Section 4: NAM Modelling of Regional Catchments

4.1 Selected Regional Catchments

Catchments of a regional scale in Ireland have been selected for further NAM modelling. The catchment selection was based on size and data quality: catchments greater than 200 km^2 that also have a good rating for the discharge data, at least at low flows. The aim of the modelling was to quantify contributions of deep groundwater flow, intermediate flow and overland flow using the NAM model, based on constraining the parameter selection using experience and the rule-base developed from the pilot catchment study. Thirty-two regional catchments were selected and are presented in Figures 4.1 to 4.4. The associated hydrometric stations are identified in Appendix 3. The key physical characteristics of the selected catchments derived from the GIS datasets are presented in Tables 4.1 to 4.3. A brief description of the physical characteristics of each catchment and comments on the associated hydrometric station is given in Appendix 7.

The stream flow along the River Liffey and the River Shannon is highly regulated. Along the River Shannon, the catchments of tributaries that flow into the river have been selected for numerical modelling. Unfortunately, no suitable catchments that flow into the River Liffey were identified for NAM modelling. The Morrell River is a tributary into the River Liffey with a catchment area of 99 km^2. The hydrometric station at Morrell Bridge (9024) is recorded by data logger which began recording flows in 2001. This catchment would have been modelled, but there are a number of gaps in the discharge record of up to five months.

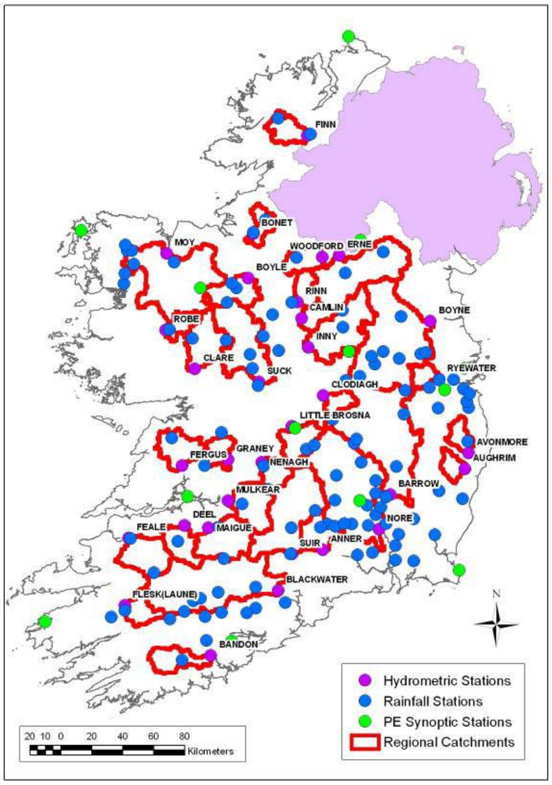

Figure 4.1. Regional catchments selected for NAM modelling.

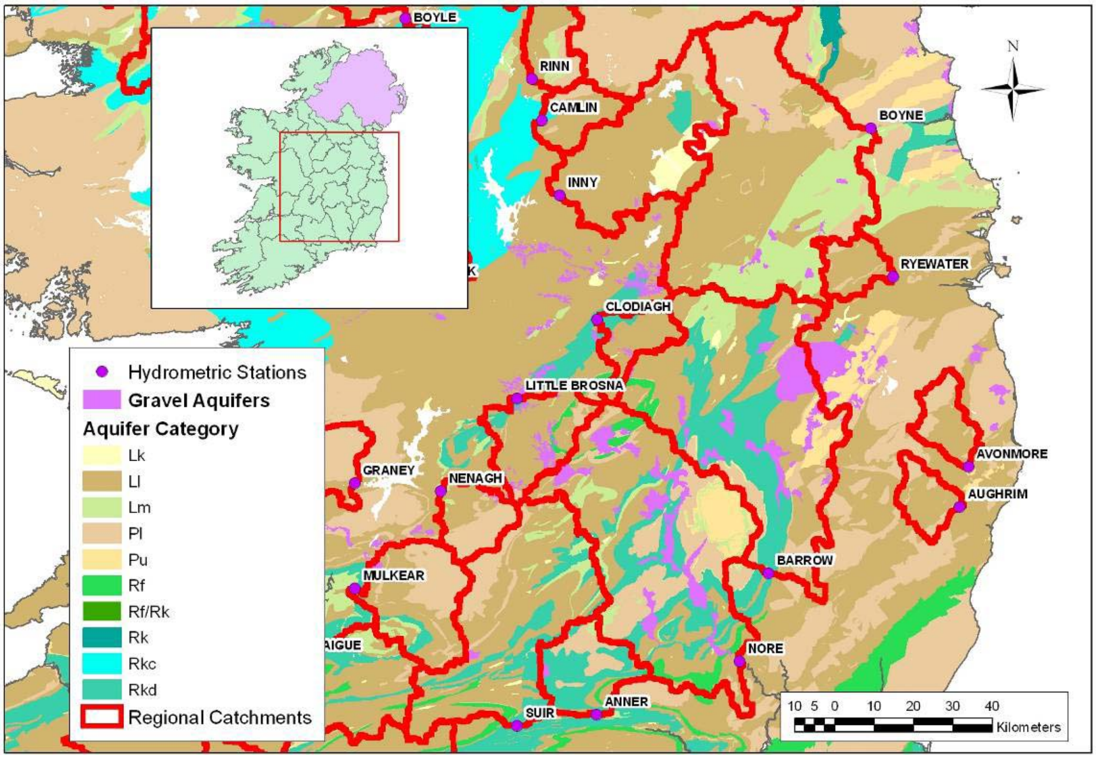

Figure 4.2. Regional catchments selected for NAM modelling in the east, south-east and midlands of the Republic of Ireland.

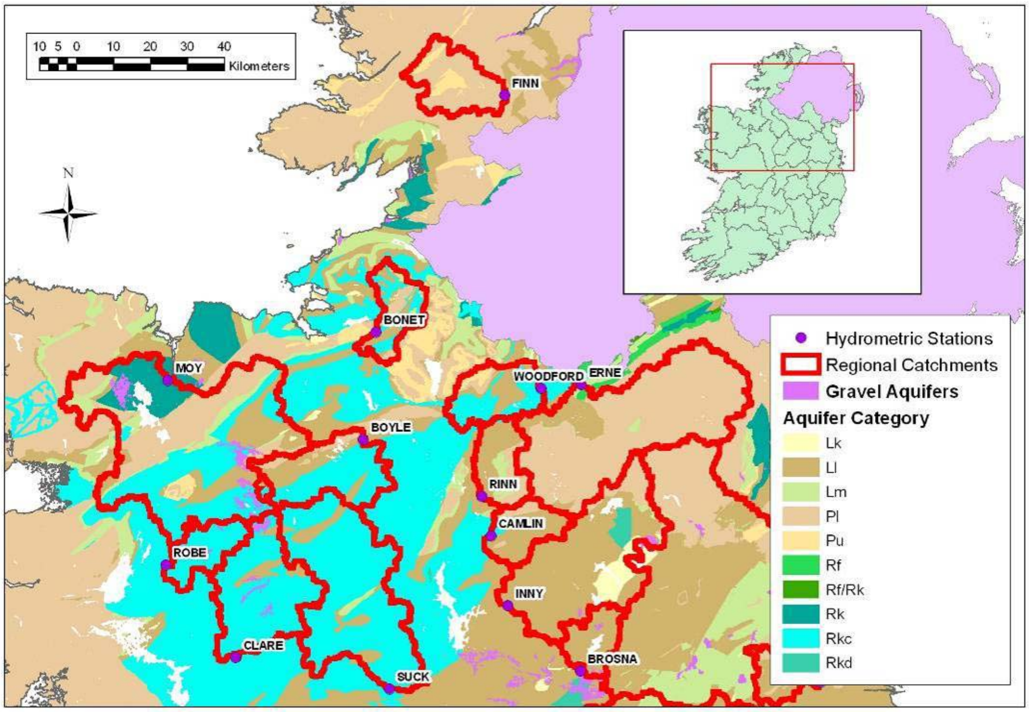

Figure 4.3. Regional catchments selected for NAM modelling in the midlands, west and north-west of the Republic of Ireland.

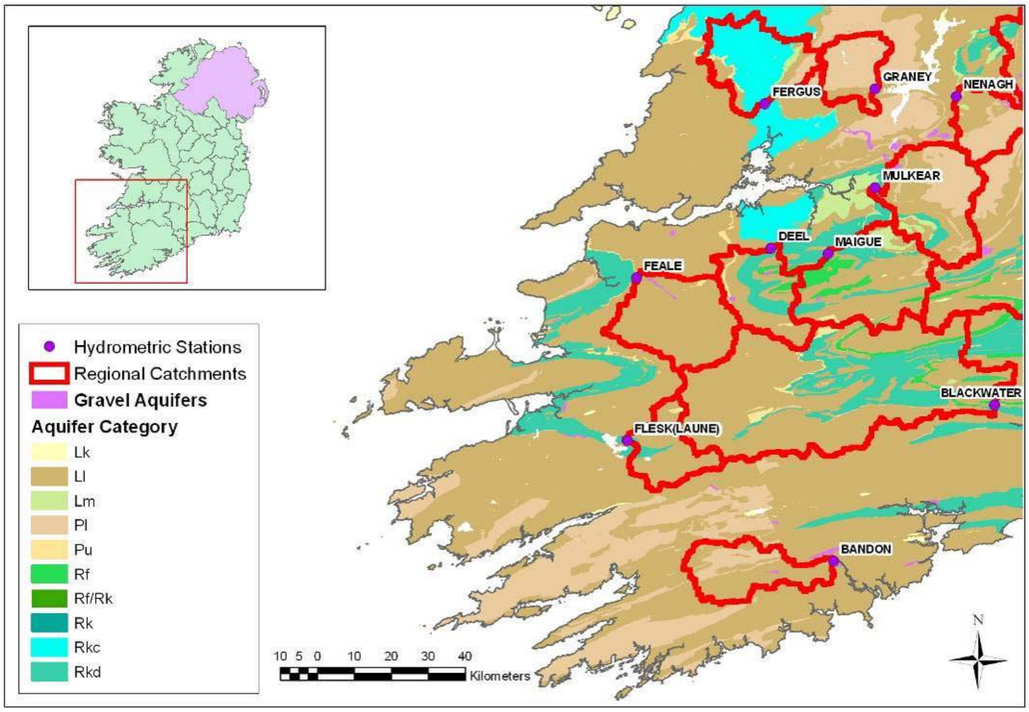

Figure 4.4. Regional catchments selected for NAM modelling in the south-west of the Republic of Ireland

Table 4.1. Percentage of the aquifer types in the selected national catchments.

WATERBODY	LOCATION	STATION_NU	AREA (km^2)	Rk (%)	Rkc (%)	Rkd (%)	Rf (%)	Lm (%)	Ll (%)	Lk (%)	Pl (%)	Pu (%)	GRAVEL (%)
ANNER	ANNER	16010	437	0.0	0.0	55.1	3.9	3.3	13.0	0.0	25.3	0.0	1.8
AUGHRIM	KNOCKNAMOHILL	10028	203	0.0	0.0	0.0	0.0	0.0	65.6	0.0	33.7	0.7	0.0
AVONMORE	RATHDRUM	10002	231	0.0	0.0	0.0	0.0	0.0	56.8	0.0	43.0	0.3	0.0
BANDON	CURRANURE	20002	424	0.0	0.0	0.0	0.0	0.0	77.2	0.0	22.8	0.0	1.6
BARROW	ROYAL OAK	14018	2419	0.0	0.0	31.5	1.4	5.5	41.0	0.0	12.8	6.2	9.5
BLACKWATER	BALLYDUFF	18002	2334	0.0	0.0	18.3	3.1	0.2	75.1	0.0	0.9	2.3	0.0
BONET	DROMAHAIR	35011	264	0.0	38.2	0.0	0.0	7.7	29.8	0.0	19.4	4.6	0.0
BOYLE	TINACARRA	26012	520	0.0	61.5	0.0	0.0	0.0	26.4	0.0	12.1	0.0	0.0
BOYNE	SLANE CASTLE	07012	2460	0.0	0.0	0.1	0.0	27.6	44.4	0.0	25.2	1.0	1.3
CAMLIN	MULLAGH	26019	253	0.0	10.7	0.0	0.0	0.0	73.7	0.0	15.5	0.0	0.0
CLARE	CORROFIN	30004	700	0.0	89.7	0.0	0.0	0.0	10.3	0.0	0.0	0.0	3.9
CLODIAGH	RAHAN	25016	254	0.0	0.0	12.9	3.1	0.0	82.6	0.0	0.5	0.0	6.0
DEEL (MUNSTER)	RATHKEALE	24013	439	0.0	0.0	22.2	7.9	0.0	64.3	0.0	0.0	5.6	0.9
ERNE	BELTURBET	36019	1492	0.0	0.1	0.0	0.5	1.5	10.1	0.0	87.7	0.0	0.0
FEALE	LISTOWEL	23002	647	0.0	0.0	1.3	0.0	0.0	98.8	0.0	0.0	1.1	0.6
FERGUS	BALLYCOREY	27002	511	0.0	66.0	0.0	0.0	2.9	19.3	0.0	8.7	3.1	0.0
FINN	DREENAN	01042	349	0.0	0.0	0.0	0.0	0.0	0.0	0.0	82.5	17.5	0.0
FLESK (LAUNE)	FLESK	22006	329	0.0	0.0	7.1	0.0	0.0	91.2	0.0	0.0	1.1	0.0
GRANEY	SCARRIFF	25030	280	0.0	0.0	0.0	0.0	0.0	20.3	0.0	79.7	0.0	0.0
INNY	BALLYMAHON	26021	1099	0.0	0.0	4.5	0.0	1.0	73.4	0.0	10.6	0.0	1.0
LITTLE BROSNA	CROGHAN	25021	479	0.0	0.0	5.4	4.3	0.8	78.3	0.0	11.2	0.0	10.1
MAIGUE	ISLANDMORE	24082	763	0.0	0.0	12.8	13.2	5.6	64.2	0.0	1.4	2.3	0.1
MOY	RAHANS	34001	1975	11.4	33.3	0.0	0.0	6.8	18.1	0.0	28.3	1.7	3.9
MULKEAR	ANNACOTTY	25001	648	0.0	0.0	6.3	0.0	4.7	49.7	0.0	39.3	0.0	1.9
NENAGH	CLARIANNA	25029	293	0.0	0.0	0.0	0.0	2.9	39.6	0.0	57.1	0.0	1.3
NORE	BROWNSBARN	15006	2418	0.0	0.0	20.7	5.6	6.8	36.1	0.0	22.5	8.0	10.5
RINN	JOHNSTON'S BR.	26008	281	0.0	2.7	0.0	0.0	17.6	53.5	0.0	26.1	0.0	0.0
ROBE	FOXHILL	30005	238	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8
RYEWATER	LEIXLIP	09001	210	0.0	0.0	0.0	0.0	1.6	79.5	0.0	18.7	0.0	0.0
SUCK	BELLAGILL	26007	1207	0.0	86.8	0.0	0.0	1.6	11.6	0.0	0.0	0.0	0.2
SUIR	CAHER PARK	16009	1583	0.0	0.0	18.5	2.3	4.8	60.0	0.0	13.1	0.0	0.5
WOODFORD	BELLAHEADY	36027	334	0.0	52.6	0.0	0.0	1.0	30.3	0.0	7.6	8.5	0.0

Table 4.2. Key physical characteristics of the national catchments (extreme vulnerability, average slope, subsoil permeabilities).

WATERBODY	LOCATION	STATION_NU	EXTREME VULNERABILITY (%) (<3m)	EXTREME (rock near surface / karst) VULNERABILITY (%) (<1M)	AVERAGE SLOPE (%)	HIGH PERMEABILITY SUBSOILS (%)	MODERATE PERMEABILITY SUBSOILS (%)	LOW PERMEABILITY SUBSOILS (%)
ANNER	ANNER	16010	30.5	10.9	4.9	15.9	46.6	3.9
AUGHRIM	KNOCKNAMOHILL	10028	75.1	47.8	14.8	2.4	47.6	5.0
AVONMORE	RATHDRUM	10002	85.8	50.1	16.8	4.1	31.8	20.3
BANDON	CURRANURE	20002	57.7	25.5	8.4	4.1	37.5	32.6
BARROW	ROYAL OAK	14018	17.6	8.0	2.8	13.1	53.9	26.3
BLACKWATER	BALLYDUFF	18002	43.2	8.7	7.1	0.6	48.3	40.0
BONET	DROMAHAIR	35011	16.2	0.9	9.8	1.3	9.8	70.8
BOYLE	TINACARRA	26012	34.0	1.6	2.5	2.0	54.9	38.9
BOYNE	SLANE CASTLE	07012	7.2	1.1	2.5	10.4	66.3	19.6
CAMLIN	MULLAGH	26019	37.0	1.8	2.6	0.4	68.2	29.1
CLARE	CORROFIN	30004	4.7	0.6	2.1	7.1	56.5	32.5
CLODIAGH	RAHAN	25016	9.1	1.2	2.1	15.6	50.6	31.9
DEEL (MUNSTER)	RATHKEALE	24013	26.5	11.3	3.7	2.9	63.8	21.7
ERNE	BELTURBET	36019	29.4	8.7	6.7	0.2	69.7	15.4
FEALE	LISTOWEL	23002	60.7	11.3	7.3	0.0	4.6	82.5
FERGUS	BALLYCOREY	27002	61.8	39.0	5.0	0.0	28.3	27.2
FINN	DREENAN	01042	83.5	18.0	12.3	0.0	20.1	68.3
FLESK(LAUNE)	FLESK	22006	59.3	21.7	12.5	3.4	24.7	49.1
GRANEY	SCARRIFF	25030	38.9	15.9	7.3	0.0	45.2	37.1
INNY	BALLYMAHON	26021	36.5	3.6	2.9	4.9	57.1	31.5
LITTLE BROSNA	CROGHAN	25021	26.1	2.5	4.2	14.1	61.6	18.0
MAIGUE	ISLANDMORE	24082	23.5	8.5	2.7	2.0	81.8	7.3
MOY	RAHANS	34001	19.3	5.6	4.8	6.0	47.9	36.6
MULKEAR	ANNACOTTY	25001	41.9	11.6	7.1	2.4	73.8	12.5
NENAGH	CLARIANNA	25029	40.4	12.7	6.6	2.5	79.3	5.2
NORE	BROWNSBARN	15006	41.9	20.9	4.3	7.2	42.4	36.3
RINN	JOHNSTON'S BR.	26008	22.0	1.3	4.3	0.0	35.4	42.1
ROBE	FOXHILL	30005	4.1	0.9	1.9	5.1	71.2	22.5
RYEWATER	LEIXLIP	09001	17.6	0.3	1.5	2.8	77.7	18.8
SUCK	BELLAGILL	26007	21.3	1.2	1.8	1.7	62.3	33.4
SUIR	CAHER PARK	16009	22.9	5.1	4.9	2.9	73.8	14.5
WOODFORD	BELLAHEADY	36027	26.1	2.5	7.1	0.9	15.4	53.9

Table 4.3. Key physical characteristics of the national catchments (peat, wet soil, channelisation, Corine 2000 land cover types).

WATERBODY	LOCATION	STATION_NU	PEAT (%)	POORLY DRAINED SOIL (%)	CHANELLISATION (%)	URBAN (%)	FOREST (%)	PASTURE (%)	LAKES (%)
ANNER	ANNER	16010	1.0	36.2	0.0	0.2	3.3	75.4	0.0
AUGHRIM	KNOCKNAMOHILL	10028	5.0	38.6	0.0	0.4	17.0	39.9	0.0
AVONMORE	RATHDRUM	10002	20.3	67.4	0.0	0.5	17.3	19.2	0.6
BANDON	CURRANURE	20002	2.1	26.9	0.5	0.7	5.3	66.0	0.2
BARROW	ROYAL OAK	14018	21.4	46.2	35.9	1.5	3.1	54.4	0.0
BLACKWATER	BALLYDUFF	18002	5.9	40.7	3.4	0.6	8.3	61.2	0.0
BONET	DROMAHAIR	35011	33.0	83.2	24.0	0.2	7.4	23.2	0.6
BOYLE	TINACARRA	26012	38.8	87.0	83.5	0.4	1.2	51.0	2.9
BOYNE	SLANE CASTLE	07012	15.0	38.4	96.5	0.8	1.6	72.5	0.7
CAMLIN	MULLAGH	26019	25.4	44.9	37.2	1.1	2.1	84.4	0.1
CLARE	CORROFIN	30004	31.7	48.6	96.0	0.7	1.0	61.2	0.5
CLODIAGH	RAHAN	25016	30.1	53.9	72.5	2.1	3.7	65.7	0.1
DEEL (MUNSTER)	RATHKEALE	24013	1.5	56.6	48.5	1.6	1.5	83.4	0.0
ERNE	BELTURBET	36019	9.3	72.9	23.2	0.7	1.0	83.9	3.4
FEALE	LISTOWEL	23002	33.1	87.2	0.3	0.6	11.1	49.3	0.0
FERGUS	BALLYCOREY	27002	13.2	29.9	26.7	1.5	4.5	43.1	2.0
FINN	DREENAN	01042	68.3	91.6	0.0	0.1	6.6	14.8	0.7
FLESK(LAUNE)	FLESK	22006	37.2	77.5	0.0	0.7	7.2	28.9	1.0
GRANEY	SCARRIFF	25030	37.0	70.1	9.7	0.3	13.1	46.5	2.0
INNY	BALLYMAHON	26021	21.1	40.0	73.8	0.4	2.4	79.9	3.5
LITTLE BROSNA	CROGHAN	25021	17.0	38.6	35.9	1.2	5.6	70.2	0.0
MAIGUE	ISLANDMORE	24082	1.7	41.0	74.5	0.7	1.2	93.3	0.2
MOY	RAHANS	34001	32.5	68.6	41.2	0.8	2.2	29.9	4.0
MULKEAR	ANNACOTTY	25001	11.3	56.5	8.1	0.6	6.9	68.3	0.0
NENAGH	CLARIANNA	25029	4.4	17.0	55.8	0.9	3.8	75.2	0.2
NORE	BROWNSBARN	15006	7.4	43.1	12.1	0.8	5.9	72.4	0.0
RINN	JOHNSTON'S BR.	26008	34.8	86.5	34.1	0.2	0.6	51.3	2.1
ROBE	FOXHILL	30005	22.0	44.9	90.2	0.8	1.9	50.3	0.5
RYEWATER	LEIXLIP	09001	0.8	72.5	18.2	2.8	2.1	78.2	0.0
SUCK	BELLAGILL	26007	33.0	60.1	37.2	0.5	1.7	64.9	0.3
SUIR	CAHER PARK	16009	9.2	33.1	7.6	0.6	4.9	74.6	0.0
WOODFORD	BELLAHEADY	36027	23.9	85.5	25.0	0.2	5.1	36.2	4.5

4.2 NAM Parameter Selection

The selection of regional catchments adds another complexity. River catchments are not necessarily composed of one aquifer type but, more often than not, contain a mixture of aquifers. For example, the Nore catchment contains karstic, productive fissured and poorly productive bedrock aquifers, and gravel aquifers. The method for estimating the NAM parameters CQ_{OF}, CK_{IF} and CK_{BF} is based on single aquifer types. For the mixed aquifer scenarios an *area percentage of each aquifer type in the catchment* approach has been used to estimate values for the NAM parameters. The NAM parameters selected are presented in Table 4.4.

Table 4.4. Range in NAM parameter values for the selected catchments used to guide the numerical modelling. *The groundwater storage zone was split into two components during modelling.

NAME	U_{MAX} (mm)	CQ_{OF}	CK_{IF} (hr)	CK_{BF} (hr)
ANNER	10 to 20	0.545 to 0.606	200 to 400	1560 to 2700
AUGHRIM	15 to 20	> 0.8	~200	2300 to 2955
AVONMORE	15 to 20	> 0.8	~200	2390 to 3100
BANDON	15 to 25	0.7 to 0.85	> 600	2200 to 3200
BARROW	15 to 20	0.71 to 0.84	> 600	1830 to 1955
BLACKWATER	15 to 25	~ 0.7	~ 200	1700 to 2400
BONET*	15 to 20	0.7 to 0.8	~ 200	CKBF1 1100 (CKBF2 1800 to 3000, CQLOW 70)
BOYLE	15 to 20	0.66 to 0.78	> 600	> 2500
BOYNE	10 to 20	0.5 to 0.7	300 to 600	2000 to 3000
CAMLIN	10 to 20	0.67 to 0.77	> 600	2300 to 3300
CLARE	15 to 20	0.6 to 0.7	> 600	> 2500
CLODIAGH	15 to 20	0.65 to 0.85	> 600	2000 to 3000
DEEL(MUNSTER)	10 to 15	0.7 to 0.83	400 to 800	1700 to 2800
ERNE	< 15	0.8 to 0.9	400-800	> 3000
FEALE	15 to 25	> 0.9	> 600	2000 to 3000
FERGUS	15 to 20	0.58 to 0.76	200 to 300	1400 to 2700
FINN	15 to 20	~ 0.9	> 600	> 3000
FLESK (LAUNE)*	15-20	0.9	~ 200	CBBF1 1100 (CKBF2 > 3000, CQLOW 60)
GRANEY	20 to 25	0.7 to 0.9	300 to 600	2800 to 3800
INNY	15 to 20	~0.8	400 to 800	2100 -3100
LITTLE BROSNA	15 to 20	0.5 to 0.79	400 to 800	2000 to 3000
MAIGUE	10 to 20	0.73 to 0.82	400 to 800	1400 to 2800
MOY	15 to 20	0.7 to 0.8	400 to 800	1700 to 3000
MULKEAR	15 to 20	0.68 to 0.83	300 to 600	2300 to 3400
NENAGH	10 to 15	0.7 to 0.85	200 to 800	2500 to 3500
NORE	10 to 20	0.7 to 0.85	200 to 300	2000 to 2900
RINN	15 to 20	0.82 to 0.88	400 to 800	2000 to 3200
ROBE	10 to 20	0.5 to 0.7	~ 200	<2500,
SUIR	10 to 15	0.65 to 0.80	>600	1800 to 2600
WOODFORD	15 to 20	0.64 to 0.8	200 to 300	1600 to 2600

4.3 Results of analysis

Assignment of NAM parameter values for the regional catchment simulations was primarily guided by the range of NAM parameter values in Table 4.4. A good correlation between the simulated and recorded hydrographs and a good water balance were a secondary objective in the modelling. For those catchments that contain a relatively large percentage of lakes (>1%), the focus of the modelling was towards a good water balance, rather than a good R^2 correlation. The final selection of NAM parameter values is presented in Table 4.5.

NAM parameter values used in simulating each catchment are presented in Table 4.6, along with the correlation factor (R^2) and water balance between the recorded and simulated hydrographs. The simulations for the models have been run for periods of time between 1990 and present. The length of the simulation for the NAM models is dependent on the suitable temporal overlap of rainfall and discharge data. In general, the simulations that are run over a period of less than four years have a weaker correlation than simulations run over a greater period of time. This is because the initial conditions of the relative water content in the root zone storage and the contributions of each flow component have to be estimated in the NAM model, and it takes approximately the first six months of the NAM simulation for flow components to be modelled accurately. The Avonmore catchment is the exception, with a simulation period of almost ten years and an R^2 correlation value of 0.49. In this instance, the poor correlation is related to data gaps of between one and two and a half months throughout the discharge timeseries.

The Finn catchment has a particularly low correlation factor (-7%). The hydrometric station for which the discharge data used (1042, Dreenan) states that it has a fair rating at low flow, and a good rating at middle and high flows. The station is not rated for peak flows. NAM modelling has identified that the peak flows are not recorded by the station (Figure 4.5). Consequently, the NAM modelling undertaken for the Finn catchment has focussed on a good correlation by eye between the recorded and simulated hydrographs at low flows. The modelling cannot focus on a good water balance because the recorded discharge data suggests that there is less flow in the catchment compared to the simulated hydrograph.

Table 4.5. Final selection of NAM parameter values for the numerical modelling of regional catchments.

NAME	U_{MAX} (mm)	L_{MAX} (mm)	CQ_{OF}	CK_{IF} (hr)	$CK_{1,2}$ (hr)	T_{OF}	T_{IF}	T_{G}	CK_{BF1} (hr)	CQ_{LOW}	CK_{BF2} (hr)
ANNER	15.00	244	0.545	400.0	23.30	0.743	0.10000	0.9	2400		
AUGHRIM	20.00	300	0.950	270.8	50.00	0.561	0.05000	0.4	2950		
AVONMORE	15.00	300	0.893	200.4	22.90	0.553	0.10600	0.6	3100		
BANDON	19.90	148	0.780	600.0	20.00	0.323	0.30000	0.7	3000		
BARROW	17.60	300	0.840	891.3	46.00	0.623	0.00026	0.342	1900		
BLACKWATER	15.00	100	0.670	250.0	27.40	0.226	0.10000	0.3	2300		
BONET	16.80	300	0.745	200.0	12.50	0.756	0.92200	0.571	1100	70	1800
BOYLE	15.00	135	0.490	600.0	50.00	0.323	0.39200	0.371	2500		
BOYNE	16.50	117	0.612	524.4	36.60	0.679	0.04630	0.458	2800		
CAMLIN	10.00	300	0.750	650.0	49.00	0.128	0.07530	0.0004	2400		
CLARE	20.00	100	0.700	600.0	38.80	0.751	0.71400	0.75	3700		
CLODIAGH	19.00	300	0.650	860.7	32.90	0.584	0.00006	0.601	2100		
DEEL (MUNSTER)	10.40	100	0.700	450.0	16.50	0.467	0.05230	0.79	1800		
ERNE	15.00	258	0.800	400.0	80.00	0.750	0.66000	0.55	3000		
FEALE	17.00	100	0.900	600.0	14.20	0.000	0.00004	0.003	2500		
FERGUS	20.00	267	0.600	204.3	50.00	0.604	0.17100	0.353	1500		
FINN	16.00	280	0.900	670.0	12.00	0.200	0.50000	0.75	3877		
FLESK (LAUNE)	18.00	300	0.950	800.0	14.00	0.409	0.45500	0.002	1100	60	3000
GRANEY	23.00	298	0.850	480.1	49.20	0.744	0.60200	0.903	2900		
INNY	16.00	135	0.800	699.7	47.60	0.577	0.18400	0.32	3017		
LITTLE BROSNA	16.00	103	0.683	500.0	37.60	0.482	0.01100	0.25	2000		
MAIGUE	12.50	163	0.750	450.0	21.90	0.529	0.09320	0.624	1500		
MOY	20.00	216	0.700	400.0	50.00	0.809	0.27500	0.75	3000		
MULKEAR	15.00	300	0.700	437.0	21.70	0.800	0.05000	0.9	2800		
NENAGH	12.30	300	0.800	200.1	22.90	0.352	0.56300	0.4	2500		
NORE	15	262	0.721	300	34.7	0.635	0.77300	0.414	2900		
RINN	15.00	87	0.870	400.0	49.00	0.550	0.60000	0.282	2100		
ROBE	17.00	300	0.650	200.0	28.90	0.840	0.62600	0.7	1800		
RYEWATER	15.20	110	0.900	700.0	13.9	0.517	0.30000	0.15	2600		
SUCK	19.5	208	0.677	209.9	50.0	0.659	0.52500	0.485	2600		
SUIR	12.00	300	0.700	608.6	43.70	0.400	0.20000	0.7	2600		
WOODFORD	19.50	156	0.715	208.5	50.00	0.600	0.50000	0.4	2600		

Table 4.6. Results of the NAM modelling for the regional catchments. OF: Overland Flow; IF: Intermediate Flow; DG: Deep Groundwater. In the instances where flow has been recorded for DG2 (groundwater body split in two) then DG1 is a component of the intermediate flow.

Catchment	Simulation period	NAM OF component (mm/yr)	NAM IF component (mm/yr)	NAM DG1 component (mm/yr)	NAM DG2 component (mm/yr)	R2	WB (%)	Simulated Effective Rainfall (mm/yr)
ANNER	01/01/1990 – 31/12/2001	172.0	180.4	140.6		0.865	0.1	493.0
AUGHRIM	01/12/1991 – 01/01/1995	462.9	381.2	197.9		0.565	0.6	1042.0
AVONMORE	01/01/1990 – 22/11/1999	537.6	454.1	175.3		0.494	1.1	1167.0
BANDON	02/01/1990 – 12/06/2001	762.2	163.7	192.1		0.796	0.7	1118.0
BARROW	01/01/1990 – 09/10/2005	172.1	93.6	165.3		0.888	-0.2	431.0
BLACKWATER	07/10/1990 – 31/12/2002	345.4	278.9	205.7		0.886	0.1	830.0
BONET	30/06/1995 – 18/01/2003	854.4	322.8	103.8	241.1	0.815	-0.8	1281.0
BOYLE	30/06/1990 – 22/03/2001	423.0	142.7	195.3		0.748	0.3	761.0
BOYNE	30/06/1990 – 31/12/2004	164.7	153.4	170.9		0.889	-0.4	489.0
CAMLIN	27/071990 – 28/09/1995	236.2	61.4	171.4		0.819	1.5	469.0
CLARE	09/01/1993 – 30/03/2001	423.0	158.2	165.8		0.82	0.3	747.0
CLODIAGH	12/10/1996 – 17/02/2003	211.6	118.2	164.2		0.842	2.7	494.0
DEEL (MUNSTER)	30/08/1995 – 08/02/2001	505.5	114.4	171.1		0.854	4.8	791.0
ERNE	30/06/1990 – 30/08/1998	291.4	166.0	143.6		0.792	0.1	601.0
FEALE	26/12/1993 – 31/12/2005	705.9	151.5	186.6		0.829	0.1	1044.0
FERGUS	01/06/1990 – 26/02/2005	86.8	368.9	174.3		0.873	0.2	630.0
FINN	01/05/1991 – 28/08/1999	961.2	144.1	134.7		-7%	-58.2	1240.0
FLESK (LAUNE)	01/01/1990 – 30/12/2000	912.3	386.2	130.5	195.7	0.807	0.6	1429.0
GRANEY	30/06/1990 – 13/10/2005	492.4	254.8	92.8		0.927	-0.3	840.0
INNY	31/01/1990 – 30/07/2003	272.2	112.5	173.3		0.729	1.6	558.0
LITTLE BROSNA	31/07/1992 – 07/09/2003	225.9	160.2	190.9		0.799	-0.8	577.0
MAIGUE	17/06/1990 – 20/02/2001	285.4	134.9	128.7		0.799	-0.6	549.0
MOY	30/06/1990 – 20/08/2000	405.2	295.6	220.2		0.859	0.5	921.0
MULKEAR	24/06/1990 – 01/06/2001	422.2	192.0	176.8		0.781	0.4	791.0
NENAGH	01/01/1990 – 31/12/1998	315.7	209.4	157.9		0.706	-0.7	683.0
NORE	02/01/1990 – 31/12/2002	214.4	130.9	199.7		0.911	-0.4	545.0
RINN	02/01/1990 – 30/12/2001	344.2	158.9	149.9		0.72	0.4	653.0
ROBE	01/01/1990 – 30/12/2004	203.9	398.0	210.1		0.839	0.7	812.0
RYEWATER	02/06/1994 – 31/12/2002	171.4	85.0	120.6		0.823	0.0	377.0
SUCK	02/01/1990 - 31/12/2002	123.5	361.7	170.8		0.917	0.1	656.0
SUIR	01/01/1990 - 31/12/2005	398.4	103.6	180.0		0.815	-0.2	682.0
WOODFORD	04/06/1990 - 19/10/1992	202.1	413.0	171.9		0.681	-3.2	787.0

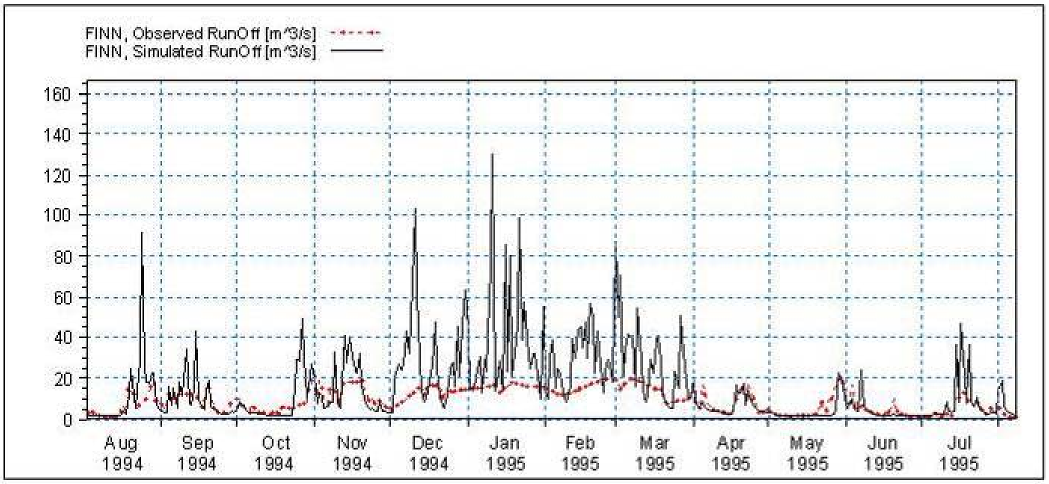

Figure 4.5. An example of the recorded and simulated hydrographs for the Finn catchment gauged at Dreenan (station number 1042) for the period August 1994 to July 1995.

Only two of the catchments – the Bonet and Feale – have had the groundwater storage zone split into two components. This was done because the NAM model over-predicted the stream flow during long recession periods using one groundwater storage unit. For these catchments, the NAM DG2 component represents the deep groundwater flow and the NAM DG1 component is part of the intermediate flow as well as the NAM IF component.

The results from the NAM modelling are valid for the period of the simulation. To ensure that the results are valid for a standard period, the flow values have been normalised to a long-term average rainfall (1961 to 1990) derived by Met Éireann (Table 4.7). This has been done by scaling the results in Table 4.6 for overland flow, intermediate flow and deep groundwater flow in relation to the long-term average rainfall. The deep groundwater flow component value can increase if the long-term average of rainfall is greater than the modelled rainfall. For the Article V Characterisation Report, the methodology for estimating recharge to aquifers indicated that poorly productive bedrock aquifers have a cap on the amount of deep groundwater flow (200 mm/yr for Ll bedrock aquifers and 100 mm/yr for Pl/Pu bedrock aquifers). It is considered that the increase in the deep groundwater flow component for catchments containing poorly productive aquifers is not significant.

Table 4.7. Flow components estimated from NAM modelling normalised by long-term rainfall (1961 to 1990). Recharge estimates from the Article V Characterisation Report are included for comparison.

Catchment	Simulation Length	Simulated Rainfall (mm/yr)	1961-1990 Rainfall (mm/yr)	Long-term average factor	Overland Flow (mm/yr)	Intermediate Flow (mm/yr)	Deep Groundwater Flow (mm/yr)	Recharge estimate (mm/yr)
ANNER	01/01/1990 - 31/12/2001	940.0	989.0	1.05	181.0	189.8	147.9	178.8
AUGHRIM	01/12/1991 - 01/01/1995	1462.0	1383.0	0.95	437.9	360.6	187.2	165.5
AVONMORE	01/01/1990 - 22/11/1999	1650.0	1528.0	0.93	497.9	420.5	162.3	156.5
BANDON	02/01/1990 - 12/06/2001	1579.6	1589.3	1.01	766.9	164.7	193.3	180.0
BARROW	01/01/1990 - 09/10/2005	855.0	858.0	1.00	172.7	93.9	165.9	172.0
BLACKWATER	07/10/1990 - 31/12/2002	1284.0	1201.0	0.94	323.1	260.9	192.4	197.1
BONET	30/06/1995 - 18/01/2003	1714.0	1520.0	0.89	757.7	378.3	213.8	243.3
BOYLE	30/06/1990 - 22/03/2001	1157.3	1143.0	0.99	417.8	140.9	192.9	168.3
BOYNE	30/06/1990 - 31/12/2004	912.0	891.0	0.98	160.9	149.9	167.0	150.0
CAMLIN	27/071990 - 28/09/1995	921.0	978.0	1.06	250.8	65.2	182.0	144.5
CLARE	09/01/1993 - 30/03/2001	1150.0	1103.0	0.96	405.7	151.7	159.0	153.1
CLODIAGH	12/10/1996 - 17/02/2003	949.0	922.0	0.97	205.6	114.8	159.5	139.1
DEEL (MUNSTER)	30/08/1995 - 08/02/2001	1131.0	1070.0	0.95	478.2	108.2	161.9	160.9
ERNE	30/06/1990 - 30/08/1998	1001.0	974.0	0.97	283.5	161.5	139.7	115.5
FEALE	26/12/1993 - 31/12/2005	1526.0	1424.0	0.93	658.7	141.4	174.1	198.7
FERGUS	01/06/1990 - 26/02/2005	1154.0	1326.6	1.15	99.8	424.1	200.4	502.7
FINN	01/05/1991 - 28/08/1999	1809.0	1817.9	1.00	966.0	144.8	135.4	100.0
FLESK (LAUNE)	01/01/1990 - 30/12/2000	1788.0	1734.3	0.97	884.9	501.2	189.8	208.4
GRANEY	30/06/1990 - 13/10/2005	1375.5	1327.8	0.97	475.3	246.0	89.6	116.1
INNY	31/01/1990 - 30/07/2003	990.0	944.0	0.95	259.6	107.3	165.2	162.9
LITTLE BROSNA	31/07/1992 - 07/09/2003	1003.0	1016.0	1.01	228.8	162.3	193.4	183.1
MAIGUE	17/06/1990 - 20/02/2001	1062.0	1112.4	1.05	299.0	141.3	134.8	163.7
MOY	30/06/1990 - 20/08/2000	1329.0	1327.0	1.00	404.6	295.2	219.9	194.8
MULKEAR	24/06/1990 - 01/06/2001	1337.5	1247.7	0.93	393.9	179.1	164.9	144.9
NENAGH	01/01/1990 - 31/12/1998	1115.0	1119.0	1.00	316.8	210.2	158.5	123.2
NORE	02/01/1990 - 31/12/2002	991.0	945.0	0.95	204.4	124.8	190.4	206.1
RINN	02/01/1990 - 30/12/2001	1041.0	1032.0	0.99	341.2	157.5	148.6	139.6
ROBE	01/01/1990 - 30/12/2004	1224.0	1172.0	0.96	195.2	381.1	201.2	204.0

Table 4.7 continued.

Catchment	Simulation Length	Simulated Rainfall (mm/yr)	1961-1990 Rainfall (mm/yr)	Long-term average factor	Overland Flow (mm/yr)	Intermediate Flow (mm/yr)	Deep Groundwater Flow (mm/yr)	Recharge estimate (mm/yr)
RYEWATER	02/06/1994 – 31/12/2002	853.4	784.8	0.91	157.6	78.2	110.9	78.2
SUCK	02/01/1990 – 31/12/2002	1094.0	1047.0	0.96	118.2	346.2	163.5	210.8
SUIR	01/01/1990 – 31/12/2005	1115.0	1077.0	0.97	384.8	100.1	173.9	154.2
WOODFORD	04/06/1990 – 19/10/1992	1268.0	1351.0	1.07	215.3	440.0	183.2	219.6

4.4 Validation of the regional catchment NAM modelling

The NAM modelling of the regional catchments focussed on achieving a good correlation and water balance for many of the catchments between the recorded and simulated hydrographs, within the suggested limits of the derived NAM parameters (CQ_{OF}, U_{MAX}, CK_{IF}, CK_{BF}) (Table 4.4). The exceptions were those catchments containing a large percentage of lakes (>1%), for which the focus was to achieve the best water balance possible (although for many the correlation was good as well). It was not possible to get a good correlation or water balance for the Finn catchment because the peak flows are not recorded in the river flow time series. The estimates for the NAM simulated deep groundwater flow contribution have also been tabulated along with the estimates of bedrock aquifer recharge in each catchment (Article V Characterisation results) for comparison (Table 4.7).

4.4.1 NAM R^2 correlation and water balance

The mean values for the R^2 correlation and the water balance are good (0.78 and 0.3% respectively, Table 4.8). The standard deviations for the R^2 correlation and water balance are relatively large (0.18 and 10.4%, respectively). This is because of the poor R^2 correlation and water balance of the Finn catchment. Excluding the results for the Finn catchment, the standard deviations for the correlation and water balance of the regional catchments is 0.1 and 1.28% respectively, which suggests the results are within a narrow range. Also the mean R^2 correlation is improved and the mean water balance is good.

Table 4.8. The correlation and water balance between the NAM simulated and recorded hydrographs for the modelled regional catchments.

Statistic	R^2	Water balance (%)
Mean	0.78	-0.15
Median	0.82	0.10
Mode	0.82	0.10
Standard Deviation	0.18	10.40
Mean (excluding Finn catchment)	0.8	-0.3
Standard Deviation (excluding Finn catchment)	0.1	1.28

4.4.2 Long-term average rainfall

There is a good correlation between the long-term average annual rainfall results for the NAM model and Met Éireann values (1961 to 1990) (R^2 = 0.94, Figure 4.6). However, the modelled long-term annual average rainfall for the Fergus catchment compared to the Met Éireann values is relatively poor (1154 mm/yr simulated and 1327 mm/yr long-term average). This suggests that approximately 200 mm/yr of rainfall is not accounted for in the NAM model for the Fergus catchment, i.e. rainfall appears to be lost from the catchment.

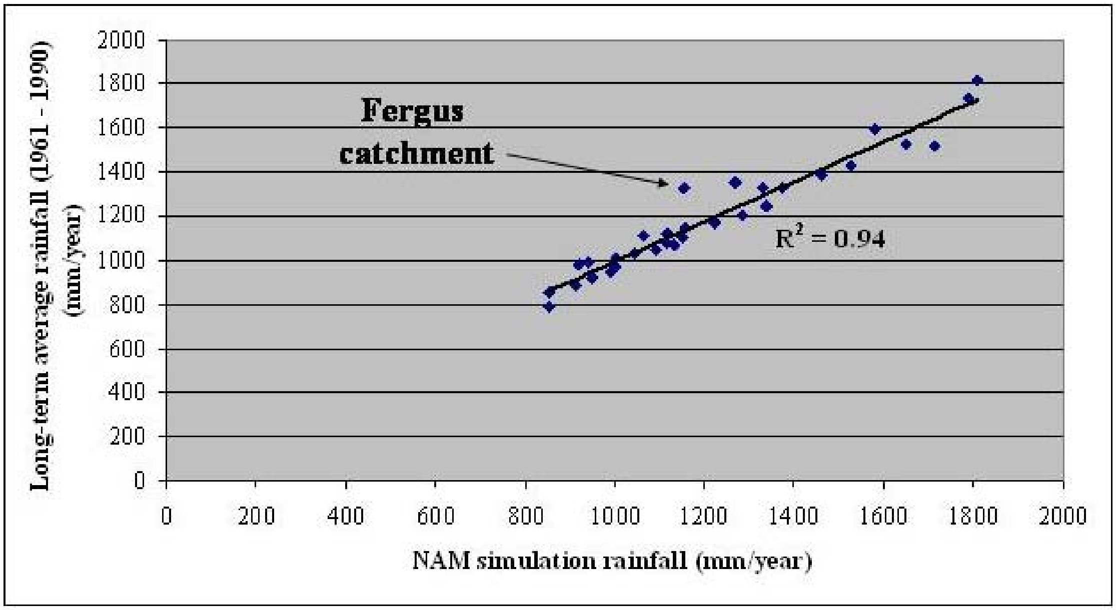

Figure 4.6. The correlation between the rainfall in the NAM simulation and the long-term average rainfall (1961-1990) for the regional catchments.

4.4.3 Deep groundwater flow

The results of the modelling for the deep groundwater flow component are presented, in Table 4.7, alongside the results of the expected recharge of bedrock aquifers for each catchment. In general, there is close agreement between these results. However, there is a large difference in the deep groundwater flow and expected recharge for the Fergus catchment. The catchment contains karstic bedrock and it is possible that water is lost across the boundary of the surface water catchment via the underground pathway. This may account for the discrepancy between the simulated rainfall and the long-term average rainfall values. Excluding the results for the Fergus catchment, the R^2 correlation between the simulated NAM deep groundwater flow contributions and the recharge estimates is 0.58 (Figure 4.7). Considering that approaches taken to estimate bedrock aquifer recharge and the deep groundwater flow contribution to streamflow are independent, the correlation is considered to be good.

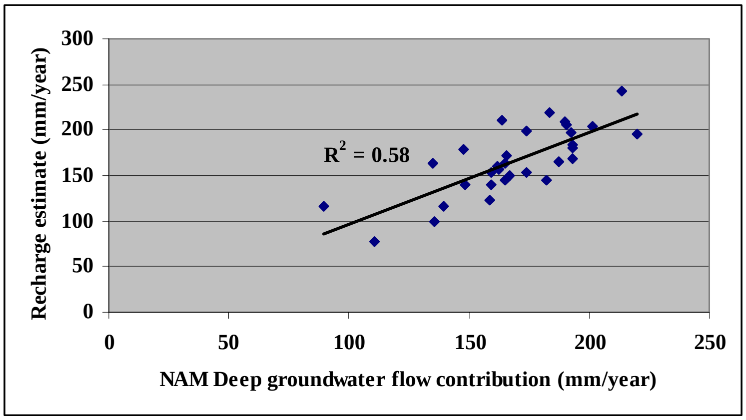

Figure 4.7. The correlation between the bedrock aquifer recharge estimate (derived from the Abstraction Programme of Measures Study) and deep groundwater flow contribution for each of the regional catchments, excluding the Fergus catchment.

4.5 Summary

Thirty-two regional catchments with an area greater than 200 km^2 were modelled numerically using NAM to estimate the contributions to stream flow from the overland, intermediate and deep groundwater pathways.

The models used NAM parameter values derived from decision tables for the coefficient of overland flow (CQ_{OF}), the surface storage zone (U_{MAX}), time constant for intermediate flow (CK_{IF}) and the time constant for deep groundwater flow (CK_{BF}). The parameter value ranges given in the decision tables were largely derived from the pilot catchment modelling exercise.

The extension of the modelling to regional catchments also focussed on achieving a good correlation and water balance between the simulated and recorded hydrographs. The exception has been for the case of catchments that contain a large percentage of lakes, for which the focus was to achieve a good water balance.

The estimates of the flow contributions from each of the pathways (overland, intermediate, deep groundwater) was normalised by average rainfall over an established long-term time period (1961 to 1990). The quantity of deep groundwater flow was found to correlate well with estimates for bedrock aquifer recharge made as part of the Article V risk assessment work.

Section 5: Summary

5.1 Conclusions

The methodology for this study was developed by a subcommittee of the WFD Groundwater Working Group to estimate contributions of surface water and groundwater in Irish rivers. The components of flow that can be identified are based on a conceptual hydrogeological model (Section 1.2) and are overland flow, intermediate flow and deep groundwater flow. The methodology was based on an integrated water balance approach to hydrograph separation, applying established techniques, for seven pilot catchments with hydrogeologically distinct scenarios. The catchments focussed mainly on poorly productive aquifer settings of Ll and Pl type (Owenduff, Shournagh, Ryewater and Deel), since these are dominant aquifer types in Ireland. In addition, two catchments containing productive bedrock aquifers were selected; karstic limestone (Suck, Rk) and mainly fissured volcanic rock (Boro, Rf). A specific mixed aquifer catchment was also considered (Bride) that occurs in the southwest of Ireland, termed the ‘Southern Synclines Scenario’. This is a mixture of Ll and Rk aquifers.

Based on a literature research a number of analytical techniques were chosen to quantify components of stream flow in the pilot catchments. These analytical techniques are Master Recession Curve analysis, Unit Hydrograph Method and hydrogeological and bedrock aquifer through-flow estimates. These analyses are considered in the context of an integrated water balance approach - using daily mean flow, daily rainfall data and monthly evapotranspiration data to estimate components of flow. The components of stream flow are separated in deep groundwater, intermediate and overland flow. Key objective of applying the above hydrograph separation techniques is to inform and constrain the conceptual lump sum rainfall runoff model NAM, developed by a team at the Danish University of Copenhagen. The correlation between the results of the analytical analyses and the numerical modelling was assessed and found to be of good quality (Table 5.1), giving a high confidence of the reasonable prediction of the assessed stream flow components. The 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. A cap on the amount of recharge was included for the poorly productive aquifers (200 mm/yr for locally important Ll aquifers and 100 mm/yr in poor Pl aquifers) to account for these types of aquifers not being capable of accepting the available recharge due to their low transmissivity. The exception to this assumption was the Shournagh catchment, where the through-flow calculations of the bedrock aquifer has suggested that there could be up to 221 mm/yr total groundwater flow through interconnected fractured zone and weathered zone.

The Master Recession Curve analysis has worked best for catchments with low effective rainfall (e.g. Ryewater catchment – effective rainfall 383 mm/yr) and with high permeability bedrock aquifers such as the Suck with a karstic bedrock. In reality there are few drought periods with no rainfall and no or little groundwater recharge in Ireland. Thus the deep groundwater component of flow is difficult to identify by hydrograph separation techniques, which does not take GW recharge into account, whereas the NAM tool accounts for the input from precipitation.

The calibration of the NAM model using data from the hydrograph separation techniques and through-flow calculations has allowed to derive the relevant parameters for the NAM tool to be identified based on hydrogeological and other catchment data. Decision tables were developed that can be used to select required parameters for modelling of further catchments that are based on key hydrogeological descriptors. Nonetheless, an understanding of the conceptual model of catchment hydrology is crucially important before undertaking numerical modelling. The key hydrogeological desciptors that have been identified include aquifer type, vulnerability and subsoils, soils, the topography (the slope), land cover and the percentage of lakes. The decision tables have been based on the assessment of GIS datasets for the pilot catchments, as well as expert judgement (e.g. in the case of gravels scenario).

Table 5.1. Summary table of results for the quanitifcation of deep groundwater flow, intermediate flow and overland flow for the pilot catchments. NAM (numerical model); MRC (Master Recession Curve); UH (Unit Hydrograph method).

		Deep groundwater flow				**Intermediate flow**	**Overland flow**	
Pilot catchment	**Hydro-geological scenario**	**NAM (mm/y)**	**MRC (mm/y)**	**Groundwater throughput calcs (mm/y)**		**NAM (mm/y)**	**NAM (mm/y)**	**UH (mm/y)**
Boro	**Rf Volcanic aquifer (mixed scenario: Rf / Ll / Pl)**	240	388 (deep + other component)	232	330	217	231	215
Bride	**'Southern Synclines' scenario (Ll and Rkd)**	200	537 (deep + other component)	153	170	269	352	336
Deel	**Ll Limestone**	159	323 (deep + other component)	158	232	210	120	168
Owenduff	**Pl Poorly Productive**	128	441 (deep + other component)	73	183	318	1322	1074
Ryewater	**Ll Limestone**	121	110	158	232	85	171	191
Shournagh	**Ll Old Red Sandstone**	220	321 (deep + other component)	153	170	205	383	357
Suck	**Karst**	171	234	-	-	362	124	354

The NAM parameters that can be estimated 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 intermediate (CK_{IF}) and the time constant for deep groundwater flow (CK_{BF}). The selection of the maximum water in the lower zone storage (L_{MAX}), overland flow threshold (T_{OF}), intermediate flow threshold (T_{IF}), deep groundwater recharge threshold (T_G), should initially be based on modelling of catchments that has been 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 recorded hydrograph. The NAM modelling for catchments including large lakes should focus on a good water balance between recorded and simulated discharges and not on a good R^2 correlation, as the simulations based on the decision tables would yield to a natural catchment without the influence of lakes. This also applies to controlled rivers, though particular attention should be drawn to the estimation of ground water recharge.

Thirty-two regional catchments across Ireland were selected for further NAM modelling to quantify components of overland, intermediate and deep groundwater flow. Many of the catchments contain mixed aquifer scenarios. For the catchments that contain a mixed aquifers the estimation of the NAM parameters should be based on the area proportion of each type of regional aquifer in the catchment. The results of the deep groundwater flow from the NAM modelling of regional catchments coincide well with the estimates of recharge of bedrock aquifers from the Article V Characterisation Report.

5.2 Limitations to the NAM model

The NAM modelling of pilot catchments was based on ideal hydrogeological scenarios for which there were suitable overlapping discharge and rainfall time series. For the modelling of further catchments there are a number of limitations.

Catchments that are selected for NAM modelling using the above methods should in general be greater than 200 km^2. Catchments that are smaller have most likely overland flow response times of less than 24 hours (i.e. less than one day). The result is that peak flows cannot be modelled accurately because the daily rainfall data averages out the flows from shorter rainfall events. In addition higher resolution gauging data is required with discharges recorded at hourly or 15 minute intervals. An example of this is the Owenduff catchment, as steep mountain catchment with an area of 119 km^2. The catchment contained dominantly poorly productive Pl aquifer and was considered to be ‘flashy’. The R^2 correlation value suffered in the NAM model because the recorded peak flows could not be simulated, as neither hourly nor subhourly rainfall data nor adequate discharge data was available. Furthermore, the GIS data sets might not be sufficiently accurate and detailed enough to determine all the relevant parameters. Finally small features such as alluvial gravels along the lower river stretch can alter the response of the catchment, which would not be adequately captured by a lumped conceptual model of this size.

The presence of lakes in a catchment has the effect of increasing the surface storage. This can result in damping (smoothing out) of the response of high and peak flows on a hydrograph, increased evaporation and possibly higher groundwater recharge. For catchments that contain large lakes (generally >1% of the catchment area) it is advised to base the NAM model on a good water balance, rather than on a good R^2 correlation if comparing to a recorded hydrograph. The effect of the lakes can be incorporated into the NAM model through the adequate selection of the average depth of the surface storage zone (U_{MAX}), which in will lead to retention of flood peaks and increased evaporation, thus reduced net precipitation. The experience is currently limited with this approach in ungauged catchment and further investigation would be beneficial.

For some of the pilot catchments it was difficult to model the overall discharge of a river at the start of the simulation in the winter months (the Deel and Ryewater catchments). This is due to the response of the model being rather slow at the start of the simulation, as the groundwater storage is not capable of filling to the required capacity before the first summer recession. It is advised for the modelling of ungauged catchments to begin the simulation in the summer months or in hydrological years. Naturally the groundwater body will be lower during a typical summer recession period which will allow the model to respond more accurately to the infiltration of rainfall at the start of the wet season.

The NAM tool allows for scenarios where the aquifer feeds significant amounts of water into other catchments, or where adjacent catchments provide groundwater recharge into the catchment. This can be incorporated by adding catchment area to the groundwater body only. This has to be done a priori, and thus is unsuitable for ungauged catchments where this contribution or abstraction is unknown.

5.3 Further application of the modelling

The results of this study will be used in part to inform groundwater classification of status. Groundwater classification will consist of a number of tests for both chemical and quantitative status of the Groundwater Body. There are five chemical and four quantitative status tests, some elements of which are common to both. The second test for groundwater is “No significant diminution of surface water chemistry and ecology”. In this test status is determined through a combination of surface water classification results and an assessment of chemical inputs from groundwater bodies into surface water bodies. The test is designed to determine whether the contribution from groundwater quality to surface water quality or any consequent impact on surface water ecology is sufficient to threaten the WFD objectives for these associated water bodies. The groundwater threshold values against which the test is conducted are surface water quality standards adjusted by dilution and, where appropriate, attenuation factors. The conditions for good chemical status are not met when an associated surface water body does not meet its objectives, threshold values are exceeded and all groundwaters contribute at least 50% of the relevant surface water standard. The dilution factor used in the test is equivalent to the shallow and deep groundwater flow in the river. Therefore it will be necessary to estimate the shallow groundwater flow as well as deep groundwater flow in all rivers that are at risk.

The results will also have a wider application to many areas of the WFD. The findings of this study will provide the framework to develop a NAM model for many catchments that are ungauged. Consequently, it will be possible to estimate the low flow conditions of catchments - or water bodies - that were previously not hydrologicaly or hydrogeologicaly understood. The estimation of low flow conditions from NAM can then be utilised in other tools that are being developed under the WFD in Ireland, such as SIMCAT, which predicts surface water quality impacts from point source pressures or other water quality modelling tools. The estimates of low flow and the impact of pollution from groundwater can be used in the decision making for river water quality management and planning.

5.4 Recommendations

This study has been able to identify and estimate three components of stream flow using an integrated water balance approach, namely overland flow or surface runoff, intermediate flow and deep groundwater flow. In many catchments in Ireland intermediate flow (i.e. the stream flow contribution that is neither surface runoff nor deep groundwater flow) consists of a number of components: Depending on the conceptual model these components can be classified as:

- Intermediate flow – flow from soils and subsoils,
- shallow groundwater flow – groundwater discharge from a heavily weathered layer on top of the bedrock,
- discrete or conduit flow – typical in karstic or certain limestone situations
- discharge from peat layers – relevant in terms of its hydrochemical contribution to streamflow.

At present there is no methodology known to the working group that allows to quantify the flow between the different intermediate components in typical Irish catchments, hence there are limited data available to calibrate or inform a more complex conceptual model. The NAM model used in this study is limited to three linear storages through which flow can occur, with the option of adding an additional groundwater component. This was used in the study where there was strong evidence from the hydrogeological scenario of a second groundwater component and the discharge characteristics could be constraint by means of transmissivity calculations. This approach excludes the application to mixed hydrogeological scenarios, where basic transmissivity calculations would be insufficient. However, to inform groundwater classification of status the shallow groundwater flow component needs to be estimated. It is recommended that further work will address a methodology to estimate the component of shallow groundwater flow.

In addition, the use of the decision tables for the parameterisation of the conceptual modelling approach should be tested on certain smaller-scale catchments to explore its applicability and validity in these circumstances. Furthermore, additional guidance for the remaining parameters used in the NAM model should be developed.

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