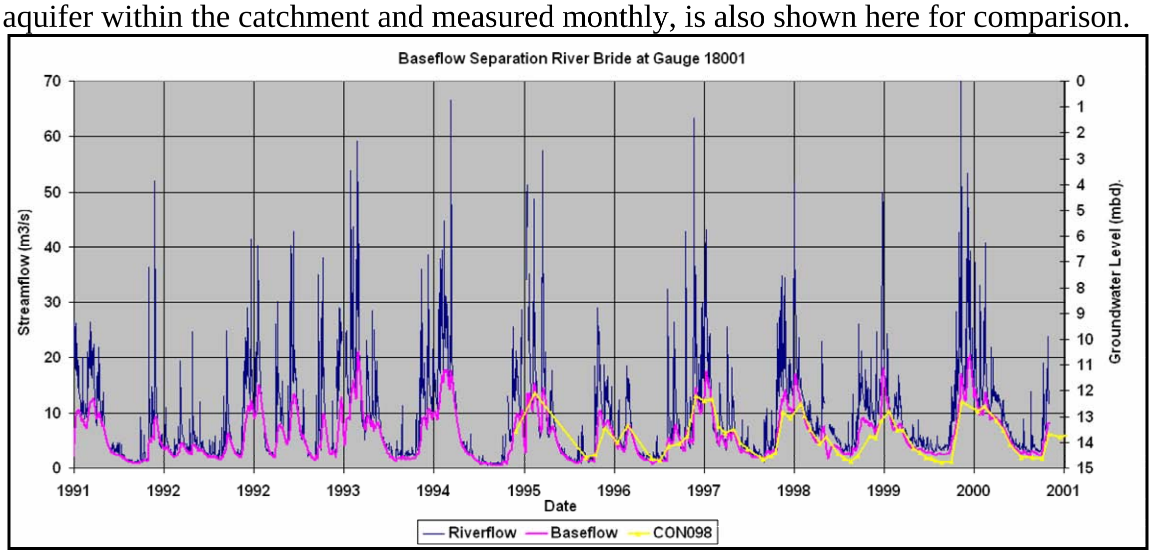

Figure 3.22 Application of the Boughton two-parameter algorithm hydrograph separation to the results of the Master Recession Curve for the Boro River.

3.4.8 Summary of results

The results of the analysis for the selected catchments have been compiled in Table 3.4. The relative storage of the deep groundwater is shown for each catchment. The effective rainfall is shown for each catchment which has been derived from Met Éireann's 1961-1990 GIS dataset. The actual storage shown is calculated as the percentage of the effective rainfall. This deep groundwater storage is equal to the annual recharge for the catchment.

The deep groundwater storage ranges from a minimum of 0.28 in the Owenduff catchment to the maximum of 0.65 for the Bride catchment. The recharge ranges from a minimum of 110 mm/yr for the Ryewater catchment to a maximum of 537 mm/yr for the Bride catchment. The deep groundwater storage alone is not a suitable indicator of groundwater recharge as it must be considered in the context of the effective rainfall. For example, although the Owenduff catchment has a lower deep groundwater storage than the Ryewater catchment. The effective rainfall is much lower in the Ryewater catchment resulting in a lower recharge than in the Owenduff catchment.

These results are discussed and compared to the findings from the other hydrological modelling and analysis later in this chapter.

Table 3.4. Results of the Master Recession Curve analysis for the pilot catchments.

Catchment	River Name	Min. Deep Groundwater Storage (%)	Average Deep Groundwater Storage (%)	Max Deep Groundwater (%)	Effective Rainfall (mm/yr)	Estimated Deep Groundwater Storage / Recharge (mm/yr)
12016	Boro	38	58	78	671	388
18001	Bride	45	65	85	826	537
7002	Deel	44	63	82	510	323
33006	Owenduff	18	28	37	1560	441
9001	Ryewater	14	29	43	383	110
19015	Shournagh	23	40	57	806	321
26007	Suck	18	35	53	660	234

3.5 NAM Model Results

The results of the NAM modelling, constrained by the findings of the Unit Hydrograph method, Master Recession Curve analysis and groundwater throughput calculations, are described below.

3.5.1 Shournagh – Gauge No. 19015 at Healys Bridge

The NAM model for the Shournagh catchment was run for the period January 1990 to May 2002. This time period was chosen based on overlapping meteorological and discharge time series. The simulation matches the recessions of the recorded hydrograph well, although the R^2 correlation is relatively low because six months of discharge data are missing for the first half of 1995 (Figure 3.23). The NAM separation of deep groundwater, intermediate and overland components of flow is presented in Figure 3.24.

The NAM estimates are: 220 mm/yr contribution of deep groundwater flow, 205 mm/yr intermediate flow and 383 mm/yr overland flow.

Table 3.5 includes a compilation of the estimates from the separation techniques. The simulated NAM deep groundwater flow estimate is at the higher end of the groundwater throughput calculation range. The NAM model's overland flow estimate compares well with the result from the Unit Hydrograph method. The intermediate component that NAM has estimated is probably composed of flow from shallow groundwater and till. The combination of estimates of the deep groundwater and intermediate components of flow from NAM is 425 mm/yr, which may suggest that the Master Recession Curve method of separation has identified a combination of flows including the deep groundwater component and part of the intermediate flow.

Table 3.5. Estimates and comparisons of various components of flow for the Shournagh catchment based on the selected hydrograph separation techniques.

Parameter	**Contribution of parameter**
Simulated Effective Rainfall	808 mm/yr
Unit Hydrograph estimate of overland flow	357 mm/yr
Groundwater throughput calculation of deep groundwater contribution *(+ flow through weathered zone)*	111-153 mm/yr *(200-221 mm/yr)*
Master Recession Curve estimate of deep groundwater flow	321 mm/yr
NAM overland contribution	383 mm/yr
NAM estimate of intermediate flow	205 mm/yr
NAM deep groundwater contribution	220 mm/yr

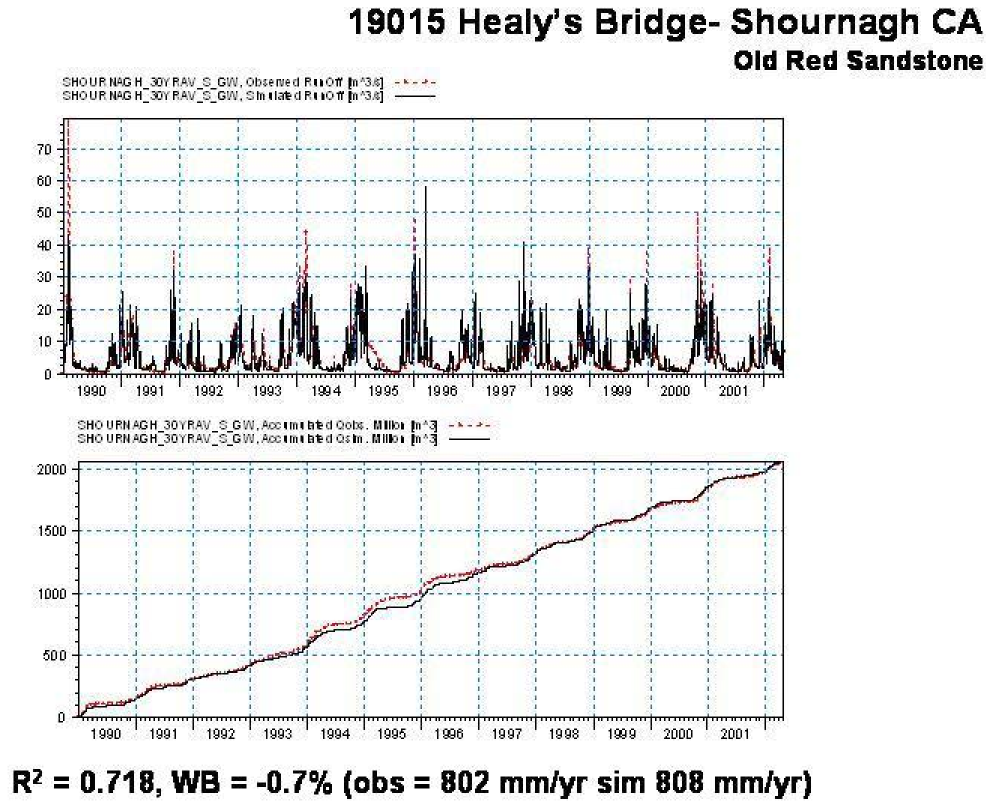

Figure 3.23. NAM simulation correlated with the recorded hydrograph data for the Shournagh catchment at the Healy's Bridge station (19015).

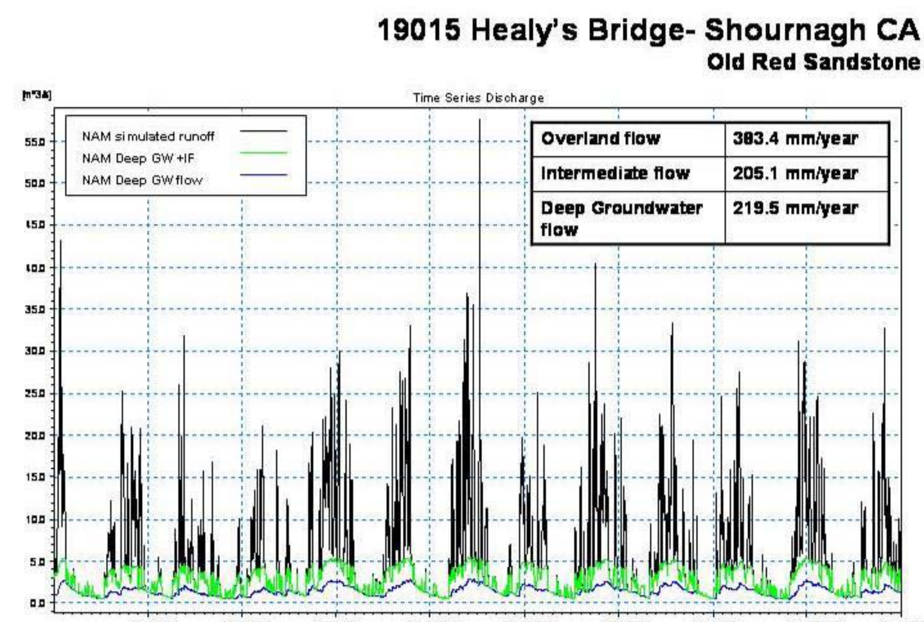

Figure 3.24. The hydrograph separation from the NAM simulation for the Shournagh catchment at the Healy's Bridge station (19015).

3.5.2 Owenduff – Gauge No. 33006 at Srahnamanragh

The NAM model for the Owenduff catchment was run for the period January 1990 and July 1994. The relatively short simulation is due to a data gap of five months in the discharge data at the end of 1994, and no data between 1996 and 2002. The overall water balance between the recorded discharge and the discharge simulated by NAM is good, yet the correlation between the recorded and simulated curves has an R^2 of 0.742 (Figure 3.25). The relatively poor correlation is primarily due to inaccurate peak flows in the recorded discharge dataset, which were created by the averaging process that produced daily average flow data.

The NAM separation demonstrates that there is a cap on the flow quantity available from the deep groundwater and intermediate components (Figure 3.26). Similar results were achieved using hourly rainfall and discharge data. The small contribution of the intermediate and deep groundwater flow components may be a result of the low permeability characteristics of the poorly productive aquifer and the large quantity of peat in the catchment. The NAM estimates are: 128 mm/yr contribution of deep groundwater flow, 318 mm/yr intermediate flow and 1322 mm/yr overland flow.

Table 3.6 includes a compilation of the estimates from the different separation techniques. The NAM results compare well with the Unit Hydrograph and groundwater throughput estimates for deep groundwater flows. The deep groundwater flow estimate from NAM is in the middle of the total groundwater throughput calculation range. The relatively high deep groundwater contribution estimated by NAM may be related to the high effective rainfall in the catchment. The intermediate flow component probably consists of flow into streams from peat and shallow groundwater. The combination of estimates of the deep groundwater flow and intermediate flow from NAM is 420 mm/yr which may suggest that the Master Recession Curve method has identified a combination of flows from the deep groundwater and intermediate components.

Table 3.6. Estimates and comparisons of various components of flow for the Owenduff catchment based on the selected hydrograph separation techniques.

Parameter	**Contribution of parameter**
Simulated Effective Rainfall	1768 mm/yr
Unit Hydrograph estimate of overland flow	1074 mm/yr
Master Recession Curve estimate of deep groundwater flow	441 mm/yr
Groundwater throughput calculation of deep groundwater contribution *(+ flow through weathered zone)*	73 mm/yr *(183 mm/yr)*
NAM overland contribution	1322 mm/yr
NAM estimate of intermediate flow	318 mm/yr
NAM deep groundwater contribution	128 mm/yr

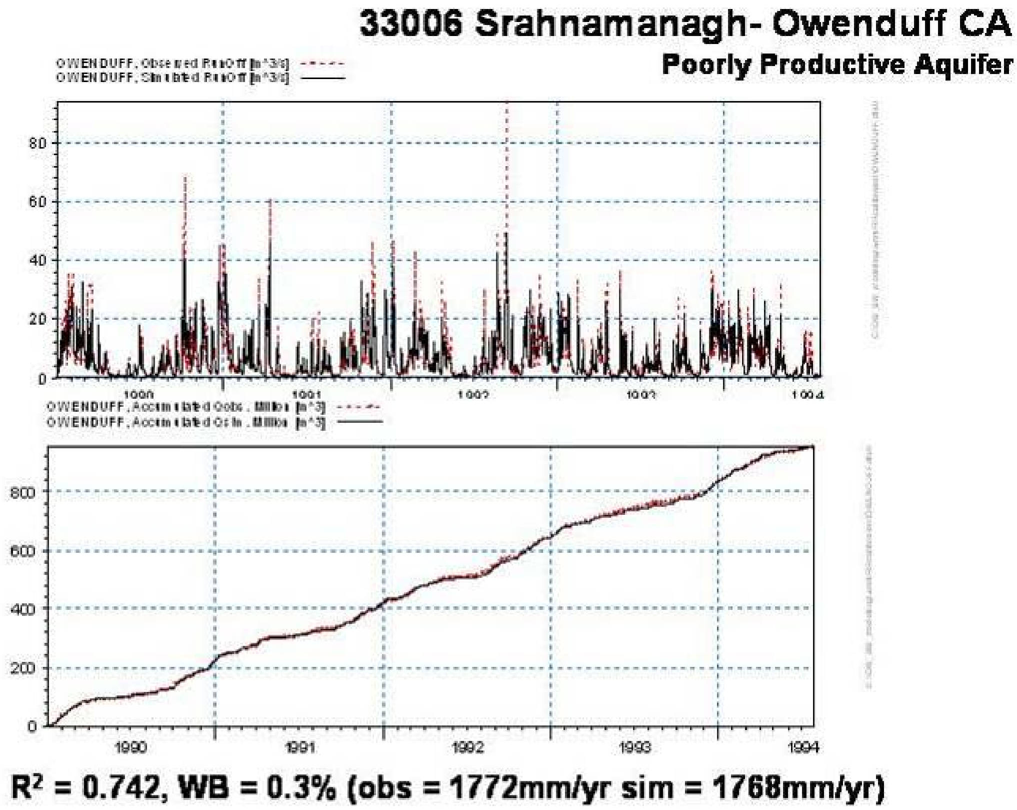

Figure 3.25. NAM simulation correlated with the recorded hydrograph data for the Owenduff catchment at the Srahnamanagh station (33006).

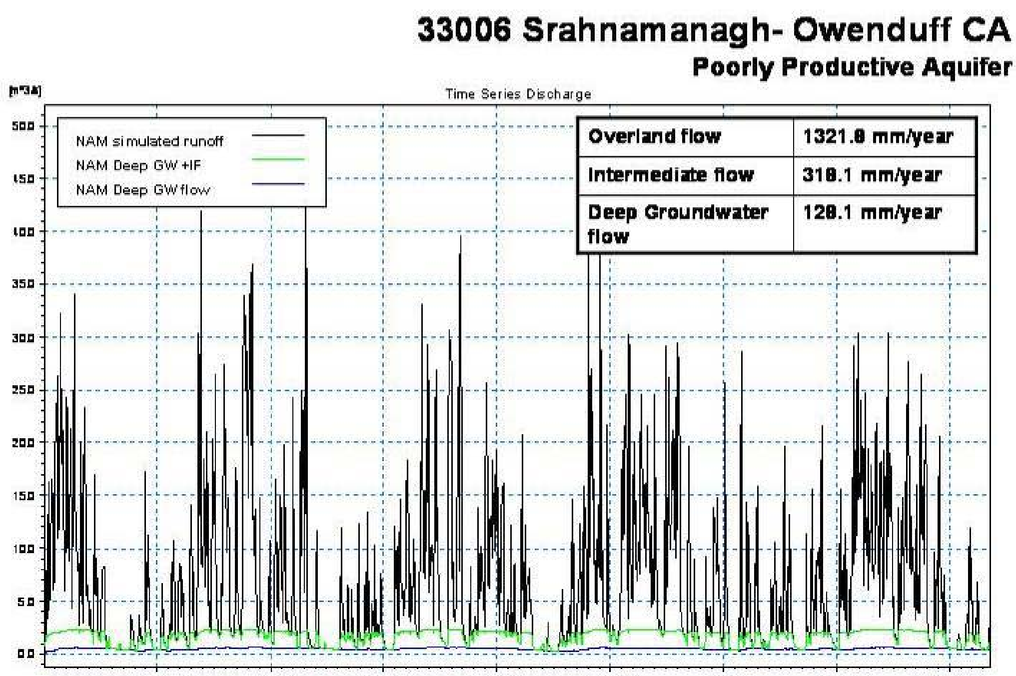

Figure 3.26. The hydrograph separation from the NAM simulation for the Owenduff catchment at the Srahnamanagh station (33006).

3.5.3 Deel – Gauge No. 7002 at Killyon

The NAM model for the Deel catchment was run for the period June 1990 to December 2002. The simulation was started in June because, unless this 'preconditioning' was done, the model underpredicted flow in the winter months of 1990. This is because the groundwater storage zone is less full during the summer months, which allows the model to adjust more easily to the infiltration of rainfall. The overall water balance between the NAM simulation and recorded hydrograph, and the R^2 correlation are good (Figure 3.27).

The groundwater storage for the model was split into two components (an upper and a lower storage) because NAM over-predicted the stream flow during long recession periods using one groundwater storage unit (Figure 3.28). The components of flow include overland flow, flow from the root zone storage, flow from the model's upper groundwater storage zone and deep groundwater (Figure 3.29). The combined contribution of flow from the root storage zone and the upper groundwater storage zone represent intermediate flow (Table 3.7).

The NAM estimates are: 159 mm/yr contribution of deep groundwater flow from a lower groundwater storage zone, 86 mm/yr flow from the model's upper groundwater storage zone, 124 mm/yr flow from the root zone storage and 120 mm/yr overland flow. A comparison of the results in Table 3.5 suggests that the estimates of NAM's deep groundwater flow and overland flow correlate well with groundwater throughput and Unit Hydrograph estimates, respectively. The Master Recession Curve analysis has probably identified a combination of deep groundwater flow and part of the intermediate flow.

Table 3.7. Estimates and comparisons of various components of flow for the Deel catchment based on the selected hydrograph separation techniques.

<table>
<tr><th colspan="2">Parameter</th><th>Contribution of parameter</th></tr>
<tr><td colspan="2">Simulated Effective Rainfall</td><td>489 mm/yr</td></tr>
<tr><td colspan="2">Unit Hydrograph Method estimate of overland flow</td><td>101 mm/yr</td></tr>
<tr><td colspan="2">Groundwater throughput calculation of deep groundwater contribution (+ flow through weathered zone)</td><td>158-232 mm/yr
(256-332 mm/yr)</td></tr>
<tr><td colspan="2">Master Recession Curve estimate of deep groundwater flow</td><td>323 mm/yr</td></tr>
<tr><td colspan="2">NAM overland contribution</td><td>120 mm/yr</td></tr>
<tr><td rowspan="2">NAM estimate of intermediate flow</td><td>NAM estimate of flow modelled from root zone storage</td><td>124 mm/yr</td></tr>
<tr><td>NAM estimate of flow modelled from upper groundwater storage</td><td>86 mm/yr</td></tr>
<tr><td colspan="2">NAM deep groundwater contribution</td><td>159 mm/yr</td></tr>
</table>

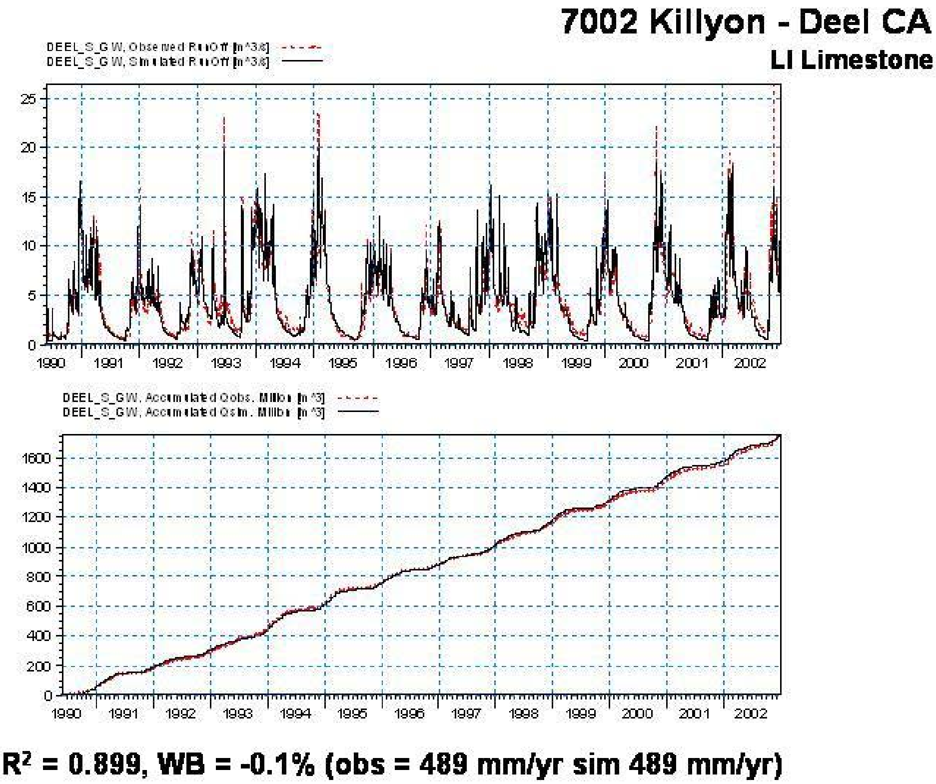

Figure 3.27. NAM simulation correlated with the recorded hydrograph data for the Deel catchment at the Killyon station (7002).

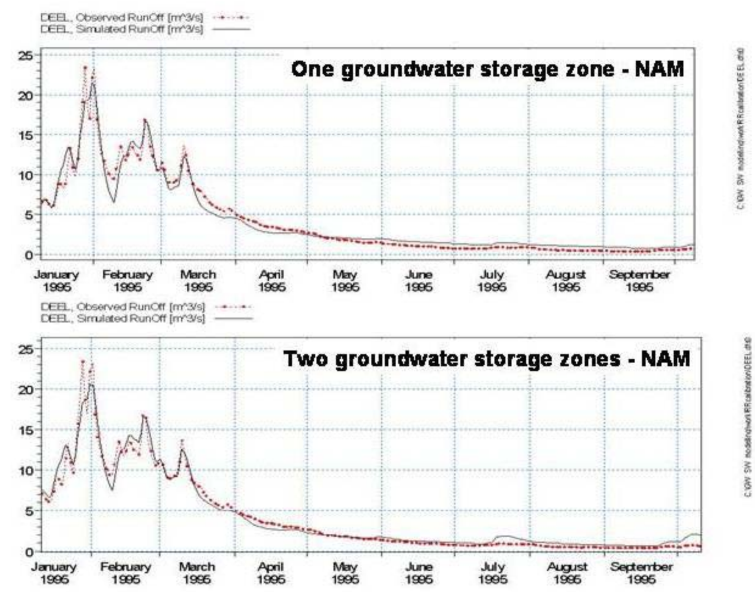

Figure 3.28. An example of the difference in the NAM simulation between modelling with one groundwater storage zone and two groundwater storage zones for the Deel catchment.

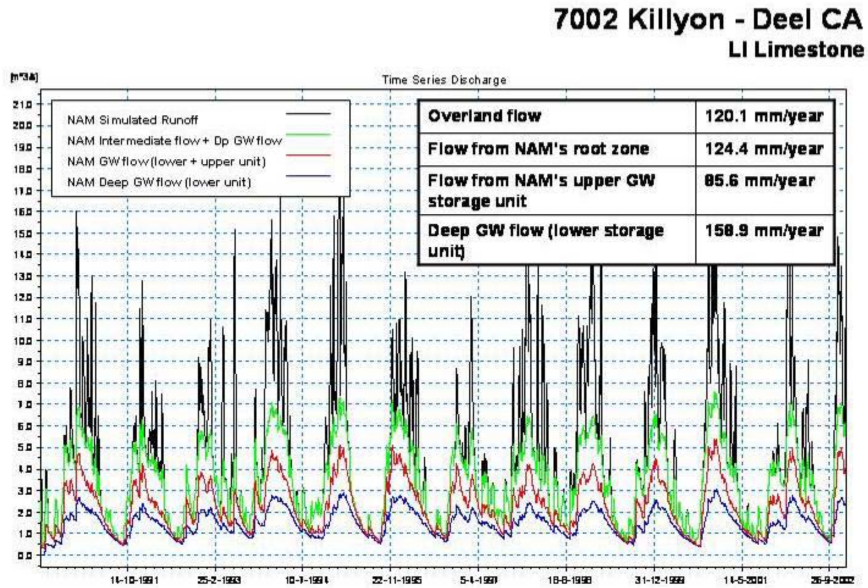

Figure 3.29. The hydrograph separation from the NAM simulation for the Deel catchment at the Killyon station (7002).

3.5.4 Ryewater – Gauge No. 09001 at Leixlip

The NAM model for the Ryewater catchment was run from June 1994 to December 2002. The simulation was not started until June 2006 is because there are a number of small gaps in the recorded discharge data (ranging from two weeks to two months) in 1990 to 1993. The water balance and R^2 correlation between the recorded and simulated hydrographs are good (Figure 3.30). The components of overland, intermediate and deep groundwater flow are illustrated in Figure 3.31.

The NAM estimates are: 121 mm/yr contribution of deep groundwater flow, 85 mm/yr intermediate flow and 171 mm/yr overland flow. Table 3.8 includes a compilation of the estimates from the variation separation techniques. A comparison of the results suggests that the NAM's deep groundwater flow and overland flow estimates compare well with the results from the Master Recession Curve analysis and the Unit Hydrograph method. Groundwater throughput calculations may, therefore, overestimate deep groundwater in this catchment.

Table 3.8. Estimates and comparisons of various components of flow for the Ryewater catchment based on the selected hydrograph separation techniques.

Parameter	**Contribution of parameter**
Simulated Effective Rainfall	377 mm/yr
Unit Hydrograph estimate of overland flow	191 mm/yr
Groundwater throughput calculation of deep groundwater contribution *(+ flow through weathered zone)*	158-232 mm/yr *(256-332 mm/yr)*
Master Recession Curve estimate of deep groundwater flow	110 mm/yr
NAM overland contribution	171 mm/yr
NAM estimate of intermediate flow	85 mm/yr
NAM deep groundwater contribution	121 mm/yr

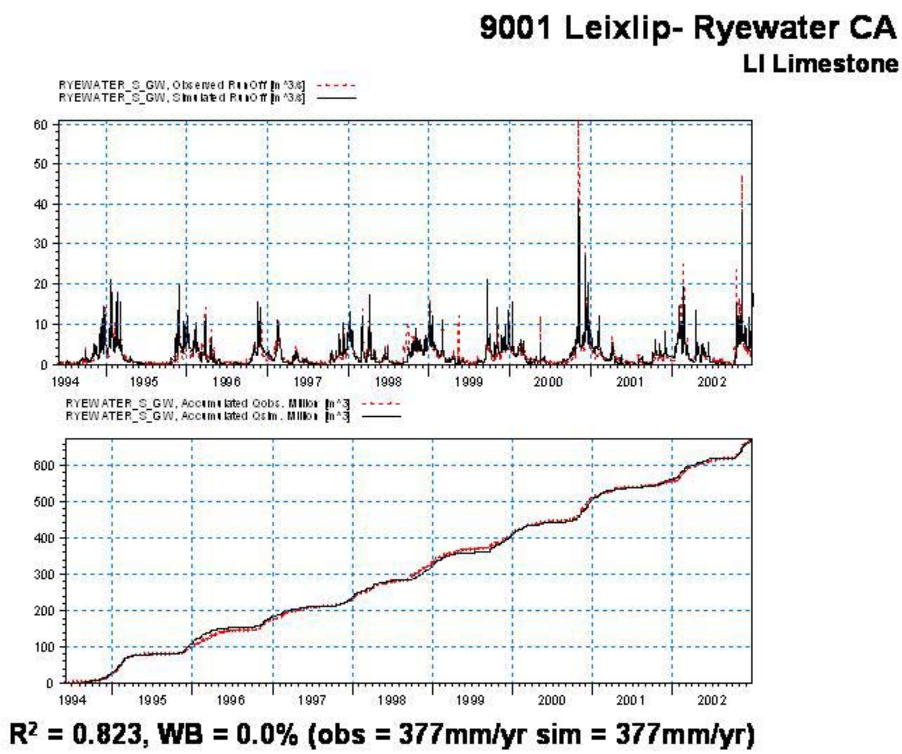

Figure 3.30. NAM simulation correlated with the recorded hydrograph data for the Ryewater catchment at the Leixlip station (33006).

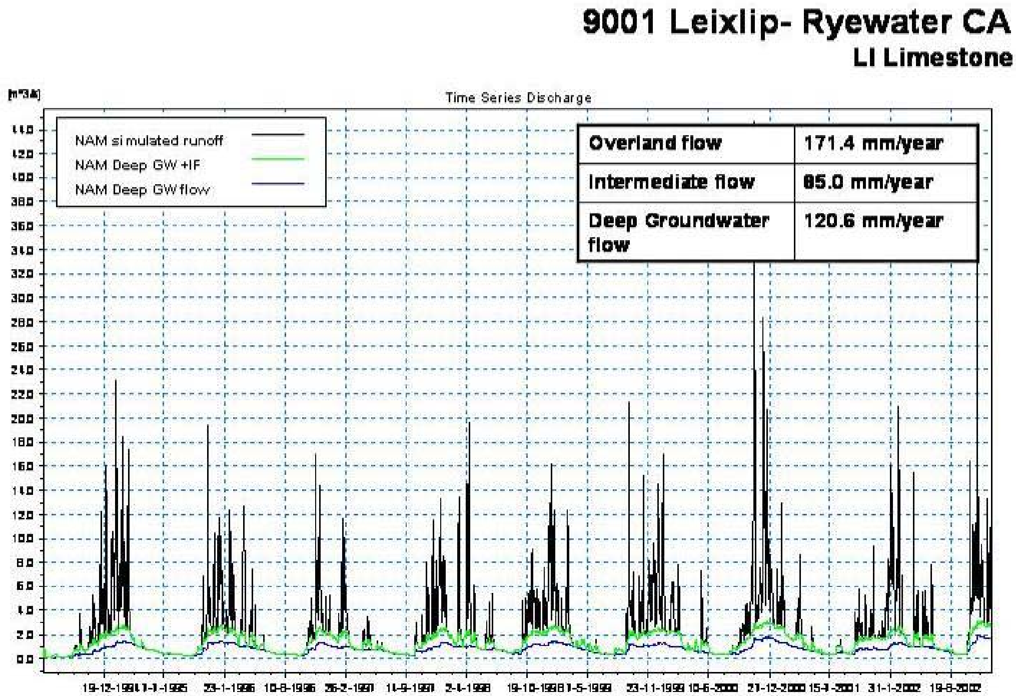

Figure 3.31. The hydrograph separation from the NAM simulation for the Ryewater catchment at the Leixlip station (33006).

3.5.5 Suck – Gauge No. 26007 at Bellagill

The NAM model for the Suck catchment was run for the period January 1990 to December 2002. The water balance and R^2 correlation between the recorded and simulated hydrographs are good (Figure 3.32). The components of overland, intermediate and deep groundwater flow are illustrated in Figure 3.33. The NAM estimates are: 171 mm/yr contribution of deep groundwater flow, 362 mm/yr intermediate flow and 124 mm/yr overland flow.

Table 3.9 includes a compilation of the estimates from the various separation techniques. The NAM deep groundwater flow estimate compares well with the estimate from the Master Recession Curve analysis. There is no deep groundwater flow estimate for the Suck catchment from groundwater throughput calculations. The estimate of the overland flow from the NAM model does not correlate well with the estimate of overland flow from the Unit Hydrograph method. However, the NAM estimate is considered to be more representative, because the Unit Hydrograph method does not account for the loss of surface runoff via karst features e.g. swallow holes. The NAM intermediate component of flow is interpreted as comprising conduit flow and flow from peat.

Table 3.9. Estimates and comparisons of various components of flow for the Suck catchment based on the selected hydrograph separation techniques.

Parameter	Contribution of parameter
Simulated Effective Rainfall	656 mm/yr
Unit Hydrograph estimate of overland flow	149 mm/yr
Groundwater throughput calculation of deep groundwater contribution	No estimate
Master Recession Curve estimate of deep groundwater flow	234 mm/yr
NAM overland contribution	124 mm/yr
NAM estimate of intermediate flow	362 mm/yr
NAM deep groundwater contribution	171 mm/yr

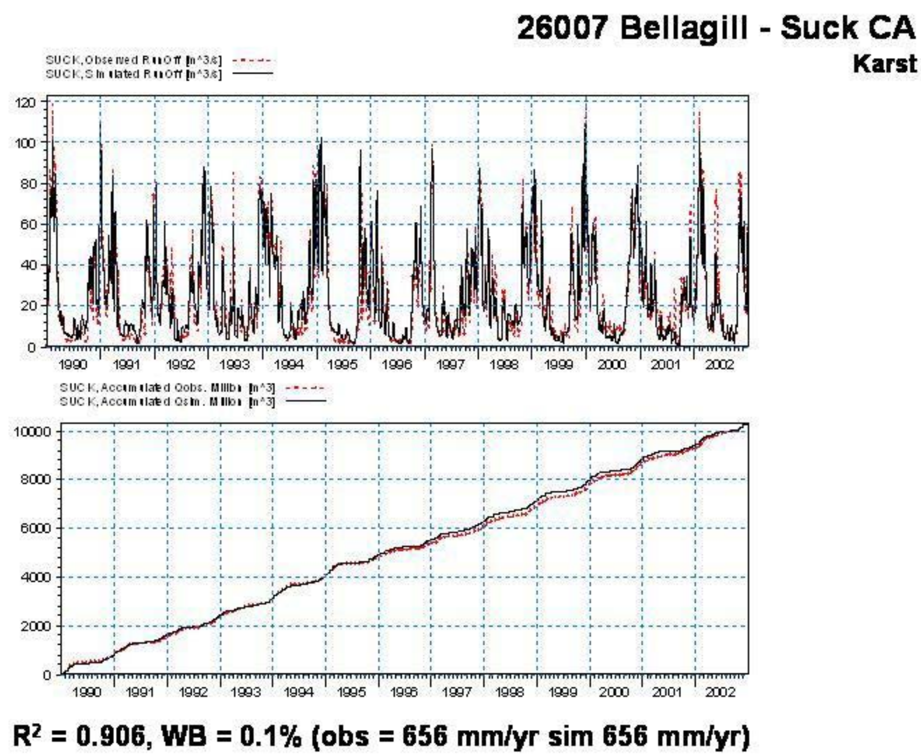

Figure 3.32. NAM simulation correlated with the recorded hydrograph data for the Suck catchment at the Bellagill station (26007).

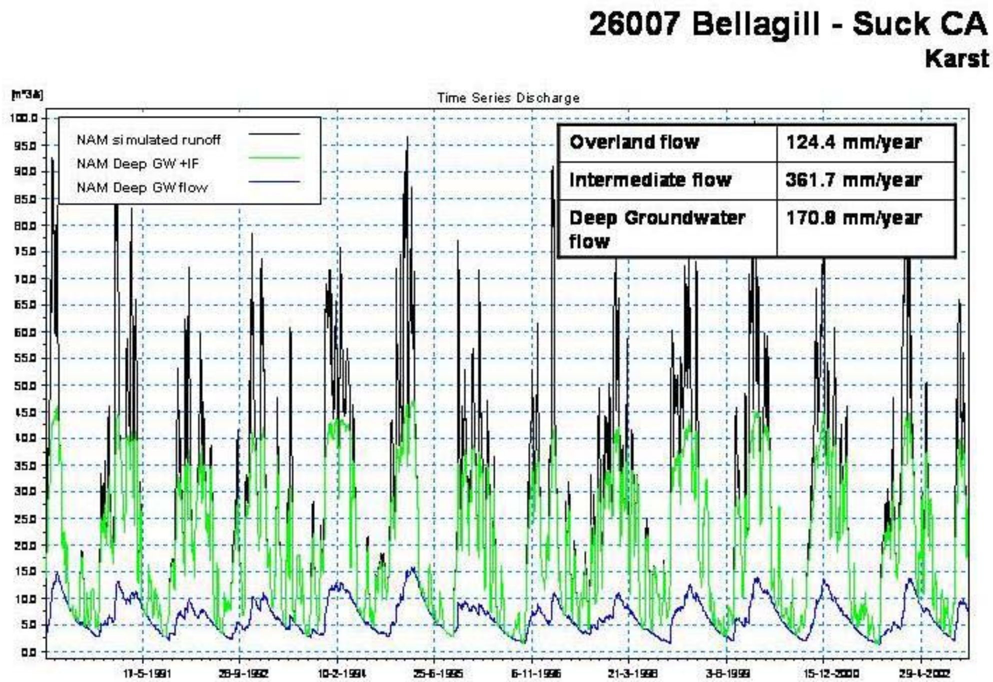

Figure 3.33. The hydrograph separation from the NAM simulation for the Suck catchment at the Bellagill station (26007).

3.5.6 Boro – Gauge No. 12016 at Dunanore

The NAM simulation for the Boro catchment was run for the period January 1990 to December 1995. The simulation was ended in 1995 because there are no discharge data between 1996 and 2003. The water balance and R^2 correlation between the recorded and simulated hydrographs are good (Figure 3.34). The groundwater storage zone has been split into two because an additional slow flow component has been identified in the comparison between the recorded and simulated hydrographs. The components of overland flow, flow from the root zone storage, flow from the upper groundwater storage and deep groundwater flow are illustrated in Figure 3.35.

The NAM estimates are: 231 mm/yr overland flow, 104 mm/yr flow from the root zone storage, 112 mm/yr flow from the model's upper groundwater storage zone, and 240 mm/yr deep groundwater flow (from the lower groundwater storage zone). Table 3.10 includes a compilation of the estimates from the variation separation techniques.

The contribution of overland flow to total river flow estimated using NAM is similar to that estimated by the Unit Hydrograph method. A comparison of the estimates of deep groundwater flow from the various techniques suggests that the Master Recession Curve identifies another slow flow regime as well as the deep groundwater (the Master Recession Curve analysis result – 388 mm/yr – is similar to NAM's combined deep groundwater flow and flow from the upper storage zone). The estimate of deep groundwater flow from throughput calculations corresponds very well with the combined NAM estimates. The combination of the NAM model's flow from the root zone storage and flow from the upper groundwater storage zone represent intermediate flow.

Table 3.10. Estimates and comparisons of various components of flow for the Boro catchment based on the selected hydrograph separation techniques.

Parameter		**Contribution of parameter**
Simulated Effective Rainfall		690 mm/yr
Unit Hydrograph estimate of overland flow		215 mm/yr
Groundwater throughput calculation of deep groundwater contribution		330 mm/yr
Master Recession Curve estimate of deep groundwater flow		388 mm/yr
NAM overland contribution		231 mm/yr
NAM estimate of intermediate flow	NAM estimate of flow modelled from root zone storage	104 mm/yr
	NAM estimate of flow modelled from upper groundwater storage	112 mm/yr
NAM deep groundwater contribution		240 mm/yr

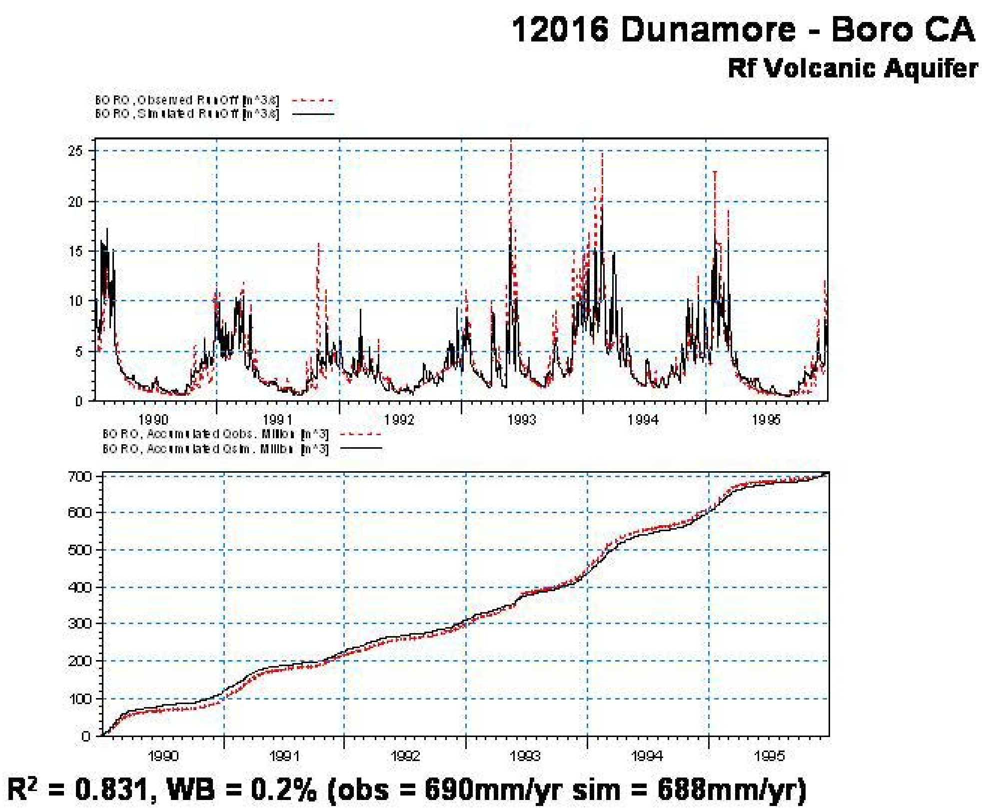

Figure 3.34. NAM simulation correlated with the recorded hydrograph data for the Boro catchment at the Dunamore station (12016).

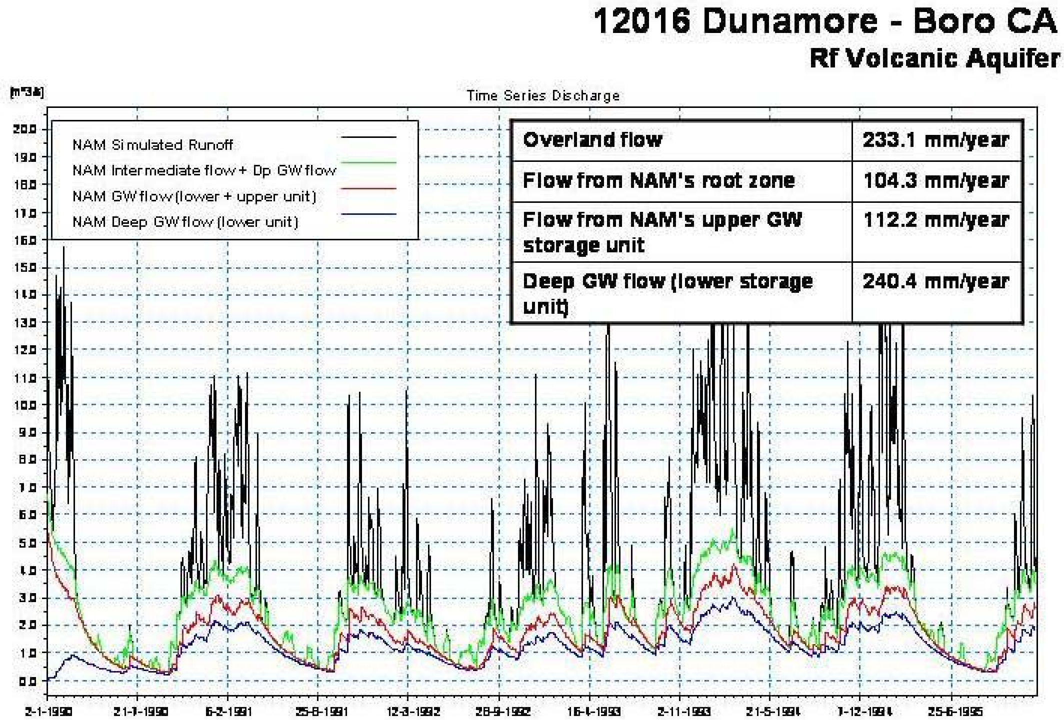

Figure 3.35. The hydrograph separation from the NAM simulation for the Boro catchment at the Dunamore station (12016).

3.5.7 Bride – Gauge No. 18001 at Mogeely

The NAM simulation was run for the period January 1990 to October 2000. Both the water balance, and the R^2 correlation between the NAM simulated and recorded hydrographs are good (Figure 3.36). The NAM model was initially run using one slow flow component. However, the overall separations suggested that there was only a small intermediate component and that there may be two groundwater storages. For this reason the groundwater storage zone was split into two and four components of flow were modelled (Figure 3.37).

The NAM estimates are: 200 mm/yr contribution of deep groundwater flow from a lower groundwater storage zone, 35 mm/yr flow from an upper groundwater storage zone, 234 mm/yr contribution from the root zone and 352 mm/yr from overland flow. The results from each of the analyses are presented in Table 3.11.

The NAM estimates of overland flow and deep groundwater flow compare well with estimates from the Unit Hydrograph method and groundwater throughput calculations. The estimate for deep groundwater flow from the Master Recession Curve analysis (537 mm/yr) is larger than the combination of flows from NAM's deep groundwater, flow from the upper groundwater storage zone and flow from the root zone storage (468 mm/yr). It is considered that the flow from the lower groundwater storage zone and the root zone storage represent intermediate flow.

Table 3.11. Estimates and comparisons of various components of flow for the Bride catchment based on the selected hydrograph separation techniques.

<table>
<tr><th colspan="2">Parameter</th><th>Contribution of parameter</th></tr>
<tr><td colspan="2">Simulated Effective Rainfall</td><td>820 mm/yr</td></tr>
<tr><td colspan="2">Unit Hydrograph estimate of overland flow</td><td>336 mm/yr</td></tr>
<tr><td colspan="2">Groundwater throughput calculation of deep groundwater contribution (+ flow through weathered zone)</td><td>111-153 mm/yr*
(200-221 mm/yr)*</td></tr>
<tr><td colspan="2">Master Recession Curve estimate of deep groundwater flow</td><td>537 mm/yr</td></tr>
<tr><td colspan="2">NAM overland contribution</td><td>352 mm/yr</td></tr>
<tr><td rowspan="2">NAM estimate of intermediate flow</td><td>NAM estimate of flow modelled from root zone storage</td><td>234 mm/yr</td></tr>
<tr><td>NAM estimate of flow modelled from upper groundwater storage</td><td>35 mm/yr</td></tr>
<tr><td colspan="2">NAM deep groundwater contribution</td><td>200 mm/yr</td></tr>
</table>

* estimate for Old Red Sandstone part of catchment only.

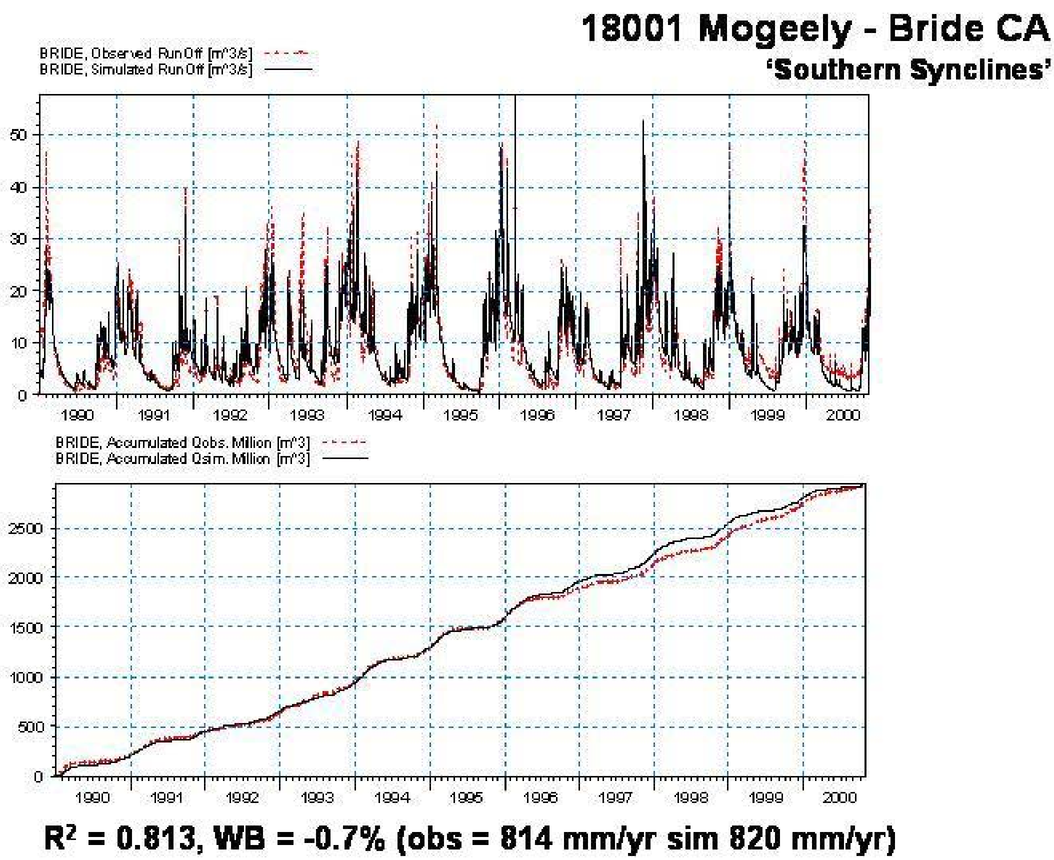

Figure 3.36. NAM simulation correlated with the recorded hydrograph data for the Bride catchment at the Mogeely station (18001).

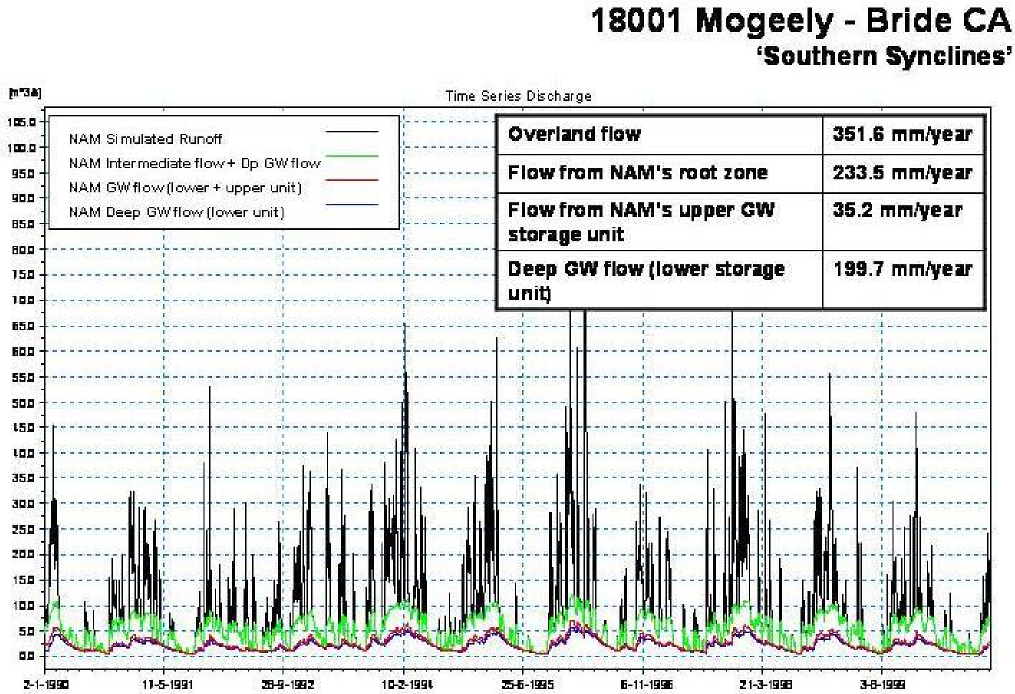

Figure 3.37. The hydrograph separation from the NAM simulation for the Bride catchment at the Mogeely station (18001).

3.6 Regionalisation of NAM parameters

The parameter values within a NAM model control the quantity of components of flow from the model's three storage units. The parameters will vary depending on the physical characteristics of each hydrogeological scenario. For example, the '*coefficient for overland flow'* will be greater for a catchment with steep slopes, poorly drained soils and poorly productive aquifers than for a relatively flat catchment with free draining soils and productive aquifers. The physical characteristics of catchments can be determined by the assessment of GIS datasets. One of the aims of this study has been to link the physical characteristics of each of the pilot catchments with the NAM parameters. It is the determination of NAM parameters for the various hydrological and hydrogeological scenarios that should be used to guide the modelling of further catchments nationally.

The various flow contributions within the NAM simulations of the the pilot catchments have been constrained based on the various hydrograph separation and analytical techniques used to determine the components of overland, intermediate and deep groundwater flow. The NAM parameters derived through the modelling of the pilot catchments are presented in Table 3.12.

Table 3.12. NAM parameters selected for the numerical modelling of the pilot catchments.

NAME	U_{MAX}	L_{MAX}	CQ_{OF}	CK_{IF}	$CK_{1,2}$	T_{OF}	T_{IF}	T_G	CK_{BF1}	CQ_{LOW}	CK_{BF2}
RYEWATER	15.2	110	0.90	700.0	13.9	0.517	0.300	0.15	2600	0	0
SHOURNAGH	10	100	0.80	219.3	18.1	0.570	0.150	0.25	2400	0	0
OWENDUFF	10.6	103	0.90	216.1	10.4	0.415	0.361	0.6	3083	0	0
SUCK	19.5	208	0.68	209.9	50.0	0.659	0.525	0.485	2600	0	0
BRIDE	15.7	287	0.75	300.0	18.5	0.665	0.437	0.55	1000	85	1750
DEEL	17	286	0.80	600.0	47.6	0.769	0.450	0.2	1000	65	2800
BORO	19.6	294	0.69	778.0	32.3	0.712	0.068	0.3	1100	75	2106

For the modelling of further catchments, the NAM parameters that can be estimated using catchment physical characteristics are the coefficient for overland flow (CQ_{OF}), the time constant for overland flow ($CK_{1,2}$), the surface storage zone (U_{MAX}), the time constant for interflow (CK_{IF}) and the time constant for baseflow (CK_{BF}). A series of decision tables have been developed to determine these NAM parameters – these have been based on the assessment of GIS datasets for the pilot catchments, as well as expert judgement (e.g. gravels scenario).

3.6.1 Coefficient of Overland Flow (CQ_{OF})

The key catchment features influencing the *coefficient of overland flow* (CQ_{OF}) in NAM are the aquifer type, soil type, subsoil permeability, areas of extreme vulnerability and slope.

Overland flow in NAM will not occur until the surface storage zone (U_{MAX}) has been filled. Once there is net precipitation, and the U_{MAX} value is reached, then further net precipitation will become overland flow as well as recharge. If the aquifer and overlying substrate are highly impermeable, then the majority of the precipitation will become overland flow. The decision table to determine the value of CQ_{OF} for each catchment is presented in Table 3.13. The determination of the range of CQ_{OF} is initially based on the aquifer type of the catchment. The catchments that consist of dominantly poorly productive aquifers have a relatively high value of CQ_{OF} compared to the more permeable karstic, fissured and gravel aquifers. The refinement of the value of CQ_{OF} within the range can be determined by considering the proportion of wet soils, extreme vulnerability, the dominant permeability of the subsoils and average slope of the catchment. The corresponding range of CQ_{OF} values for the pilot catchments is shown to the right of Table 3.13. For a catchment that contains a mixed aquifer scenario, the CQ_{OF} value can be estimated based on the area proportion of each type of aquifer in the catchment.

For karstic and fissured aquifers CQ_{OF} values can be relatively high, because the overburden will have a strong influence on recharge. Similarly, the values of CQ_{OF} for the gravels can be relatively high, and can be wide-ranging. The value chosen for a catchment is based on expert judgement and is dependent on the proximity of gravels to the rivers or streams in a catchment. If gravels are close to a stream or along the length of the river bed, the groundwater table during the winter months would be expected to be relatively high within them. Consequently, the recharge within the gravels may be limited compared to gravels further away from the stream. For this reason if gravels are in close proximity to a river (e.g. along the Nore River) then the CQ_{OF} would be expected to be nearer to 0.6 and if they are not in close proximity to a river (e.g. Curragh) the CQ_{OF} would be expected to be nearer to 0.2. This does not suggest that there would be 60% overland flow modelled above gravels along rivers. The equation for the amount of overland flow in NAM is presented below:

$$Q_{OF} = \begin{cases} CQ_{OF} \cdot \dfrac{(L/\,L_{MAX}) - T_{OF}}{1 - T_{OF}} \cdot P_N & \text{for } L/\,L_{MAX} > T_{OF}, \quad \textit{Equation 16a} \\ 0 & \text{for } L/\,L_{MAX} =< T_{OF}, \quad \textit{Equation 16b} \end{cases}$$

The gravels in Ireland have a recharge value in the region of 90% (Brown *et al.*, 2006) and, as such, would have a high *threshold value for overland flow* – probably greater than 0.8. Until the relative soil moisture content (L/L_{MAX}) reaches the threshold for overland flow, no overland flow will occur. Once the relative soil moisture content exceeds the threshold value for overland flow, then the percentage of overland flow will become proportional to [($L/\,L_{MAX}$ –T_{OF}/ (1-T_{OF})] and CQ_{OF}. For example, if CQ_{OF} equals 60%, T_{OF} equals 0.8, and $L/\,L_{MAX}$ equals 0.9, then the percentage of overland flow will be 30%. Only when $L/\,L_{MAX}$ becomes 1.0 will there be 60% overland flow, i.e. when the root zone becomes completely saturated.

Table 3.13. Decision table for the determination of the NAM coefficient of overland flow (CQ_{OF}).

NAM Parameter	Regional Aquifers	Broad range of NAM parameter value	Characteristics of vulnerability, suboils, soils and slope datasets		Refinement of NAM parameter value	Pilot catchment
CQ_{OF}	Pl / Pu / Ll	0.5 – 0.9	High % of poorly drained soils (>30%)		**0.9** if poorly drained soils >50%	Owenduff
					0.8 – 0.9	
			Low % of poorly drained soils (<30%)	High % of low permeability subsoils (>50%) or slope >5%	**0.8**	Shournagh / Boro (Ll/Pl) / Bride (Ll)
				Low % of extreme vulnerability (<30%)	**0.7 – 0.85** Tend towards **0.85** if slope >5%	
				Otherwise	**0.5 – 0.7**	
	Rkd / Rkc	0.5 – 0.7	High % of extreme vulnerability (>30%) or low % of low permeability subsoils (<30%)		**< 0.5**	Bride (Rkd)

			Otherwise		**> 0.5**	Suck
	Rf / Lm	0.5 – 0.8	High % of poorly drained soils (>30%)		**0.7 – 0.8**	
			Low % of poorly drained soils (<30%)		**0.5 – 0.7**	Boro (Rf)
	Rg / Lg	0.2 – 0.6	Proximity to river	Gravels close to river	**0.6**	
				Gravels not close to river	**0.2**	

3.6.2 Surface Storage Zone (U_{MAX})

The *surface storage zone* in a catchment (U_{MAX}) in NAM is controlled by vegetation – which can intercept moisture – and depressions. The amount of water that is stored in the surface storage zone is also controlled by evaporation and drainage to the subsurface. The decision table for Umax is based mainly on the type of land cover in a catchment area (Table 3.14). The range of Umax values for the pilot catchments are controlled by the proportion of forestry, agricultural land and outcropping rock. Forestry has a higher potential to intercept the moisture from rainfall compared to agricultural land and bare rock.

Table 3.14. Decision table for the determination of the NAM surface storage zone (U_{MAX}).

NAM Parameter	**Corine**	**Broad range of NAM parameter value**	**Slope**	**Lakes**	**Poorly drained soils**	**Urban**	**Pilot catchment**
U_{MAX} (mm)	>5% Forestry & Semi-natural areas	**15 -25**	Steep slope (>5%): lower end of limit	Lakes > 1%: 15 – 20	High percentage of poorly drained soils (>50%): upper end of limit	If >2% urban areas: upper end of limit	Boro / Bride
	Forestry 0 – 5% & Pastures > 40%	**10 – 20**	Relatively flat slope (<5%): upper end of limit		Low percentage of poorly drained soils		Suck / Deel / Ryewater / Shournagh

	Forestry 0%, Pastures <40% and Bare rock >20%	**8 - 15**			(<20%): lower end of limit		Owenduff

The U_{MAX} value selected for a catchment can be further refined dependent upon the average slope, coverage by lakes, coverage by wet soils and the amount of urban area. For example, the U_{MAX} value would be expected to be at the lower end of the land cover ranges if the average slope of a catchment is relatively steep (>5%). Also, a high percentage of lakes will act as storage, resulting in a value of U_{MAX} at the upper end of the land cover ranges. Similarly, a high proportion of wet soils and urban areas will intercept rainfall and affect U_{MAX}.

3.6.3 Time Constant for Intermediate Flow (CK_{IF})

The key drivers that have been found to influence the *time constant for intermediate flow* (CK_{IF}) from the work on the pilot catchments include the average and slope, and permeability of the subsoil. The decision table for CK_{IF} is presented in Table 3.15. The initial decision on determining the CK_{IF} is based on the average catchment slope. If the catchment is very steep (average slope > 10%), then the CK_{IF} will be relatively low (approximately 200 hours) and the subsoil permeability has no influence. For catchments with an average slope between 5% and 10%, the CK_{IF} will vary greatly depending on the subsoil permeability and percentage of extreme vulnerability. The exception is found with catchments that contain greater than 20% peat. The contribution of flow from peat can be very slow and overprint other subsoil parameters. For catchments with a low average slope, long intermediate flow time constants are expected, irrespective of the subsoil permeability.

Table 3.15. Decision table for the determination of the NAM constant for intermediate flow (CK_{IF}).

NAM Parameter	Slope / Bedrock aquifer	Refinement of NAM parameter value and subsoils			Pilot catchment
CK_{IF} (hours)	Slope >0.07	**~ 200**			Owenduff
	Slope 0.03 – 0.07	**~ 400**	Low permeability subsoils > 40%	**400 - 800**	Boro
			Low permeability subsoils 20% - 40%	**300 - 600**	
			Low permeability subsoils < 20%	**200 – 300**	Shournagh / Bride
			Peat > 20%	**> 600**	
	Slope <0.03	**> 600**			Deel / Ryewater
	Karst or productive fissured bedrock aquifer	**< 400**	If > 50% peat: **> 600**		Suck

The aquifer type will also affect the timing of the intermediate flow component, but is masked by the slope and permeability catchment descriptors. The exception to this is in the case of karstified limestone, where shallow groundwater flows through solution-enlarged fissures in the upper epikarstic layer. Groundwater flow through epikarst is rapid and, in turn, the intermediate flow time constant is expected to be short (< 400 hours), except in circumstances of a high proportion of peat in a catchment.

3.6.4 Time Constant for Deep Groundwater Flow (CK_{BF1}, or CK_{BF2} in the instance of separating the groundwater storage zone)

The *time constant for deep groundwater flow* in NAM is primarily controlled by the aquifer types in a catchment. The decision table for the time constant for deep groundwater flow is presented in Table 3.16. For poorly productive Pl and Pu aquifers (such as the granites in the west of Ireland), the time constant will be greater than 3000 hours, independent of the slope (the transmissivity will be extremely low). For poorly productive Ll aquifers the time constant has been found to range between 2000 and 3000 hours. Karstic or productive fissured bedrock aquifers generally have lower time constants. However, the modelled time constant may be modified based on the average slope and/or percentage of peat in the catchment. For a catchment that contains a mixed aquifer scenario, the CK_{BF1} value can be estimated based on the area proportion of each type of aquifer in the catchment.

Table 3.16. Decision table for the determination of the NAM time constant for deep groundwater flow (CK_{BF}).

<table>
<tr><th>NAM Parameter</th><th>Regional Aquifers</th><th colspan="3">Refinement of NAM parameter value</th><th>Pilot catchment</th></tr>
<tr><td rowspan="4">CK_{BF1}</td><td>Pl / Pu</td><td colspan="3">> 3000</td><td>Owenduff</td></tr>
<tr><td rowspan="3">Ll</td><td rowspan="3">2000 – 3000</td><td>> 20% peat and < 5% slope: tend towards 3000</td><td rowspan="3">If modeller identifies another component of slow flow then: CK_{BF1} 1000 – 1500 and CK_{BF2} determined from rules to the left.</td><td>Deel</td></tr>
<tr><td>Otherwise ~ 2500</td><td>Ryewater</td></tr>
<tr><td>< 20% peat and > 5% slope: tend towards 2000</td><td>Shournagh / Bride (Ll)</td></tr>
</table>

	Karst or productive fissured bedrock aquifer	**< 2500**	If peat > 30%: CK_{BF1} **> 2500**	If modeller identifies another component of slow flow then: CK_{BF1} **1000 – 1500** and CK_{BF2} **> 2500**	Boro (Rf) / Bride (Rkd) / Suck (Rkc)

The time constant for deep groundwater flow is expressed as CK_{BF1} for the Owenduff, Shournagh, Ryewater and Suck catchments. The NAM model's groundwater storage zone has been separated into two (a lower and upper unit) for the Deel, Boro and Bride catchments because an additional component of slow flow was identified in the recorded discharge dataset compared to the simulated model. In this instance, the time constant for deep groundwater flow (from the lower unit) is expressed as CK_{BF2} and the time constant for the additional slow flow component (from the upper unit) is expressed as CK_{BF1}. In further NAM modelling there may be an argument to separate the NAM model's groundwater storage zone of flow into lower and upper units where more than one slow flow recession can be identified in the recorded hydrograph. In this case, the time constant CK_{BF1} will represent a slow flow time constant that should be estimated by the modeller to be within a range that is greater than the NAM model's time constant for intermediate flow (CK_{IF}), but less than the time constant for deep groundwater flow (CK_{BF2}). If the slow component of flow in a catchment is separated into two components, then the selection of CK_{IF} should still be estimated using the decision tree in Table 3.15.

If the groundwater storage zone is separated into two, then the percentage peat in a catchment will still affect the value of CK_{BF2}. This is because the time constant for deep groundwater flow takes into account the time taken for flow through the peat substrate as well as through the aquifer.

3.6.5 Other NAM parameters

The parameters for the NAM modelling that have *not* been estimated based on the pilot catchments are the maximum soil moisture content in the root zone storage available for vegetative transpiration (L_{MAX}, measured in mm) and the threshold values for overland flow, intermediate flow and deep groundwater flow (the L/L_{MAX} value at which that component of flow occurs).

Based on NAM modelling of the Neagh Bann catchment study in Northern Ireland (Bell *et al.*, 2005) it is suggested to use the following default values for the initial modelling of further national catchments:

Maximum soil moisture content in the root zone storage, L_{MAX}: 120 mm;
Threshold value for overland flow, T_{OF}: 0.6;
Threshold value for intermediate flow, T_{IF}: 0.5;
Threshold value for groundwater flow, T_G: 0.4.

The value of these parameters should be altered during the modelling to improve the correlation and water balance. There are certain circumstances within catchments that will indicate the threshold values. If a catchment has mainly dry soils or high permeability subsoils, then the threshold value for overland flow (T_{OF}) will tend towards unity, i.e. the root zone storage must be saturated before overland flow will occur. If a catchment contains mainly exposed karst aquifers or gravel aquifers, then the threshold value for overland flow (T_{OF}) will tend towards unity, and the threshold value for intermediate flow (T_{IF}) will tend towards zero, i.e. flow will be routed to the intermediate component almost as soon as precipitation occurs.

3.7 Sensitivity of the NAM model

Optimum NAM parameters have been derived for the pilot catchments (Table 3.17). These parameters have been selected from within the bounds of the model's suggested range. Altering the parameters affects both the correlation and water balance between simulated and recorded hydrographs, and the quantity of flow contributed from the different pathways. The NAM parameters have been altered for the Ryewater catchment to assess the sensitivity of the model.

Table 3.17. Modelled NAM parameters for the Ryewater catchment and NAM's suggested boundary values.

NAM Parameter	Modelled Value	Suggested Lower Bound	Suggested Upper Bound
U_{MAX}	15.2	10	20
L_{MAX}	110	100	300
CQ_{OF}	0.90	0.1	1.0
CK_{IF}	700	200	1000
$CK_{1,2}$	13.9	10	50
T_{OF}	0.517	0	0.99
T_{IF}	0.300	0	0.99
T_G	0.150	0	0.99
CK_{BF}	2600	2	4000

The approach taken has been to consider the effects on the simulation and contributions to flow of successively increasing and decreasing each parameter by 25% of NAM's suggested range, one at a time (Table 3.18).

In general, altering a NAM parameter value by 25% within the suggested range has little effect on the correlation between the simulated and recorded hydrographs, and the water balance. However, the results of the correlation and the water balance are poorer with the altered parameters and would suggest that optimum NAM parameters have been modelled for the Ryewater catchment.

The results of the contributions of flow from overland, intermediate and deep groundwater pathways vary by a large amount (Table 3.18). However, the mean, median and mode values are similar to the results from the optimim modelled catchment, and the standard deviation is quite small (22 mm/yr maximum) (Table 3.19).

The effect of altering two or more NAM parameters from the optimum modelled values will be to further worsen the correlation (R^2 value) between the simulated and recorded hydrograph, and the water balance. The limitations on attaining a good correlation and water balance is the size of the catchment (catchments greater than 200 km^2 are generally modelled more easily than catchments less than 200 km^2 with the same available discharge and meteorological data), a sufficient length of rainfall timeseries for a catchment (generally greater than five years) that has few gaps, the location of rainfall stations in a catchment over a range of topographies that might exist, a sufficient length of discharge data that overlaps with the rainfall data, and few lakes or no artificial controls (e.g. weirs) that can artificially affect the recorded discharge curve.

Table 3.18. Results from altering successive parameters of the NAM modelling by 25% of the suggested range.

Parameter	**Correlation (R^2)**	**Water Balance (%)**	**Overland Flow (mm/yr)**	**Intermediate flow (mm/yr)**	**Deep GW flow (mm/yr)**
Results for optimum modelled parameters	**0.823**	**0.0**	**171**	**85**	**121**
U_{MAX} = 12.7	0.810	0.9	180	67	130
U_{MAX} = 17.7	0.817	2.6	160	90	127
L_{MAX} = 100	0.810	1.2	175	79	123
L_{MAX} = 160	0.813	4.3	151	76	150
CQ_{OF} = 0.675	0.806	3.1	135	81	161
CQ_{OF} = 1	0.804	1.4	183	78	115
CK_{IF} = 500	0.814	0.7	164	104	109
CK_{IF} = 900	0.797	1.7	195	62	120
$CK_{1,2}$ = 10	0.777	1.9	170	79	128
$CK_{1,2}$ = 23.9	0.805	2.0	169	79	129
T_{OF} = 0.267	0.781	0.6	206	73	98
T_{OF} = 0.767	0.764	3.7	115	83	179
T_{IF} = 0.05	0.819	1.5	164	89	124
T_{IF} = 0.55	0.807	2.4	181	62	134
T_G = 0	0.815	1.7	156	75	146
T_G = 0.40	0.789	2.2	197	85	95
CK_{BF} = 1600	0.819	1.2	170	79	128
CK_{BF} = 3600	0.814	2.4	170	87	120
Range	0.777 – 0.819	0.9 – 4.3	115 - 197	62 - 104	95 - 179

Table 3.19. Mean, median, mode and standard deviation results for the deep groundwater, intermediate and overland flow values from the modelling of the Ryewater catchment with the altered NAM parameters in Table 3.18

Statistics	Deep Groundwater Flow (mm/yr)	Intermediate Flow (mm/yr)	Overland Flow (mm/yr)
Mean	128.3	79.3	169.0
Median	127.0	79.0	170.0
Mode	120.0	79.0	170.0
Standard Deviation	20.1	10.1	21.7

3.8 Summary

Deep groundwater and overland flow components have been quantified for the seven pilot catchments by considering groundwater throughput calculations, and Master Recession Curve and Unit Hydrograph analyses. The results of the analyses have informed the NAM model and constrained the quantities that flow from the three storage units.

Since the amount of rainfall can vary across the country, and because groundwater recharge is related to the amount of rainfall, the results are reported volumetrically in millimetres per year and not as a percentage. The results are summarised in Table 3.20. For the Boro, Bride and Deel catchments, a fourth component of flow has been identified – an upper groundwater storage unit – which is combined with the flow from the NAM model's root zone storage to quantify the intermediate flow in Table 3.20. There is no methodology to assign the contribution of flow from the upper groundwater storage unit of NAM to the components of flow in the conceptual model. However, it is likely to represent a flow contributions from a combination of subsoils (till, peat, gravel) and/or shallow groundwater, depending on the hydrogeological scenario of the given catchment.

Table 3.20. Summary of results for the quantification of deep groundwater flow (red), intermediate flow (green) and overland flow (blue) for the pilot catchments. Abbreviations: NAM (numerical 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 throughput 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**

The deep groundwater component of flow for the NAM model has been constrained by the groundwater throughput calculations for the Boro, Bride, Deel, Owenduff and Shournagh catchments. The Master Recession Curve analyses for these catchments contain an additional component of flow, as well as deep groundwater. In reality, it is difficult to separate deep groundwater flow from hydrographs for Irish hydrogeological scenarios, because the climate is generally continuously wet and there are few drought periods. Consequently, it has been difficult to identify discharge from the deep groundwater storage zone with the Master Recession Curve analysis.

The overland flow component of the NAM model has been constrained using the Unit Hydrograph method. In general, the results correlate well with the NAM model results. However, for the Suck catchment the quantity of overland flow is much larger for the Unit Hydrograph method compared to the NAM model. The reason for this is probably that the Unit Hydrograph method of overland flow separation has not taken into account the loss of surface runoff via karstic features.

Four of the NAM parameters (coefficient for overland flow CQ_{OF}, surface storage zone U_{MAX}, time constant for intermediate flow CK_{IF}, and time constant for deep groundwater flow CK_{BF}) required for the modelling have a relationship to the hydrogeological scenario they occur within. Descision tables have been developed – based on GIS analyses of physical characterics of the pilot catchments – to determine the optimum parameters to be used for modelling.