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WATER RESOURCE

AND DEMAND OF

NORTHERN IRELAND,

HYDROLOGICAL STUDIES.

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6. SOURCE YIELDS

6.1 Objective

The objective of this aspect of the study is to assess the yield of existing and potential water sources in Northern Ireland. Although groundwater resources are included, the main emphasis of the work is on surface water resources and particularly the yield of impounding reservoirs and loughs. The approach to yield calculation has been to develop a regional storage/yield relationship for Northern Ireland. This relationship is based on an analysis of a number of river flow records which are described in section 6.2. Section 6.3 outlines the meteorological data used for extending and infilling two of these flow records (section 6.4) and for calculating average runoff for each reservoired catchment. The development of the regional storage yield diagram and its application to individual reservoirs, in order to estimate the yield with a 20 and 50 year return period of failure, is described in sections 6.5 and 6.6 respectively. For the larger resource of Silent Valley yields have also been estimated by carrying out a more detailed simulation of reservoir behaviour. The final sections summarise the estimation of the yield of direct river abstractions, the hydrology of Lough Neagh and the groundwater resources of the province.

6.2 River Flow Records

The Water Data Unit (NI) have operated a total of 73 gauging stations, some of which record only levels whilst others have been discontinued. Records of mean daily flows are archived for 30 stations with ICS Computing Limited in Belfast. Given the time constraints of the present study only these archived records were considered in detail, these are listed on Table 6.1. Most of these records are from rated river sections with cableways and the overall quality of the data is good.

Table 6.1 Summary of flow data from Northern Ireland

NUMBER	STATION	PERIOD	ADF cumecs	BFI	Q95 %ADF	Q80 %ADF	AREA sq km	SAAR mm
201002	FAIRY WATER AT DUDGEON BRIDGE	1972-1980	4.780	0.266	6.63	12.53	161.2	1218
201005	CAMOWEN AT CAMOWEN TERRACE	1972-1980	6.368	0.424	15.44	25.03	274.6	1166
201006	DRUMRAGH AT CAMPSIE BRIDGE	1972-1980	7.573	0.356	5.63	12.46	324.6	1155
201007	BURN DENNET AT BURNDENNET BRIDGE	1976-1980	3.691	0.466	19.89	30.45	145.3	1175
201008	DERG AT CASTLEDERG	1979-1980	16.389	0.259	5.55	19.46	337.3	1500
202999	ALTNAHEGLISH RESERVOIR INFLOWS	1926-1959	0.247	-----	22.82	47.31	7.3	1489
203010	BLACKWATER AT MAYDOWN BRIDGE	1970-1981	16.128	0.404	6.73	17.58	951.4	1043
203011	MAIN AT DROMONA	1970-1980	5.805	0.448	12.80	23.17	228.8	1234
203012	BALLINDERRY AT BALLINDERRY BRIDGE	1970-1980	8.874	0.461	16.93	26.19	419.5	1087
203013	MAIN AT ANDRAID	1970-1980	15.659	0.357	11.86	21.28	646.8	1175
(203017)	UPPER BANN AT DYNES BRIDGE	1970-1981	5.392	0.317	5.84	14.67	335.6	1002
203018	SIX MILE WATER AT ANTRIM	1970-1980	5.248	0.488	11.30	25.93	277.3	1070
203020	MOYOLA AT MOYOLA NEW BRIDGE	1971-1980	7.239	0.410	14.52	25.13	306.5	1167
203021	KELLS WATER AT CURRYS BRIDGE	1971-1980	3.149	0.301	7.05	15.31	127.0	1309
(203024)	CUSHER AT GAMBLES BRIDGE	1972-1981	3.765	0.322	4.06	10.20	176.7	936
203025	CALLAN AT CALLAN NEW BRIDGE	1971-1981	2.744	0.403	11.99	21.83	164.1	975
(203026)	GLENAVY AT GLENAVY	1975-1980	0.653	0.403	19.60	24.33	44.6	1050
203027	BRAID AT BALLEE	1972-1980	3.850	0.487	12.70	30.05	177.2	1201
203028	AGIVEY AT WHITE HILL	1973-1980	2.397	0.307	8.39	17.31	98.9	1177
203029	SIX MILE WATER AT BALLYCLARE	1973-1980	1.628	0.467	11.43	24.45	58.4	1175
203033	UPPER BANN AT BANNFIELD	1975-1980	2.722	0.336	8.60	16.79	100.8	1400
204001	BUSH AT SENEIRL	1972-1976	5.273	0.447	14.98	23.29	306.1	1138
(205003)	LAGAN AT DUNMURRY	1970-1981	7.362	0.399	13.07	22.64	444.7	947
205004	LAGAN AT NEWFORGE	1972-1980	8.693	0.460	9.84	18.97	490.4	950
205005	RAVERNET AT RAVERNET	1972-1980	1.249	0.399	1.92	8.56	69.5	922
(205006)	LAGAN AT BLARIS	1972-1980	4.499	0.371	5.36	13.40	315.9	950
205008	LAGAN AT DRUMILLER	1974-1980	1.708	0.355	2.40	8.61	85.2	975
(205010)	LAGAN AT BANOGE	1974-1980	3.289	0.195	1.22	4.07	189.8	950
205995	WOODBURN COMPLEX	1886-1980	0.688	-----	24.70	53.32	28.2	1172
(206001)	CLANRYE AT MOUNT MILL BRIDGE	1976-1980	2.294	0.504	5.54	16.13	132.7	997
(206002)	JERRETSPASS AT JERRETSPASS (RIVER)	1976-1980	1.081	0.455	2.96	15.36	32.4	950
206995	ANNALONG AT MOURNE CONDUIT	1895-1979	0.630	0.365	13.02	27.30	14.2	1654

1. RECORDS FROM STATION NUMBERS IN BRACKETS TO BE USED WITH CAUTION
2. MONTHLY STATIONS-----NO BFI-----Q95 AND Q80 FROM MONTHLY DATA

Discussion with WDU identified some poorer quality flow records. These included stations where the natural flow regime is significantly influenced by artificial factors (such as reservoirs or canals), stations where, as a result of an unstable control, there is wide scatter of points on the rating curve and the flow record is of low accuracy; and stations having a better quality gauging station either up or downstream. These inferior (for the purpose of the current study) flow records amount to 8 of the 30 processed records and their station numbers are shown in parenthesis in Table 6.1. Figure 6.1 shows the location of each of the gauging stations used in the study.

It will be seen from Table 6.1 that all the standard hydrometric stations have short records: the average record length is 8 years with no data available before 1970. This data was therefore enhanced from the following sources:-

(i) Annalong gauge 1895-1979. (Figure 6.2). This gauge is a rectangular plate weir with low flow notch, maintained in good condition, with little leakage and clean straight approach section. The calibration of the direct flow recorder is unknown as is the detailed history of datum checks on the weir. The site lacks a staff gauge. However, it is thought that the quality of record may well be equal to that of other long flow records in the British Isles and given that the catchment feeds the major source for Belfast, it was considered essential that an attempt was made to analyse this record. Manual abstractions of flows from the large, 4ft square, logarithmic chart records was carried out by W.D.U. (NI). These flows were read at three hourly intervals during rapid changes of river flow and at daily intervals during periods of relatively constant discharge. The data was then processed by the Institute of Hydrology to produce a mean daily flow record from 1895, although there are many missing periods (Table 6.2).

Figure 6.1 Location of gauging stations used in study

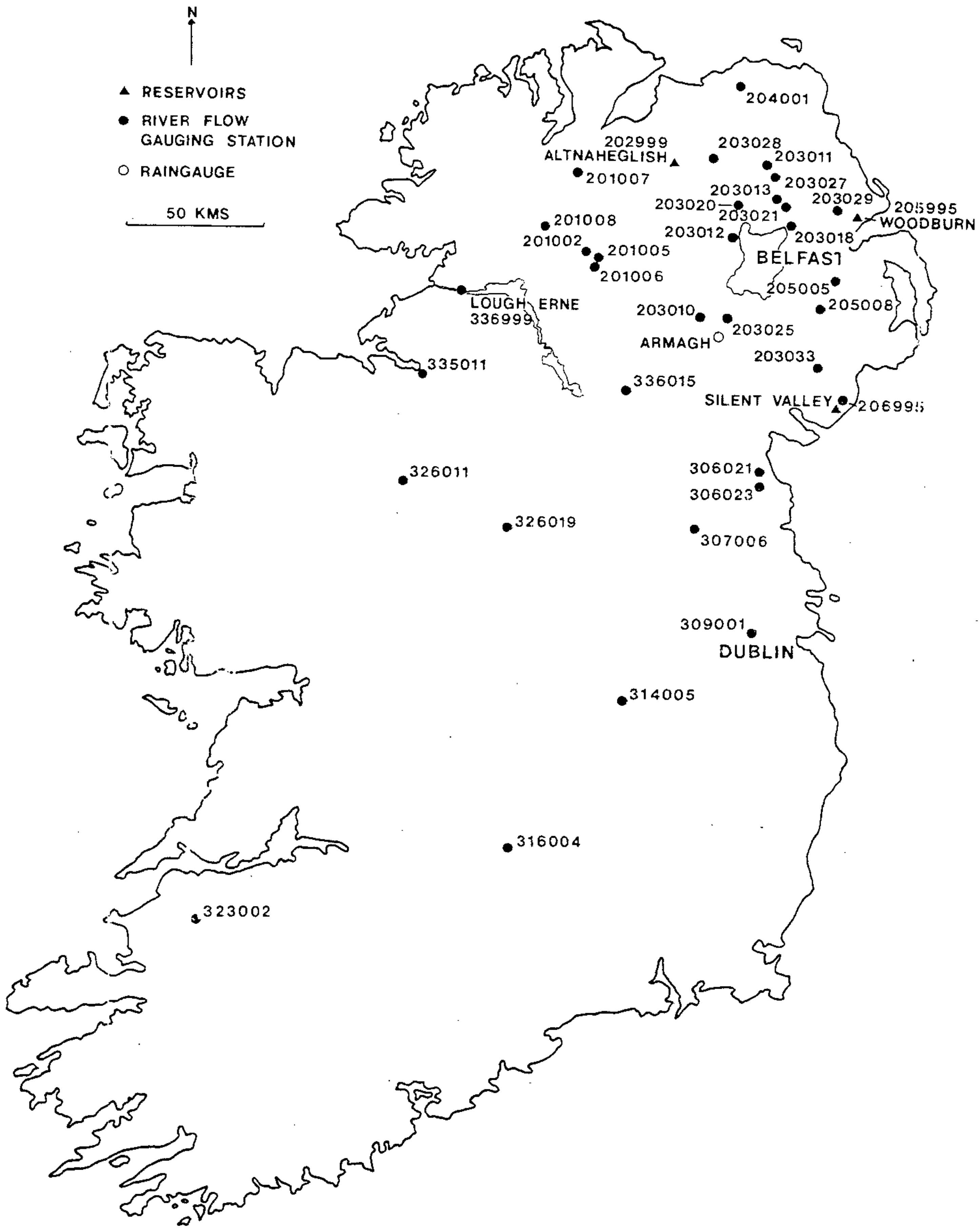
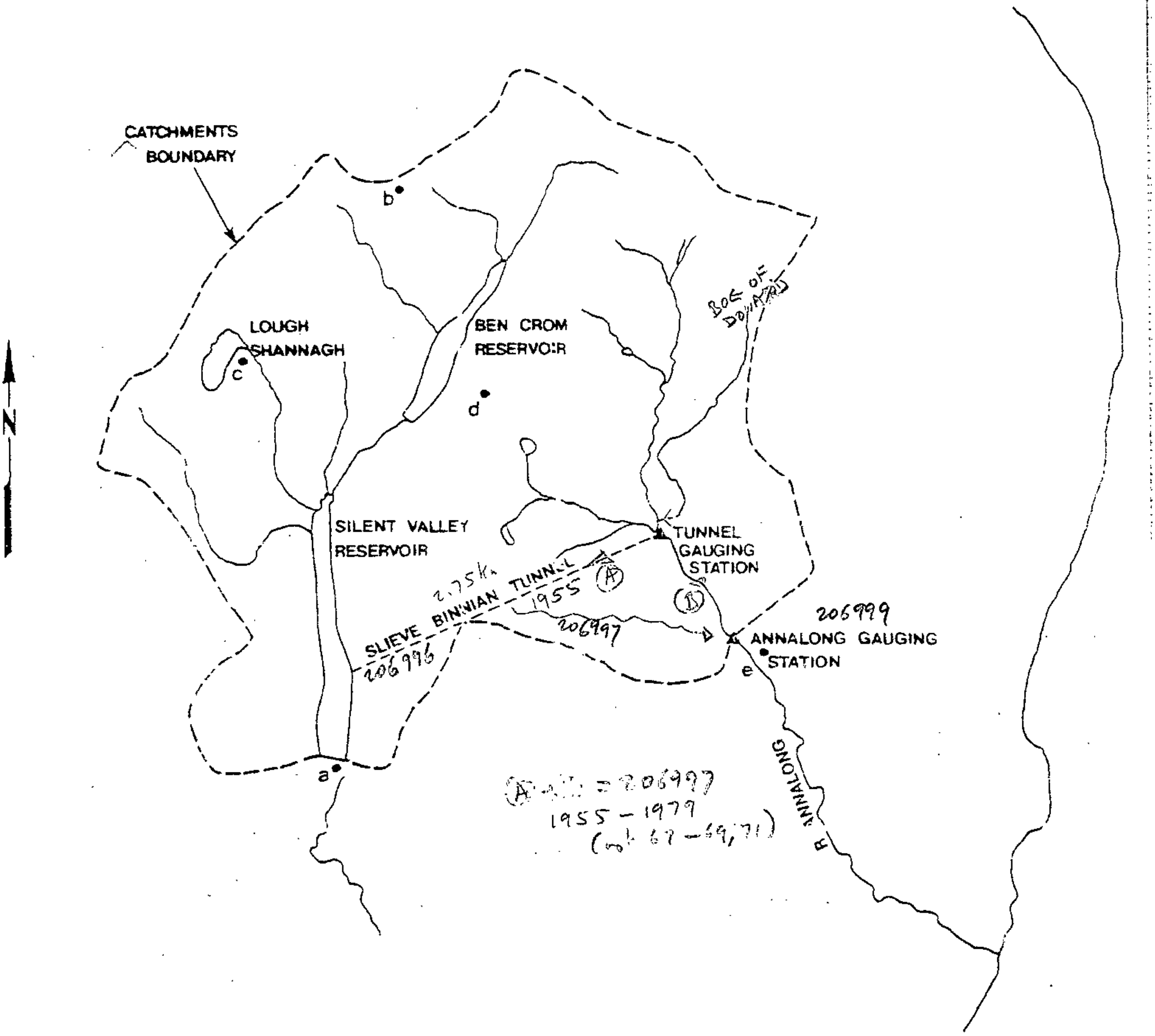


Figure 6.2 Silent Valley location map



Composite
206995

1895 – 1940 | 1955 – (1979)

RAINGAUGES:
- a Silent Valley Water Works
- b Slieve Bearnagh
- c Lough Shannagh
- d Slieve Lamagan
- e Annalong

Table 6.2 Available records for the Annalong catchment

ANNALONG GAUGED FLOWS		TUNNEL GAUGED FLOWS		MONTHLY CATCHMENT RAINFALL	DAILY ARMAGH RAINFALL
					1853
1895-1897	incomplete				
1898-1899	complete				
1900	missing				
1901	incomplete				
1902-1905	missing				
1906-1909	incomplete				
1910-1911	complete				
1912-1916	incomplete				complete
1917	complete				
1918-1919	incomplete				
1920-1927	complete				
1928	incomplete				
1929-1934	complete				
1935	incomplete				
1936-1939	complete				
1940	incomplete			1939	
1941-1960	missing	1955-1958	incomplete		
		1959-1963	complete		
1960-1979	incomplete	1964-1966	incomplete	complete	
		1967-1971	missing		
		1972-1974	incomplete		
		1975-1979	complete	1980	1980

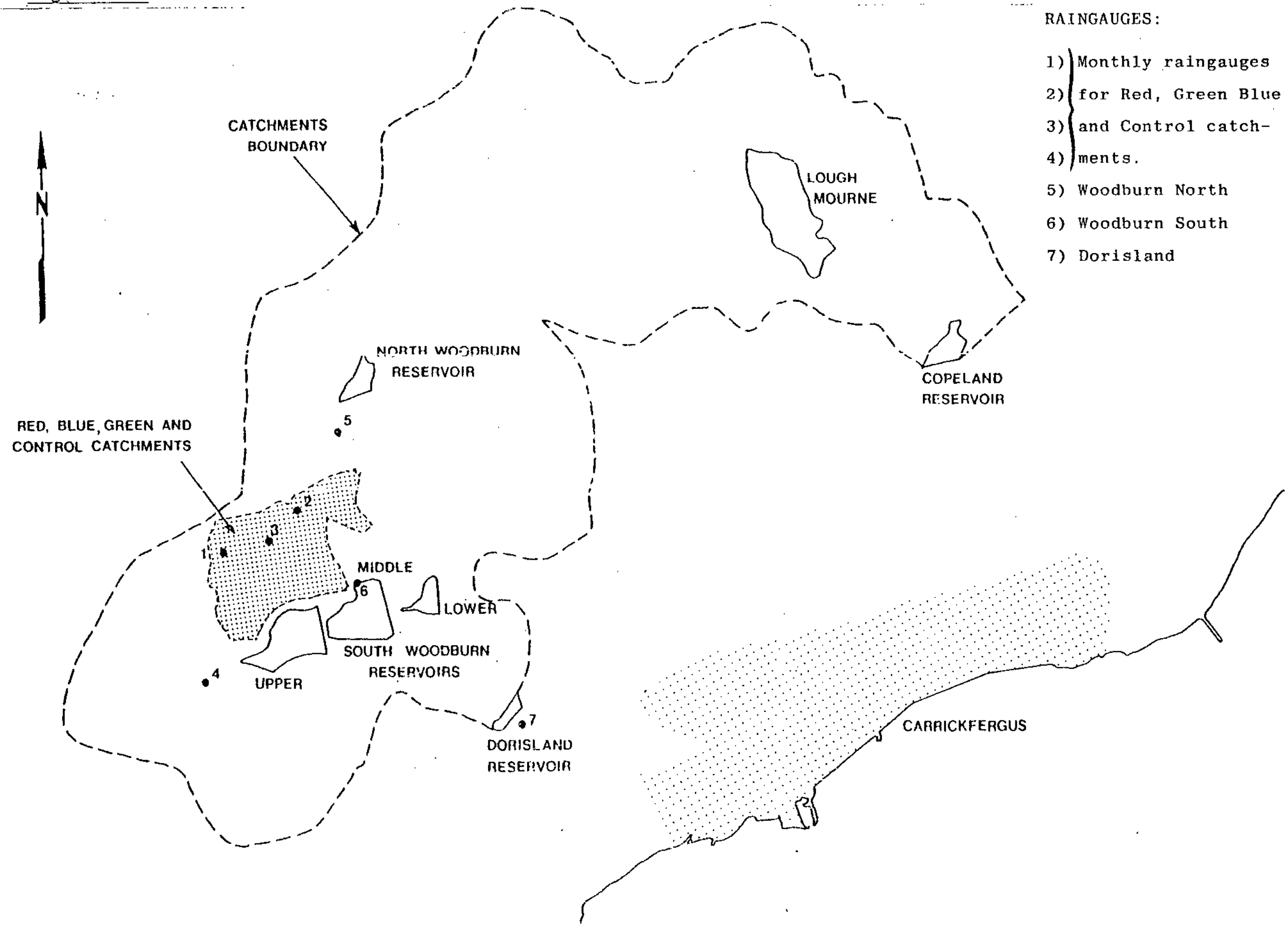
The Slieve Binnian tunnel was constructed in 1955 to divert the river Annalong flows to the Silent Valley reservoir and thereby increase its yield (Colebrook, 1955). The intake to the tunnel is constructed as a mass concrete stilling pool with two orifices to the tunnel and an overflow weir discharging water into the old river course. Flows down the tunnel are measured by a non-standard direct flow recorder using these rectangular orifices as a control. The detailed calibration is not known. Charts are available from 1955 to 1979 and manual abstractions of these charts has been carried out by the Institute of Hydrology to provide a record of mean daily flows.

To compute natural catchment flow post 1955 it is necessary to sum the tunnel diversion discharge and the flows at the original Annalong gauge. Unfortunately this is not possible because of gaps in the Annalong record. However, an examination of the tunnel charts revealed that the tunnel diverts all but the peaks of the extreme floods, (it was designed to divert 97% of its catchment's runoff). It was therefore possible to estimate flows at the Annalong site by multiplying tunnel flows by 1.347 to allow for the difference in area and mean annual effective rainfall of the partial and total catchment areas.

(ii) Altnaheglish catchment 1926-1959. Despite extensive enquiries by W.D.U. (NI) the origin of this weekly inflow record is unknown. Monthly flows have been calculated and used in the storage yield analysis.

(iii) Woodburn experimental catchments. Four experimental catchments were instrumented by the Belfast City and District Water Commissioners to study "the effects of afforestation on water runoff" (Savill, 1974). The catchments, named the Red, Blue, Green and Control areas, are shown in Figure 6.3. Direct flow Lea recorders were installed in 1959 together with weirs having 90 degree v-notches for low flows, and rectangular weirs for higher flows. A weighted mean of the four monthly flow records (Appendix 1) have been used to develop a rainfall runoff relationship for the Woodburn complex which has enabled

Figure 6.3 Woodburn complex location map



RAINGAUGES:

1) Monthly raingauges
2) for Red, Green Blue
3) and Control catch-
4) ments.
5) Woodburn North
6) Woodburn South
7) Dorisland

synthetic monthly flows to be estimated.

(iv) Republic of Ireland. Discussion with the Office of Public Works, Dublin, identified 27 stations (from a network of 200) with record lengths in excess of 20 years, having natural flows of acceptable accuracy. This data has been transferred to IH and was initially examined to identify which catchments had similar flow regimes to those of Northern Ireland. Eleven such records were identified, their locations are shown in Figure 6.1 and their catchment details are listed on Table 6.3. The Electricity Supply Board, Dublin, also operate gauging stations and have made available monthly gauged outflows and inflows to Lough Erne based on measurement at Cathleen Falls power station and changes in Lough level.

(v) South West Scotland. In view of the proximity of south west Scotland to parts of Northern Ireland it was considered appropriate to use flow records from the Solway Purification Board. The catchments were selected on the basis of record length and similarity to the reservoired catchments of Northern Ireland, that is, having high annual average rainfall and impermeable geology. The details of the selected catchments are summarised in Table 6.4

Values of average flow (ADF) in cumecs, base flow index (BFI)†, the 95 and 80 percentile discharge from the flow duration curves (Q95 and Q80), catchment area and standard annual average rainfall 1941-70 (SAAR) are shown in Table 6.1, 6.3 and 6.4. An inspection of these data indicate that the variation in flow indices between catchments is small in Northern Ireland in relation to the rest of the British Isles, that the catchments are generally impermeable and that a single regional storage yield relationship may be appropriate to use throughout the province. This analysis of both flow data and catchment characteristics provided an objective basis for selecting flow records from outside Northern Ireland which were similar to those within the province.

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† The ratio of base flow discharge to total discharge (Institute of Hydrology 1980).

Table 6.3 Summary of flow data from Republic of Ireland

NUMBER	STATION	PERIOD	ADF cumecs	BFI	Q95 %ADF	Q80 %ADF	AREA sq km	SAAR mm
306021	GLYDE AT MANSFIELDTOWN	1955-1980	4.857	0.640	11.94	25.45	321	921
306023	DEE AT DRUMGOOLESTOWN	1954-1980	3.837	0.553	11.13	21.14	302	924
307006	MOYNALTY AT FYANSTOWN	1956-1980	2.954	0.559	9.11	22.27	179	959
309001	RYEWATER AT LEIXLIP	1956-1982	2.561	0.496	3.94	12.69	215	860
314005	BARROW AT PORTALINGTON	1955-1981	6.384	0.513	7.22	19.85	398	966
316004	SUIR AT THURLES	1954-1981	4.157	0.516	5.84	16.62	236	950
323002	FEALE AT LISTOWEL	1946-1980	22.203	0.309	5.94	14.62	646	1281
326011	BREEDOGE AT BELLA BRIDGE	1953-1980	1.920	0.365	4.06	12.24	112	1150
326019	CAMLIN AT MULLAGH	1953-1980	4.743	0.503	8.64	23.55	260	968
335011	BONET AT DROMHAIR	1957-1981	9.432	0.343	8.72	21.34	294	1430
336015	FINN AT ANLONE	1956-1979	2.805	0.363	3.67	13.69	175	1022
336999	ERNE AT POWER STATION (INFLOWS)	1900-1983	96.755	-----	11.48	32.48	4349	1489

1. MONTHLY STATIONS-----NO BFI-----Q95 AND Q80 FROM MONTHLY DATA

Table 6.4 Summary of flow data from South West Scotland

NUMBER	STATION	PERIOD	ADF cumecs	BFI	Q95 %ADF	Q80 %ADF	AREA sq km	SAAR mm
79002	NITH AT FRIARS CARSE	1957-1982	25.57	0.380	10.98	23.06	799	1598
79003	NITH AT HALL BRIDGE	1959-1982	5.25	0.270	6.72	15.32	155	1692
79004	SCAR WATER AT CAPENOCH	1963-1981	5.14	0.310	6.42	19.29	142	1700
79005	CLUDEN WATER AT FIDDLERS FORD	1963-1982	7.45	0.370	6.93	15.44	238	1407
79006	NITH AT DRUMLANRIG	1967-1982	15.27	0.340	9.13	18.42	471	1613
80001	URR AT DALBEATTIE	1963-1980	5.45	0.350	4.87	15.50	199	1321
81002	CREE AT NEWTON STEWART	1963-1980	14.85	0.270	7.03	18.22	368	1715
81003	LUCE AT AIRYHEMMING	1967-1982	5.75	0.230	5.10	11.86	171	1433
82001	GIRVAN AT ROBSTONE	1963-1980	6.11	0.340	9.17	17.90	245	1435

6.3 Meteorological data

(a) Rainfall data

Annual rainfalls for gauged catchments (Table 6.5) were provided by the Meteorological Office Belfast and are used to estimate average annual losses for Northern Ireland. In addition standard annual average rainfall 1941-70 (SAAR) for each of the reservoired catchments (except Silent Valley) were obtained from Table C3.7 of Water Statistics 1980 and are shown in Table 6.10.

Monthly rainfall for extending the Woodburn flow records was based on the North Woodburn raingauge from 1886-1980. These were calculated for the combined Red, Blue, Green and Control catchment areas by using a ratio of point to catchment rainfall based on SAAR values. For the period of concurrent flow and rainfall data (1960-1970) a more accurate monthly catchment rainfall was calculated by weighting the data from 6 raingauges in or near the catchments. (Figure 6.3, Appendix).

Table 6.6 shows the ratio of the 1941-58 average annual rainfall to the 1941-70 annual rainfall for five gauges in the Silent Valley area. Inconsistencies in the ratios for the Silent Valley waterworks gauge (due to relocating the gauge in 1958) and the Slieve Lamagan gauge were discussed with the Meteorological Office (Belfast and Bracknell). Following these discussions the Meteorological Office revised catchment SAAR values based on 1:250,000 isohyetal maps (Table 6.7). Monthly catchment rainfall for the Annalong and Silent Valley catchments for the period 1939 to 1980 were then determined by weighting the three consistent raingauges by the appropriate gauge and catchment SAAR value.

(b) Actual evaporation

For each reservoired catchment actual evaporation (Ea) is required to estimate the average annual discharge from catchment rainfall. Penman potential evapotranspiration (Ep) for short grass, adjusted for mean catchment altitude, has been used as an estimate of catchment

Table 6.5 Annual catchment rainfall for Northern Ireland catchments

	DUDGEON BRIDGE	CAMOWEN TERRACE	CAMPSIE BRIDGE	CASTLEDERG	MAYDOWN BRIDGE	DROMONA	BALLINDERRY BRIDGE	ANDRAID	ANTRIM	GLENONE BRIDGE	MOYOLA NEW BRIDGE	CURRYS BRIDGE	GAMBLE'S BRIDGE	CALLAN NEW BRIDGE	GLENAVY	BALLEE	WHITE HILL	BALLYCLARE	BANNFIELD	SENEIRL	DUNMURRY	RAVERNET	BLARIS	MOUNT HILL BRIDGE	JERRETSPASS
	201002	201005	201006	201008	203010	203011	203012	203013	203018	203019	203020	203021	203024	203025	203026	203027	203028	203029	203033	204001	205003	205005	205906	206001	206002
YEAR																									
1941-70	1174	1170	1174	1462	1005	1416	1158	1238	1066	1113	1267	1215	1046	965	1009	1299	1120	1056	1455	1239	1007	935	915	1252	1020
1971					788	1193	907	1024	878	919	1105										796				
1972	1222				983	1239	992	1082	954	1048	1194	1079		932	898						954	920		1330	1115
1973	1165	1057	1079		895	1222	919	1052	890	926	1169	1022	881	828	842	1083	971			1125	842	750	777	1025	851
1974	1297	1132	1189		1021	1322	1083	1151	1081	1092	1354	1218	1019	1015	949	1201	1157	1111		1159	1011	1040	922	1300	1053
1975	1031	842	887		723	1039	779	929	817	797	1025	914	701	683	755	996	879	833		938	718	700	672	1005	755
1976	1152	1086	1048	1495	955	1245	1111	1093	1011	1052	1324	1110	975	906	948	1151	1028	1012	1548	1101	918	950	861	1391	967
1977	1218	1143	1167	1608	950	1345	1071	1182	1024	1094	1286	1194	1020	961	883	1250	1126	1024	1481	1165	953	930	875	1243	959
1978	1291	1205	1221	1718	844	1416	1158	1238	1098	1183	1330	1191	994	897	958	1299	1064	1151	1484	1177	1098	1030	972	1239	949
1979	1338	1217	1256	1718	1015	1345	1181	1263	1141	1146	1343	1227	1067	955	1080	1247	1098	1151	1382	1227	1067	967	935	1239	1040
1980	1402	1158	1237	1796	980	1419	1119	1296	1138	1226	1295	1257	1056	996	1130	1335	1142	1162	1461	1269	1057	980	941	1280	1013

Table 6.6 Rainfall ratios for the Silent Valley and Annalong raingauges

	GAUGE	IRISH GRID REFERENCE	SAAR 1941-70 mm	RAINFALL RATIO 1941-58/1941-70 %
(a)	Silent Valley Water Works	J305 216	1355	96.0
(b)	Slieve Bearnagh	J314 279	1770	98.6
(c)	Lough Shannagh	J298 259	1808	98.4
(d)	Slieve Lamagon	J322 255	1787	101.2
(e)	Annalong	J355 255	1240	98.5

Table 6.7 SAAR (1941-70) for Silent Valley and Annalong Catchments

CATCHMENT	SAAR (mm)	AREA (ha)
Silent Valley (residual catchment below Ben Crom excluding Annalong diversion)	1730	1418.8
Ben Crom	1845	810.2
Silent Valley Plus Ben Crom excluding Annalong	1772	2229.0
Annalong above Tunnel Diversions	1726	1011.6
Annalong above Mourne Conduit	1654	1421.8
Silent Valley, Ben Crom and Annalong above Tunnel Diversion	1758	3240.0

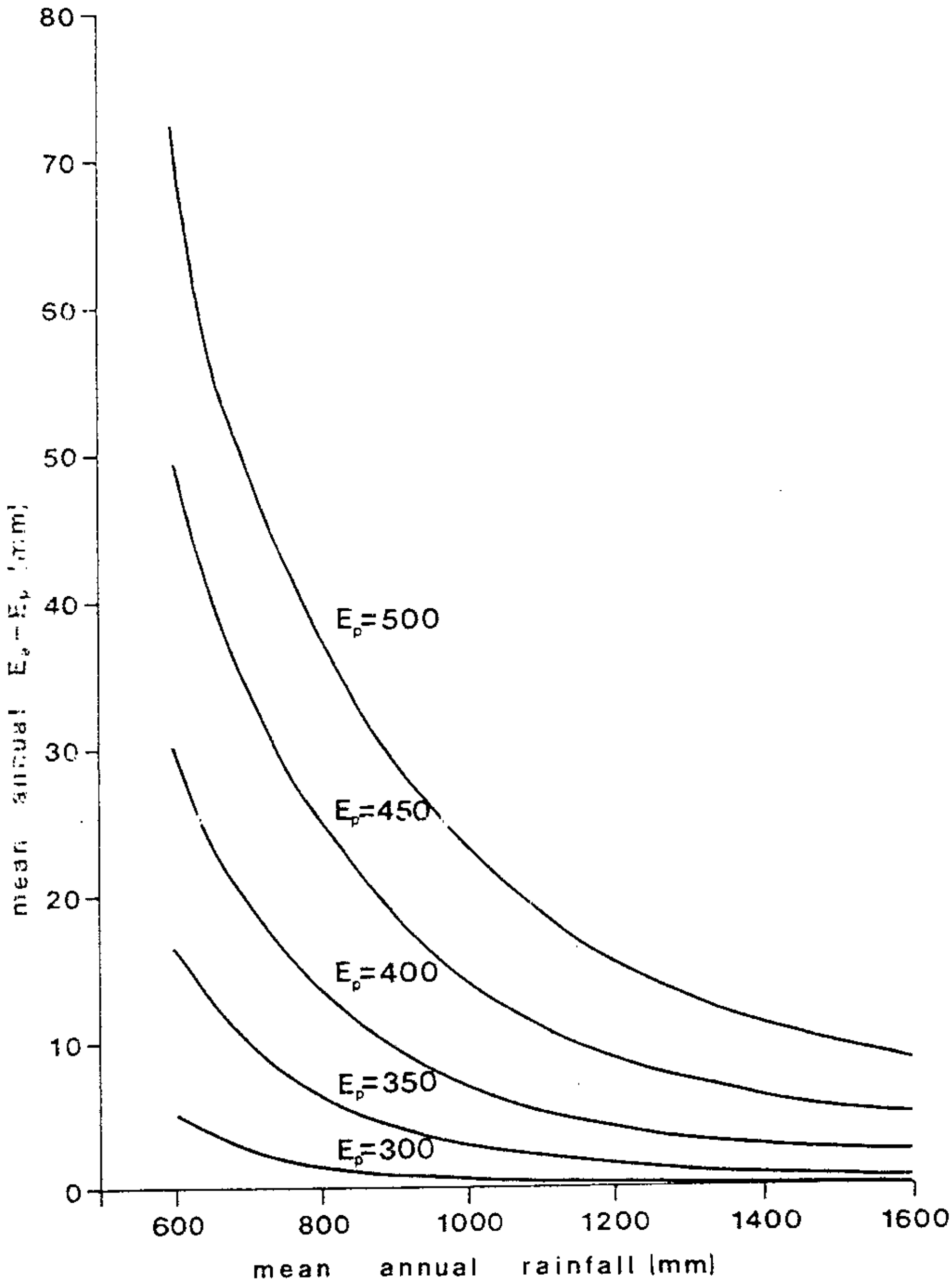
actual evaporation. An investigation of catchment losses showed that the difference between mean Ea and mean Ep is very small in Northern Ireland; the results are described below.

The mean and standard deviation of annual losses (rainfall minus runoff) were calculated for each gauged catchment. Ten catchments with eight or more years of flow data and a low standard deviation of annual losses were used for further analysis. The average annual losses for this group of catchments was 373 mm. The mean Ep values (Table C.3.5.3 DOE, N. Ireland 1980) calculated for climatological stations in Northern Ireland were adjusted to sea level using a 'lapse rate', provided by the Meteorological office, of 29.3 mm/100 m. The average Ep of 13 climate stations was 440 mm adjusted to sea level. (These 13 stations excluded coastal sites, the Silent Valley Water Works site which seriously over-estimated Ep, and sites with less than 10 years of data). This value of 440 mm is used as the mean sea level Ep throughout Northern Ireland, from which any catchment Ep can be calculated. A mean altitude adjusted Ep of 397 mm was calculated for the ten gauged catchments and compared with the actual losses from the catchment water balance of 373 mm, giving a mean difference between Ep and Ea of 24 mm. This assumes that all losses may be attributed to evaporation and this is supported by the impermeable catchment geology.

A second and independent method of estimating the difference between Ep and Ea employed a soil-moisture deficit model described in the following section. This model estimated daily Ea and was run for a range of Ep and SAAR values. The rainfall was distributed according to the daily rainfalls at Armagh Observatory over the period 1941-70. The results are shown in Figure 6.4 where the difference between Ep and Ea can be estimated for a site with a given value of SAAR and Ep. Entering Figure 6.4 with a mean SAAR of 1146 mm and Ep of 397 mm for the catchments in the water balance study yields a difference of 5 mm between Ep and Ea.

In view of the small differences between Ep and Ea from both methods and the fact that most reservoirs have SAAR values in excess of 1000 mm, where any differences between Ep and Ea would be smaller than the water balance catchment sub set, it was concluded that Ep could be

Figure 6.4 Relationship between potential evaporation E_p and actual evaporation E_a



assumed to be equal to Ea. Furthermore, most reservoirs are located in upland areas with impermeable soil and geology so the only losses would be evaporation. Hence mean annual runoff can be estimated from SAAR - Ep.

(c) Soil Moisture Deficit

The extension of the Annalong and Woodburn flow records also require estimates of the soil moisture deficit (SMD) appropriate to each catchment. There are no published long term SMD data available for Northern Ireland and so values have been estimated from climatological data. A recent study of SMD models (Calder, 1983) has shown that a reliable estimate of SMD can be achieved using a mean estimate of potential evaporation, daily rainfall and a simple, 2 layer, soil moisture extraction model.

One of the longest daily rainfall records in Northern Ireland is Armagh Observatory (1853-1982). Armagh is approximately 50 km from Silent Valley and 65 km from the Woodburn complex and it has a much lower SAAR of only 866 mm. However the daily catchment rainfall values can be estimated using the ratio of (catchment SAAR/Armagh SAAR) to provide a reasonable basis for SMD calculation. The method for estimating mean annual catchment potential evaporation has been described earlier; values for the Silent Valley and Woodburn catchments were 325 mm and 380 mm respectively.

Daily SMD values were calculated for each site using the simple two layer model, daily catchment rainfall and the seasonal distribution of mean annual potential evaporation. The 'start of month' SMD values were extracted from the results for use in the flow extension models described in section 6.4.

6.4 Record Extension

(a) Model development

It was necessary to infill gaps in the Annalong record and to extend the Woodburn flow sequence to provide additional data on which to base the regional storage yield analysis and to carry out a more detailed simulation of the Silent Valley reservoir system.

Concurrent flow and rainfall data and long rainfall records were available at both locations and a regression model was used for data extension. This method provides objective parameter estimation and avoids the need to make subjective judgements about catchment processes which is necessary with most conceptual models. Regression analysis is used to construct simple linear relationships between any set of inputs and an output variable, such that the difference between the observed and predicted sums of squares is a minimum.

Data inputs for the regression were rainfall, evaporation and soil moisture deficit (SMD); outputs were monthly flows, with all variables expressed in mm. Model formulation is selected partly by experience but aided by an analysis of variance and an inspection of the residuals (the difference between the observed and predicted monthly discharge). The GENSTAT statistical package was used to assist with the analysis. This program was designed by Rothamstead Experimental Station to perform analysis of variance, and incorporate extensive model building aids such as transformations, residual plotting and subset search routines.

Table 6.8 lists the variables used in developing the regression model. Fitting natural and logarithmic flows was carried out at each site based on the rainfall and SMD data available. Examples of the Annalong and Woodburn correlation matrices are shown in Appendix 1. The following checks were carried out to ensure that there were:-

(1) No major errors in a simple water balance of the rainfall, evaporation and flow data used to calibrate the model.

(2) No tendency to over or under predict at high, medium or low flows.

(3) No seasonal trend in the residual flows (fitted - observed).

(4) No trend in the residuals throughout the period of record.

Table 6.8 Definition of variables used for record extension

VARIABLE	DESCRIPTION
FL1,FL2 FL3,FL4	The mean monthly flow from the previous 1,2,3 and 4th month respectively.
RR	The current month's effective rainfall (catchment rainfall less evaporation). If actual evaporation exceeds rainfall, RR is set to zero. This happened rarely.
RRL1,RRL2, RRL3,RRL4.	Effective rainfall (RR) lagged by 1,2,3 and 4 months respectively. It was considered unnecessary to include higher lag terms because the catchments are small, flashy and impermeable.
SMD	The start of month soil moisture deficit described in section 6. 3
SMDL1,SMDL2, SMDL3,SMDL4	The SMD lagged by 1,2,3 and 4 months respectively.
EVAP	Actual evaporation during the current month.
EVAP1,EVAP2	Actual evaporation lagged by 1 and 2 months respectively.

(b) Application to the Woodburn Complex

A regression was carried out on the 11 complete years (1960-1970) of catchment runoff and rainfall data for the Red, Blue, Green and Control catchments (Appendix 1). The best equation obtained, fitting the monthly flow Q in mm is:-

$$Q = 22.2 + 0.497\ RR + 0.098\ RRL1 - 0.410\ SMD - 0.588\ SMDL2 \qquad (1)$$

$R^2 = 81.5\%$, standard error of Q = 15.1 mm.

All terms were significant above the 99% confidence level. Additional evaporation, lagged rainfall and SMD terms were not significant at the 95% level and hence they do not lead to any improvement in the estimation of monthly flows. Equation (1) enables monthly runoff to be calculated for the Woodburn catchment from 1895 - 1979.

The average daily flow (ADF) 1941-70 of the reconstructed sequence was compared with the ADF calculated for the regional analysis. These were very similar, being 58.4 Ml/d and 61.2 Ml/d respectively. The results of a storage yield analysis will be heavily reliant on the estimate of average flow. Therefore, for consistency with the regional study, the synthetic sequence was adjusted to comply with a 1941-70 ADF of 61.2 Ml/d.

(c) Application to the Annalong catchment

The modelling based on adjusted tunnel flows (section 6.2) was carried out on the period of record January 1955 to December 1979, the only period for which corresponding catchment runoff and rainfall data are available (Table 6.2). Although a number of gaps remain the statistical package used was able to make optimum use of all data.

The best fit equation obtained on monthly data is given below (in mm).

$$Q = 32.46 + 0.703\ RR - 0.437\ SMD \qquad (2)$$

$R^2 = 75.7\%$, standard error of Q = 23.1 mm.

All the terms were significant above the 98% confidence level. Inclusion of additional terms were not significant at the 95% level. Equation 2 enables runoff to be estimated from 1853 to 1979 for the Annalong catchment using rainfall and SMD data. Monthly catchment rainfall based on the 3 local gauges has been used from 1939 to 1980, but before this the Armagh rainfall, transferred using a SAAR ratio of 1.91, has been used.

The ADF of the synthetic sequence (1941-70) was compared with the ADF from the regional study. They were very similar, being 52.94 Ml/d and 51.77 Ml/d respectively. The synthetic sequence was adjusted to comply with an ADF of 51.77 Ml/d as was carried out for Woodburn. The adjusted series was used to infill gaps (Table 6.2) and to extend the Annalong record.

(d) Comparison of Woodburn and Annalong model

It is interesting to note that the structure of both the Woodburn and Annalong models is similar; in both cases natural rather than logarithmic flows were fitted best. From equation (2) it can be seen that the Annalong flows are related only to the current monthly rainfall and SMD, whereas equation (1) for Woodburn includes more lagged terms. Any physical interpretation of the differences in the regression models must be made with caution but the generally steeper and more impermeable Annalong catchment would be expected to have a 'flashier' flow regime with less 'hydrological memory' than the more subdued topography of Woodburn. This is reflected in the absence of lagged terms in equation (2). The larger error for the Annalong model may be due to this flashier flow regime, to a larger catchment area, or to the lower accuracy of catchment rainfall (there were no raingauges on the catchment to the tunnel in contrast to Woodburn where there were 6 gauges on the catchment). However the reconstructed flows for the Annalong catchment will provide a much smaller percentage of the total record. Within the constraints of the current study it is thought that both composite flows adequately represents the historical flows. Furthermore the average flow over the period 1941-1970 for the two flow sequences is very close to that estimated from rainfall-evaporation. This independent check supports the results of the evaporation studies of section 6.3.

6.5 Regional storage yield relationship

In order to estimate the yield of a large number of sources a generalised storage yield relationship was developed which could readily be applied to any reservoir in Northern Ireland.

A storage yield analysis was carried out on each of the available flow records by calculating the storage requirement Si needed to maintain a yield Y from:-

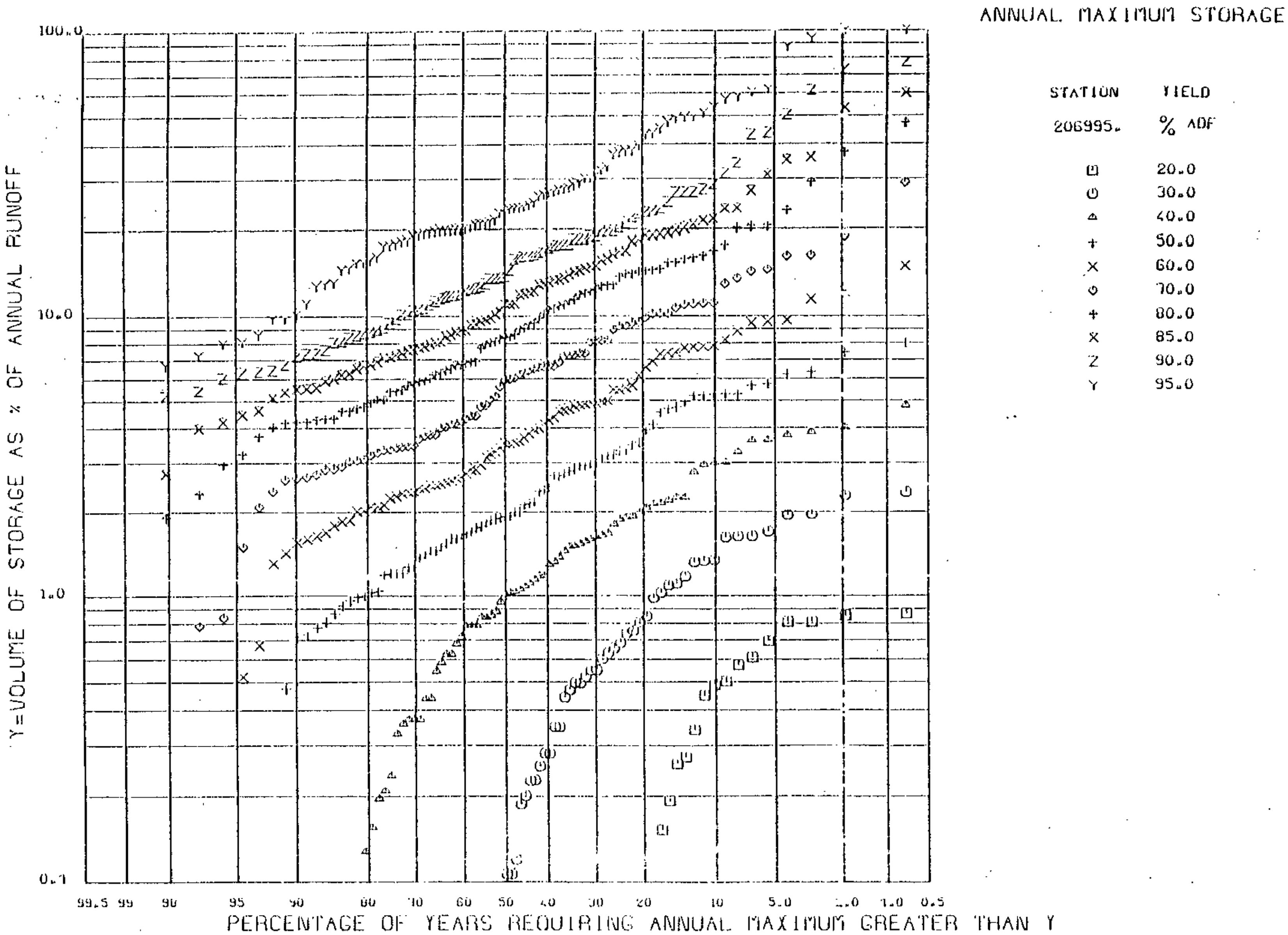
$$S_{i+1} = Si - Qi + Y$$

where Qi is the daily (or monthly) discharge. The value of Si will increase during a drought and decrease as 'reservoir' inflows exceed the yield. The 'reservoir' will spill when Si is negative, in which case Si is reset to zero. The maximum value of Si, for any drought event, is thus the storage needed to just maintain the given yield. This simulation is carried out for the complete record and a series of Sj, the annual maximum values of Si are extracted. These values are ranked from the smallest (j=1) to the largest, and the non-exceedance probability Fj is calculated using the Blom plotting position:-

$$Fj = \frac{j - 0.375}{n + 0.25}$$

where n is the number of years of data. The entire procedure is repeated for different Y values. Figure 6.5 shows a plot of the storage requirement Sj against percentage exceedance on log-normal probability paper for a number of different yields. The yield is expressed as a percentage of the average daily flow (ADF), and Sj as a percentage of the annual runoff volume (ARV). (This facilitates comparison of storage yield relationships for catchments with different average flows). A smooth curve may be drawn through the points on Figure 6.5, and the storage required to maintain a yield for a given percentage of years without reservoir failure may be estimated.

__Figure 6.5__ Storage yield diagram for Annalong catchment 1895-1979



The above analysis was carried out on each of the following flow sequences:-

1) Short records (< 10 years) from the N.I. hydrometric network, i.e. the stations included in Table 6.1.

2) Longer records (20-40 years) from the Republic of Ireland shown in Table 6.3 and South West Scotland (Table 6.4).

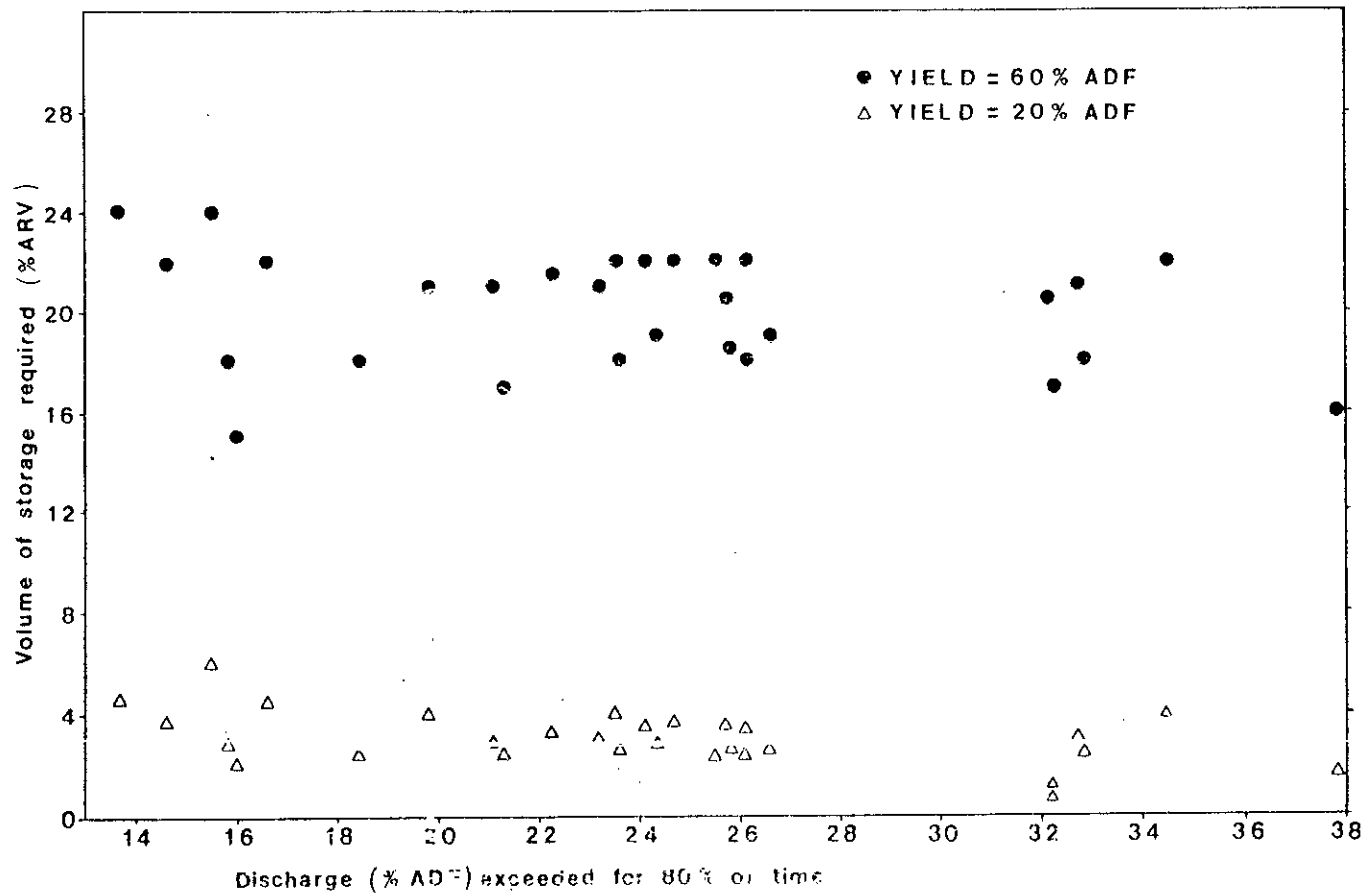
3) Monthly flow records for Lough Erne (1900-1983) and Altneheglish reservoir (1929-1950).

4) Monthly gauged and reconstructed records for Woodburn (1886-1980).

5) Daily gauged (1895-1979), and monthly gauged and reconstructed flows for Annalong (1895-1979). The pre 1895 data was not used for the final analysis because of its poorer accuracy due to estimation from the Armagh raingauge.

The relationship between the storage yield diagram and the catchment flow regime (indexed by the 80 percentile exceedance discharge from the flow duration curve) was investigated using an enlarged data set for the Republic of Ireland. The 10 year return period storage for yields of 20% ADF and 60% ADF were plotted in Figure 6.6 against the 80 percentile exceedance discharge, Q80. Although the figure suggests that there may be some tendency for flashy, impermeable catchments with low values of Q80 to require larger storages, the relationship was poor. The conclusion of Section 6.2 was that catchments in Northern Ireland are generally more impermeable than those of the Republic and moreover that reservoired catchments were among the most impermeable areas of the North. Thus despite the inconclusive results shown on Figure 6.6, it was thought desirable only to use the catchments from the Republic with similar values of Q80 to those in the North. These eleven catchments were put into two groups, those with a Q80 between 20% and 25% ADF and the remainder, having Q80 between 12% and 16% ADF. For each group of stations the average storage frequency relationship was found by averaging individual station plots for a given yield. The flashier group of catchments showed a slightly greater storage requirement for a given yield and frequency and this curve was used

Figure 6.6 Relationship between 10 year return period storage and 80 percentile exceedance discharge for Republic of Ireland catchments



in subsequent comparisons of storage yield diagrams. This averaging procedure was repeated on the impermeable catchment data sets from Northern Ireland and South West Scotland.

As a result of the number of severe droughts in the period 1972 - 1979 (Section 6.8) it was thought that the storage frequency relationship based on the short Northern Ireland records would be biased. This was checked by comparing the storage yield relationship for the Annalong derived from the period 1895-1979 with that derived from the period 1972-1979. The results are shown on Figure 6.7 which illustrates the large underestimation of yield for a given storage from the short record. (For yields of 20% ADF and in excess of 80% ADF there were insufficient events to make comparisons). The pooled Northern Ireland and the Republic of Ireland storage yield diagrams were thus adjusted to allow for this bias. In the case of the Republic of Ireland the adjustment was based on the period 1956-1979 which was typical of the records used from the south.

A comparison of daily with monthly based storage yield relationships for the Annalong record showed that the monthly analysis underestimates the 50 year return period storage requirement for amounts ranging from 1% - 7% of the annual runoff volume, for yields of 20% and 95% of the average flow. This arises because daily data give a more accurate and larger estimate of within month storage requirements. This adjustment was made to the final storage yield relationship for each of the monthly records. For each storage frequency curve the storage required for 2% of the years was estimated for each yield. This was also carried out for each of the individual long period records and the results are listed in Table 6.9 and plotted on Figure 6.8. The figure illustrates that there is good agreement between each of three small upland catchments; Altnaheglish, Woodburn and Annalong and with the pooled curve from Northern Ireland (except at the lower yields). The Republic of Ireland pooled curve plots below this group as does the Lough Erne analysis. The difference between the Lough Erne and Republic of Ireland curves compared with all the Northern Ireland curves may be due to:-

1) Differences in flow regime caused by differences in catchment

Figure 6.7 Sensitivity of storage-yield to period of record - Annalong

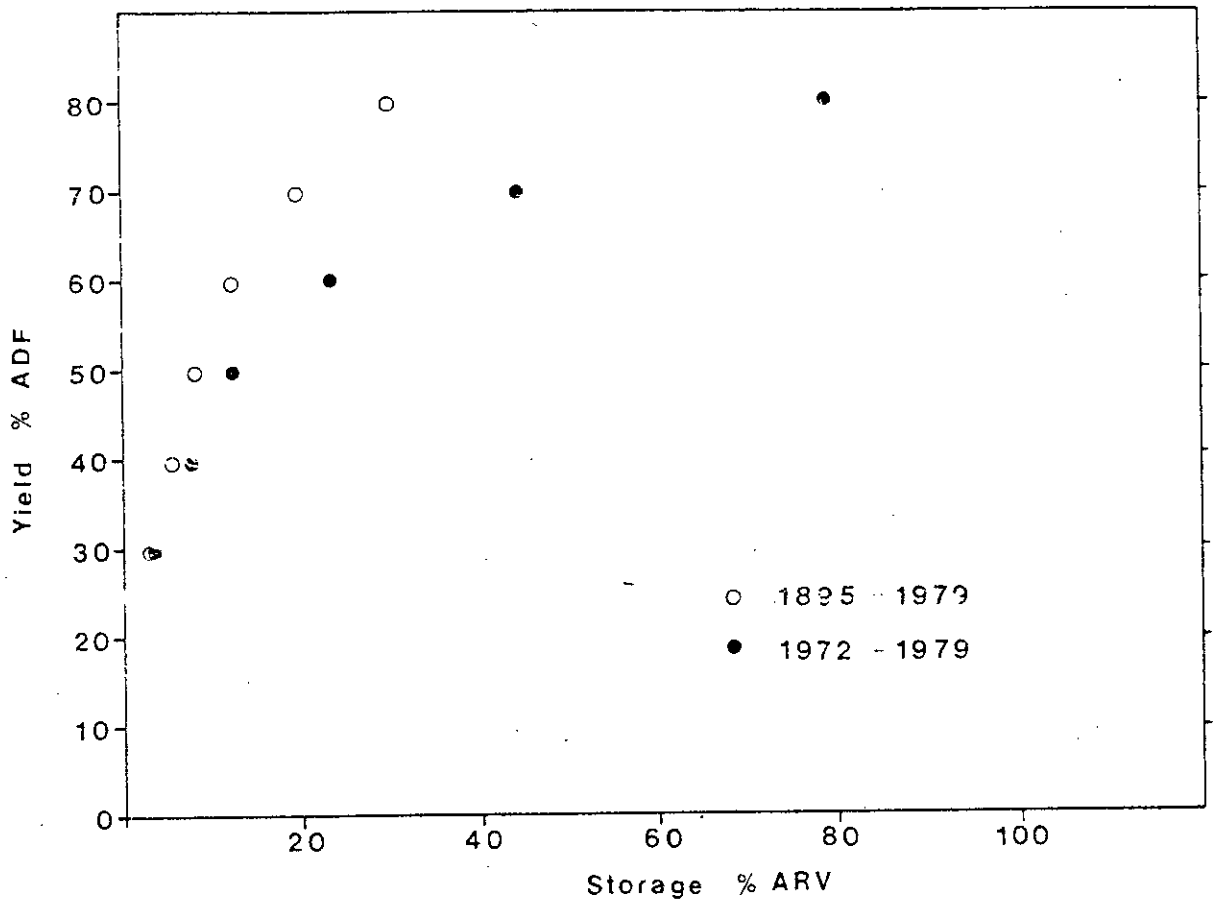


Table 6.9 Storage requirement for 50 year return period of failure

YIELD % ADF	LOUGH ERNE [1]	ALTNAHEGLISH [1]	WOODBURN [1]	ANNALONG [1]	REPUBLIC OF IRELAND [2]	NORTHERN IRELAND [3]	SOUTH WEST SCOTLAND [4]
20	4.5	2.3	3.4	1.7	6.1	-	3.1
30	8.3	3.8	6.2	3.3	8.6	7.8	5.8
40	12.8	6.6	8.7	5.6	11.6	10.6	9.6
50	18.7	9.8	12.6	9.3	15.3	11.9	15.3
60	24.6	14.3	16.9	14.3	24.1	16.2	21.5
70	37.8	20.2	22.5	22.9	30.2	18.0	27.1
80	52.1	29.0	31.8	35.0	48.0	28.4	35.5
85	64.4	35.3	37.6	45.8	60.6		43.0
90	99.6	48.8	48.8	71.2	95.8		58.4
95	150.3	59.2	63.2	91.6	130.2		92.6

1 Adjusted for daily data

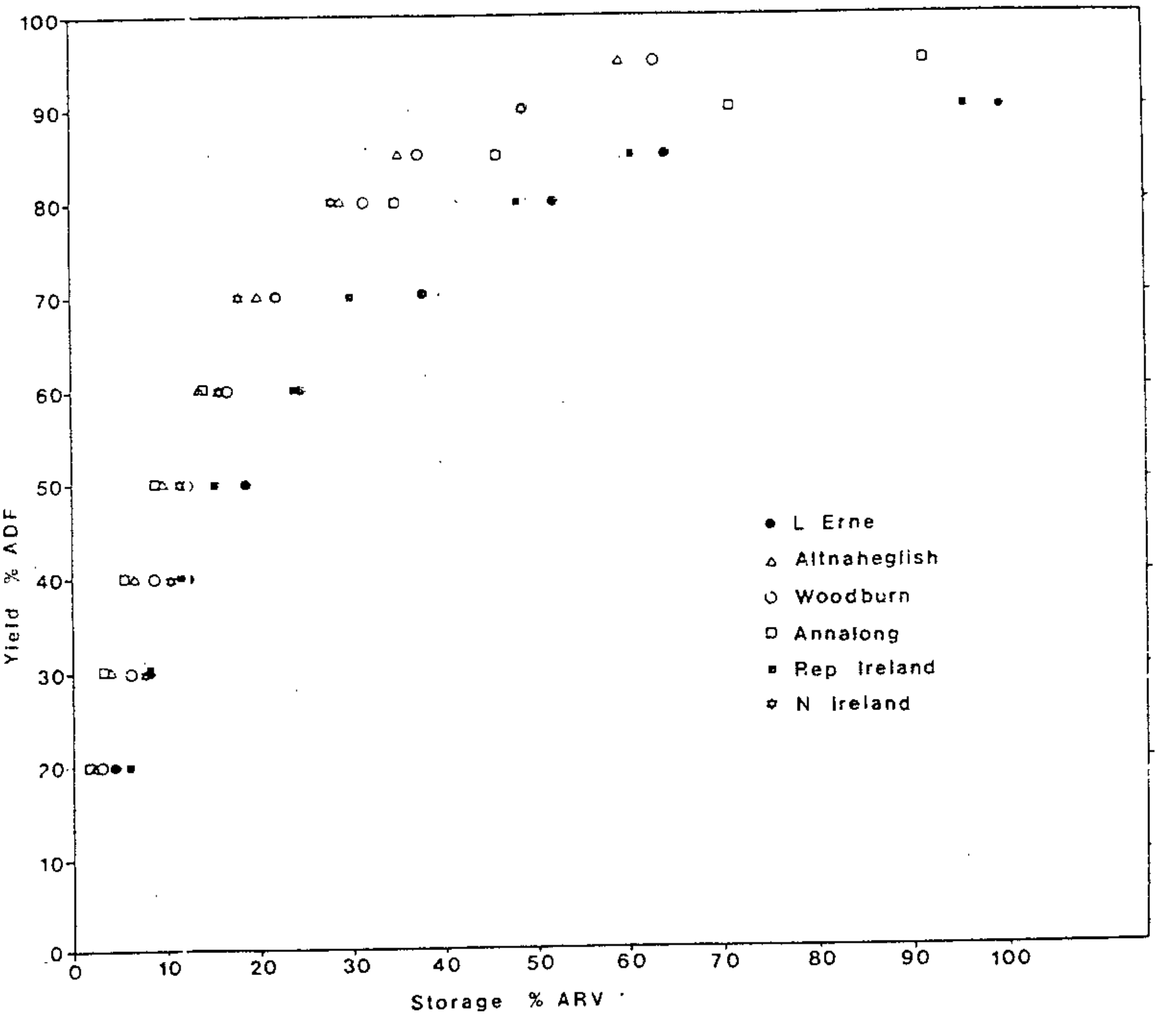
2 Mean of 5 flow records adjusted for short length of record

3 Mean of 6 flow records adjusted for short length of record

4 Mean of 9 stations

All storage requirements expressed as a percentage of annual runoff volume.

Figure 6.8   50 year return period Storage Yield relationships



soil, physiography, annual average or seasonal distribution of rainfall. In considering the Lough Erne results it should also be noted that the catchment is very large (4349 km^2), with an extensive area of Lough, and although useful for assessing the frequency of extreme events it is not representative of the small reservoired catchments of Northern Ireland.

2) Differences caused by the incidence and distribution of extreme droughts, the errors in adjusting frequency curves based on short records and in estimating storage requirements from the invidual station storage frequency plots.

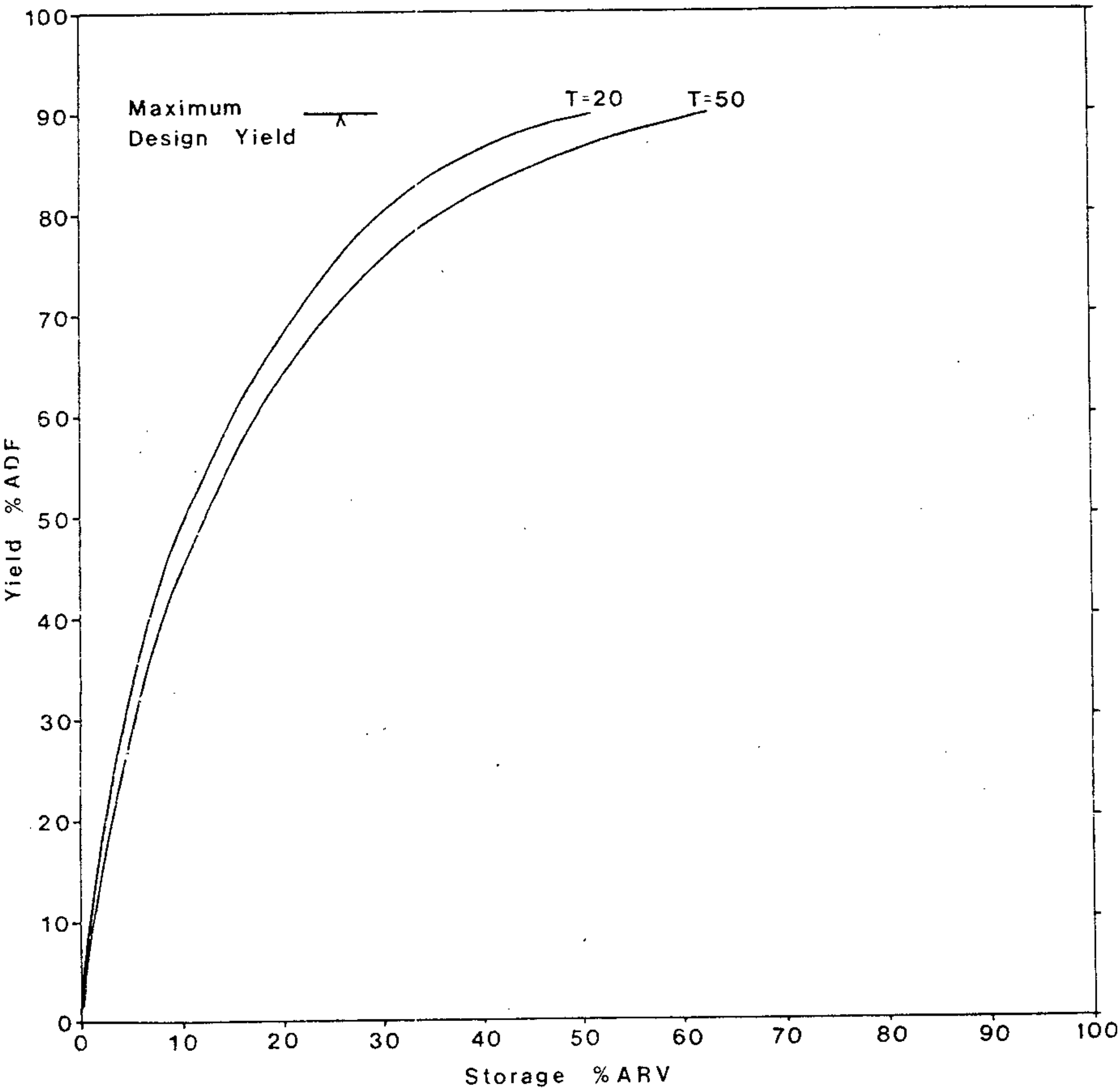
3) Errors in the regression models leading to an over estimate of low flows. The close agreement between the gauged Erne record and the Annalong and Woodburn records in ranking historical events suggest that this is not a serious problem. Furthermore, most of the notable droughts are gauged in the Annalong record and thus any errors in the reconstructed flows will have a minimal influence on the storage yield relationship.

In view of the long lengths of record, similarity of catchment type with other reservoirs in Northern Ireland and consistency of results, the storage yield relationships for Altnaheglish, Woodburn and Annalong are considered to be the most appropriate for yield estimation. The difference between the three plots is small and a composite curve based on the largest of the three storage volumes for each yield (Woodburn for yields less than 70% ADF and Annalong for higher yields) has been used as the regional design curve for Northern Ireland. For the reservoirs with a storage of less than 5% ARV the yield will be more dependent on the characteristics of individual catchments and the error in yield estimation is correspondingly higher. The above approach was repeated to estimate the 20 year return period storage yield relationship:- the two final curves are shown in Figure 6.9.

Figure 6.10 compares the regional design curve with the following generalised storage yield relationships:-

1) South West Scotland - based on the above analysis for a return period of 50 years.

Figure 6.9   Regional design curves for Northern Ireland



2) North West Water Authority (NWWA, 1981) - based on the most conservative design from a minimum runoff analysis of four long flow records. Return period is 50 years.

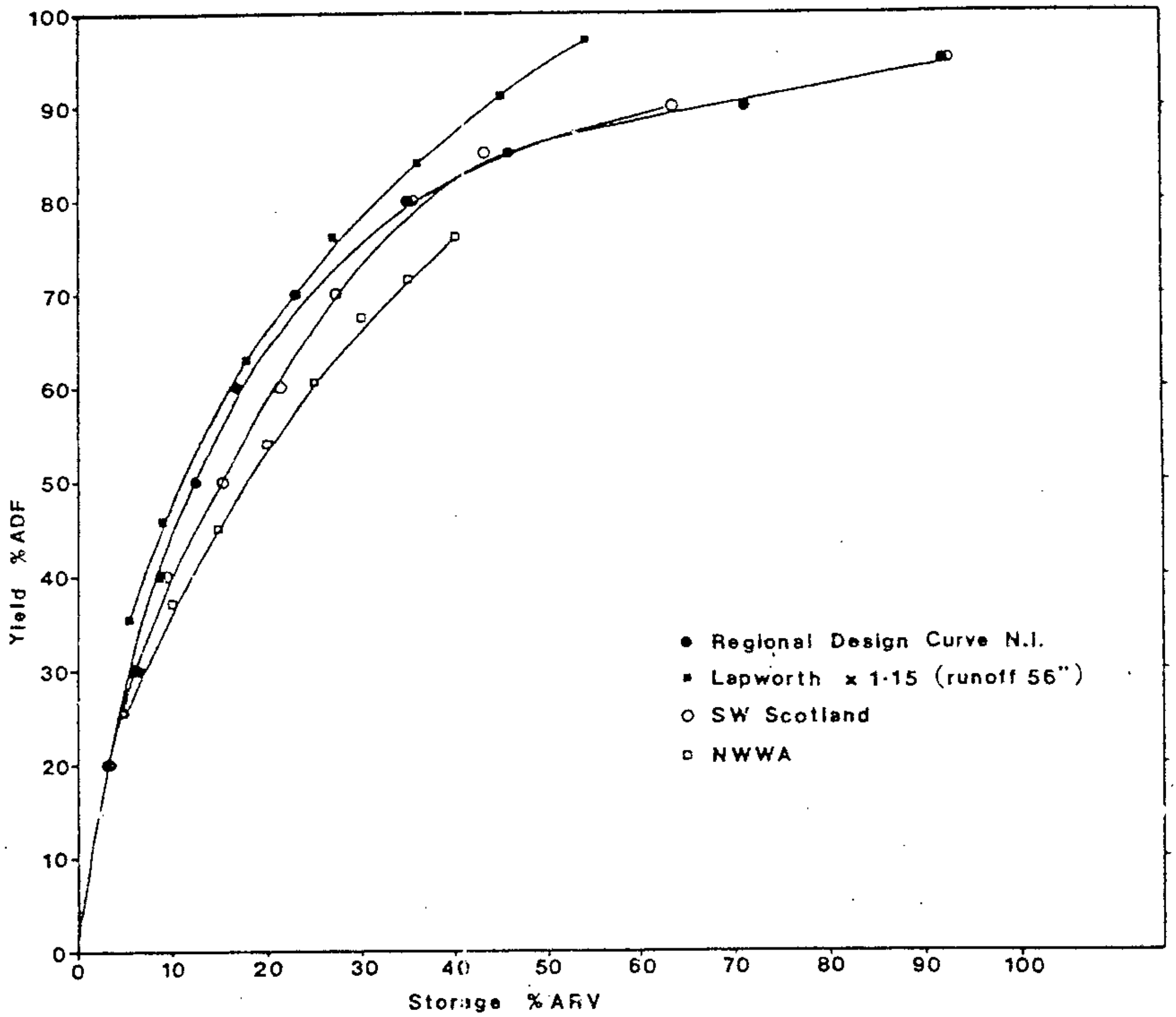
3) Lapworth curve - based on an annual runoff similar to the Silent Valley reservoir of 56" per annum and after adjusting for an increase in yield by a factor of 1.15. This adjustment accords with current design practice in Northern Ireland.

Figure 6.10 illustrates that for a given storage the yield is higher in Norther Ireland than in South West Scotland and North West England. The relationship between these three region curves is supported by a recent study of the coefficient of variation of annual rainfall over Europe (Tabony, 1982). This study was based on 185 raingauge records in Europe using data from 1861-1970 and over 2000 raingauge records in the UK dating from 1911. The results indicated that the year to year variability of rainfall is much lower over Northern Ireland than Great Britain and most of the Republic of Ireland. The coefficient of variation varies from 11.5% in Northern Ireland to 13% in South West Scotland and 14% in North West England.

Figure 6.10 shows that the Lapworth curve generally overestimates yield compared with the Regional Design Curve. However the position of the Lapworth curve on Figure 6.10 depends on the annual runoff of the reservoired catchment and for a site with a much lower runoff than Silent Valley the Lapworth curve would be below the regional design curve for most yields.

A feature of the NWWA study (NWWA 1981) is that a maximum yield of 76% ADF, corresponding to a 5 year refill period, is set on all sources. Refill periods associated with yields of 85% ADF for this study are in excess of 5 years and for yields of 90% ADF they are in excess of 8 years. In view of these very long refill periods and the errors associated with estimating the average flow of each reservoired catchment, the maximum yield available for any source has been set at 90% ADF for a return period of failure of 50 years and 90.5% ADF for a return period of failure of 20 years. For such sources the scope for increasing the yield by operating the source conjunctively is obviously limited.

Figure 6.10 Comparison of regional storage yield relationships



6.6 Yield estimation

(a) Regional Storage Yield Analysis

In order to apply the regional storage yield relationship to a particular reservoir the average flow of its catchment must be calculated. The mean altitude of each reservoired catchment was used to make an altitude adjustment to the mean sea level value of Ep for Northern Ireland. Section 6.3 showed that the difference between Ep and Ea were minimal and hence the average runoff in mm could be calculated from the difference between SAAR and Ep (Table 6.10).

Published values (D.O.E. N.Ireland, 1980) of direct and indirect catchment areas (Table 6.10) were used. Within the scope of the present study it was not possible to estimate the efficiencies of individual catchwaters and so their effective area was assumed to be 80% of their actual area. This value was based on previous design practice in Northern Ireland. (In the case of the Annalong tunnel diversion to Silent Valley reservoir, an analysis of the tunnel flows indicated that a catchwater efficiency of 100% could be used). Table 6.10 also shows the indirect area as a percentage of the total area - reservoirs with a high percentage may warrant a more detailed investigation of their catchwaters. The total effective catchment area was calculated which, together with the annual runoff in mm, enabled the average daily flow (ADF) to be calculated in Ml/day. Published values of usable volume were expressed as a percentage of the annual runoff volume (ARV = ADF x 365.25) from which the yield (% ADF) could be estimated from figure 6.9. For some catchments with more than one reservoir the total volume of storage has been used and treated as if it were one source. For yield calculation this implicitly assumes that the lower reservoir will only spill when all upstream reservoirs are full. Any departure from this will result in a reduction in reservoir yield. Table 6.10 lists these yields for a return period of 50 and 20 years expressed in units of Ml/day. From these gross yields the compensation flow must be deducted to produce the net yield. These are listed where published compensation flows are available.

Table 6.10 Yields of Reservoirs in Northern Ireland

Source	Catchment Average			Catchment Area (Km²)				Usable Volume		ADF Ml/d	Gross Yield (Ml/d)	
	SAAR (mm)	Altitude (m)	Ep (mm)	Direct DA	Indirect IA	Total DA+0.8IA	IA as % of DA+IA	Ml	% of ARV		T=20	T=50
Eastern Division:-												
Woodburn Complex (1)	1172	200	380	15.64	15.74	28.23	50	8193	36.6	61.21	51.91	49.15
Silent Valley System (2)	1758	397	325	22.29	10.11	32.40	56	20634	44.4	127.12	112.12	107.67
Lough Cowey	846	29	430	4.20	-	4.20	-	804	46.0	4.78	4.25	4.09
Ballysallagh Upper (3)	981	151	395	2.24	2.69	4.39	55	663	25.8	7.04	5.31	5.02
Ballysallagh Lower (4)	981	134	400	0.13	3.40	2.85	96	477	28.8	4.53	3.59	3.37
Conlig Upper and Lower (5)	958	93	410	1.61	-	1.61	-	178	20.0	2.42	1.63	1.55
Clandeboye Lake	958	93	410	2.71	-	-	-	227	15.3	4.07	2.43	2.27
Holywood Low (6)	983	102	410	0.89	-	0.89	-	41	8.0	1.40	0.61	0.54
Holywood East	983	170	390	0.84	-	0.84	-	146	29.3	1.36	1.08	1.02
Creightons Green (7)	1008	153	395	1.59	-	1.59	-	545	55.9	2.67	2.42	2.36
Portavo	856	24	435	2.91	3.52	5.73	55	245	10.2	6.60	3.22	2.94
Stonyford	1034	206	380	6.83	8.00	13.23	54	3688	42.6	23.69	20.80	19.85
Leathemstown	1101	241	370	6.81	-	6.81	-	453	9.1	13.63	6.30	5.69
Boomers (8)	999	161	390	1.46	-	1.46	-	247	27.8	2.43	1.90	1.78

(1) Storages of six reservoirs have been combined. More accurate yield estimates of 47.57 Ml/d and 45.89 Ml/d are given by considering separate reservoirs

(2) Storage of Ben Crom and Silent Valley reservoirs have been combined. Catchwater efficiency of 1.0 assumed for Tunnel diversion. No allowance for yield of Mourne Conduit intake from River Annalong. Simulation yields are 117.1 Ml/d and 112.8 Ml/d adjusted for Daily data.

(3) No allowance for Prescribed flow (PF) of 0.35 Ml/d.

(4) No allowance for PF of 0.25 Ml/d.

(5) Storage of Upper and Lower Conlig are combined.

(6) Reservoir not currently in use.

(7) No allowance for PF of 0.05 Ml/d.

(8) Indirect area is not known.

Table 6.10 contd. Yields of Reservoirs in Northern Ireland

Source	Catchment Average			Catchment Area (Km^2)				Usable Volume		ADF Ml/d	Gross Yield (Ml/d)	
	SAAR (mm)	Altitude (m)	Ep (mm)	Direct DA	Indirect IA	Total DA+0.8IA	IA as % of DA+IA	Ml	% of ARV		T=20	T=50
Northern Division:-												
Killylane	1423	325	345	2.73	9.04	9.96	77	1327	12.4	29.40	15.88	14.64
Dungonnell (1)	1557	343	340	5.10	7.38	11.00	59	945	7.0	36.65	15.03	13.01
Quolie Upper (2)	1518	354	335	4.21	-	4.21	-	236	4.7	13.64	4.47	3.61
Quolie Lower (3)	1420	334	340	1.46	-	1.46	-	173	11.0	4.32	2.20	2.01
Lough Fea	1360	250	365	4.00	7.52	10.08	-	1260	12.6	27.46	14.90	13.78
Ballinrees (4)	1268	150	395	-	10.67	8.54	100	1182	15.9	20.41	12.41	11.68
Altikeeragh (2)	1218	220	375	0.24	3.97	3.42	94	127	4.4	7.89	2.49	2.00
Altnahinch (5)	1639	348	340	8.83	-	8.83	-	1250	10.9	31.40	15.94	14.52
Ballywillin	879	100	410	-	1.99	-	-	59	6.3	2.56	0.99	0.86
Proposed Scheme												
Glenwhirry (6)	1330	300	350	60.49	51.39	104.08	46	43600	45.5	270.03	239.65	230.20

(1) No allowance for Pf of 0.010 Ml/d.

(2) Very low storage:- yield will depend on river flow characteristics

(3) Excludes area of Upper Quolie.

(4) Yield excludes pumped storage from Bann.

(5) No allowance for compensation discharge of 3.21 Ml/d.

(6) Includes catchment area and storage volume of Killylane reservoir.

Usable storage of 43600 Ml used for Glenwhirry reservoir, Scheme II, stage 2. No allowance made for proposed compensation flow 17.5 Ml/d.

The catchment area from the consultants' report has been used but a revised SAAR has been estimated.

Table 6.10 contd. Yields of Reservoirs in Northern Ireland

Source	Catchment Average SAAR (mm)	Catchment Average Altitude (m)	Ep (mm)	Catchment Area (Km²) Direct DA	Indirect IA	Total DA+0.8IA	IA as % of DA+IA	Usable Volume Ml	% of ARV	ADF Ml/d	Gross Yield (Ml/d) T=20	T=50
Southern Division:-												
Seagahan (1)	1036	220	375	12.35	-	12.35	-	2241	27.4	22.35	17.43	16.29
Altmore Upper	1281	250	365	3.00	-	3.00	-	177	6.4	7.52	2.93	2.53
Altmore Lower (2)	1281	220	375	3.08	-	3.08	-	59	2.1	7.64	1.43	1.11
Clay Lake (3)	1123	220	375	5.31	0.95	6.07	15	1882	41.4	12.43	10.84	10.34
Ballylane Lake	1047	175	390	0.93	-	0.93	-	174	26.5	1.67	1.29	1.20
Spelga (4)	1800	451	310	7.04	-	7.04	-	3272	31.2	28.72	23.32	22.20
Fofanny	1708	482	300	3.74	1.36	4.83	27	391	5.7	18.62	6.79	5.77
Lough Island Reavy	1528	201	380	1.70	11.17	10.64	87	7683	62.9	33.44	30.26	30.10
Camlough (5)	1051	195	385	6.90	6.53	12.12	49	3705	45.9	22.10	19.67	18.88
Corbet Lough	823	107	410	3.60	-	3.60	-	727	49.9	4.07	3.64	3.52
Proposed Schemes (6)												
Lough Island Reavy (7)	1511	183	385	5.55	15.26	19.80	275	8400	37.7	61.04	52.10	49.35
Kinnahalla (8)	1521	340	340	4.43	14.20	15.20	320	6800	37.9	49.15	42.00	39.79
Camlough (9)	1150	200	380	3.21	5.16	13.34	36	4800	46.7	28.12	25.03	24.04

(1) Excludes PF of 1.14 Ml/d.

(2) Excludes Upper Altmore. Very low storage:- yield will depend on river flow characteristics

(3) Excludes maximum PF of 9.30 Ml/d.

(4) Excludes PF of 2.27 and four annual flushes of 45.46 Ml.

(5) Excludes PF of 9.09.

(6) Catchment area and SAAR values from consultant reports have been used - in some cases these differ from those quoted in N.I. Water Statistics 1980.

(7) Excludes Fofanny reservoir and proposed compensation flow of 7.1 Ml/d. Proposed effective areas of indirect catchments used.

(8) Excludes Spelga reservoir and proposed compensation flow of 4.06 Ml/d. Proposed effective areas of indirect catchments used.

(9) Based on total usable storage, excludes proposed compensation flow of upto 11.4 Ml/d.

Table 6.10 contd. Yields of Reservoirs in Northern Ireland

Source	Catchment Average			Catchment Area (Km^2)				Usable Volume		ADF Ml/d	Gross Yield (Ml/d)	
	SAAR (mm)	Altitude (m)	Ep (mm)	Direct DA	Indirect IA	Total DA+0.8IA	IA as % of DA+IA	Ml	% of ARV		T=20	T=50
Western Division:-												
Altnaheglish (1)	1489	366	330	7.28	-	7.28	-	1759	20.8	23.10	15.96	15.06
Killea	1234	201	380	1.68	-	1.68	-	76	5.3	3.93	1.38	1.14
Creggan	1210	131	400	2.72	-	2.72	-	582	26.4	6.03	4.64	4.34
Lough Fingrean (2)	1250	192	385	1.13	1.81	2.94	62	810	31.9	6.96	5.70	5.36
Lough Macrory (3)	1100	183	385	2.41	9.47	9.70	80	209	3.0	18.99	4.75	3.70
Lough Bradan (4)	1408	210	380	2.88	6.52	8.10	69	626	7.5	22.80	9.63	8.44
Glencordial (5)	1250	305	350	5.56	3.50	8.36	39	64	0.8	20.60	1.61	1.11
Killyfole	1075	150	395	4.50	3.48	7.28	44	719	14.5	13.55	7.89	7.32
Ballydoolagh Lough	1101	143	400	1.70	2.70	3.86	61	618	22.8	7.41	5.35	5.02

(1) Excludes Glenedra intake.

(2) Revised direct (1.13 Km^2) and indirect (1.81 Km^2) areas. Catchwater efficiency of 1.0 used.

(3) Excludes Lough Fingrean. Revised direct (2.41 Km^2) and indirect (9.47 Km^2) areas. Catchwater efficiency of 0.77. Very low storage:- yield will depend on flow characteristics.

(4) Revised direct (2.88 Km^2) and indirect (6.52 Km^2) areas.

(5) Very low storage:- yield will depend on river flow characteristics.

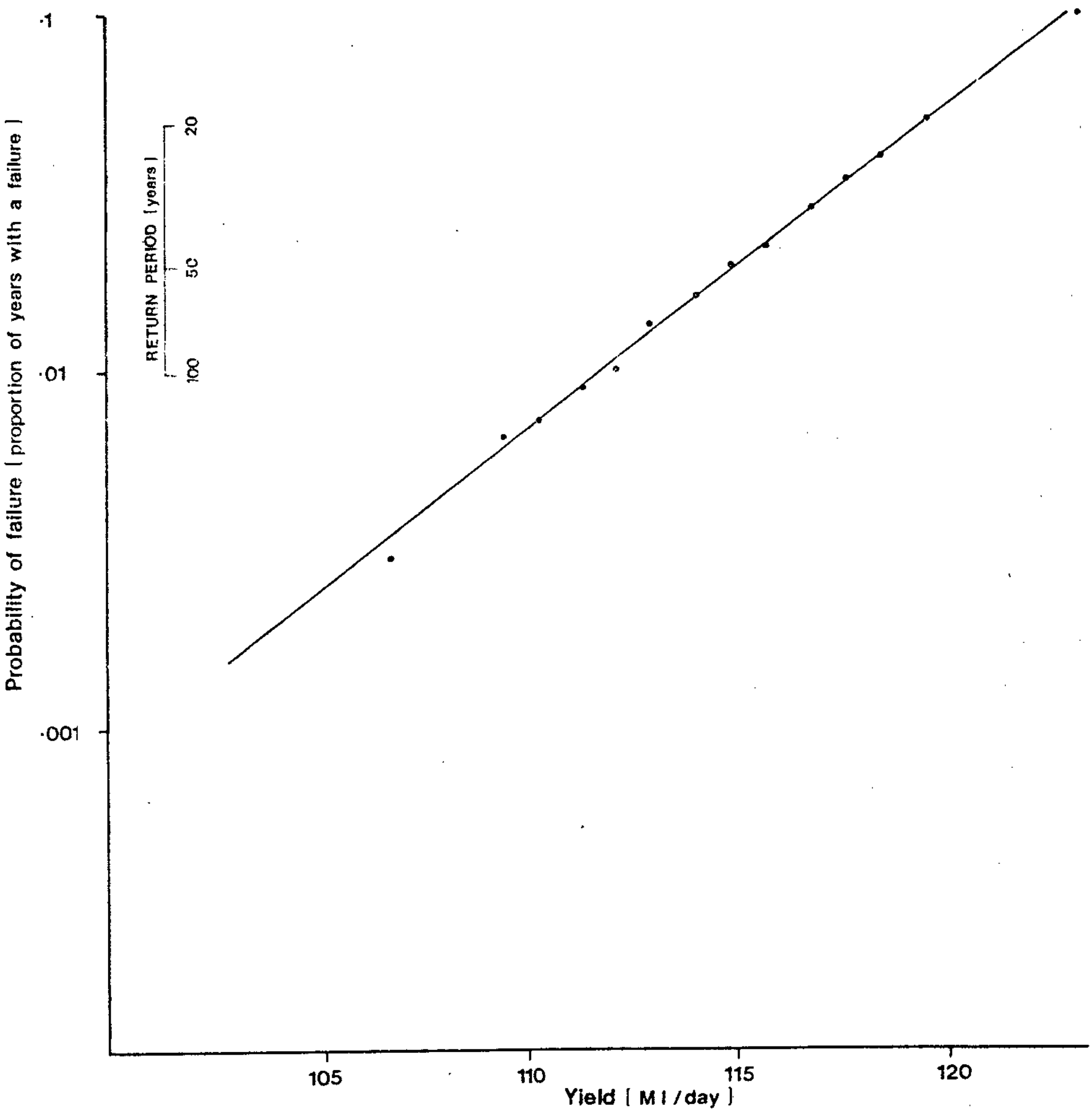
(b) Simulation of Silent Valley Reservoir - fixed yield

The objectives of these additional analyses are to provide an independent check on the regional analysis and, in the following section, to investigate the effect of rationing water supplies on the frequency of failure. The method adopted for the yield evaluation is that attributed to Gould (McMahon and Mein, 1978). This method requires that the reservoir is divided into several (N) states of equal storage. Each year of the inflow data is treated separately and is routed through the reservoir, on a monthly basis, starting the reservoir in each of the N states and noting the state in which it finishes. When this procedure has been repeated for each year of data the results are collated in a transition matrix. This expresses the probability of ending in any of the N states, conditional on the starting state. A tally of the failures which occur is also kept and a combination of these two matrices enables the probability of failure to be calculated. This method will provide a more reliable yield estimate than the regional analysis when it is based on a long term flow sequence at the site.

The frequency of failure is defined in the same way as in the regional study, that is the proportion of years containing a total reservoir failure, the reciprocal of which is the return period of failure T_F. Yields with a T_F of 20 and 50 years are estimated for comparison with the regional analysis. Discharge from the Annalong flow record from 1895-1979 were transferred to Silent Valley inflows by allowing for differences in catchment area and effective rainfall. The Silent Valley system includes two reservoirs Silent Valley and Ben Crom. The operation of these two reservoirs involves filling Ben Crom before spilling any water to Silent Valley, and so the two reservoirs can be lumped together and treated as one storage unit of 20634 Ml capacity.

Having established the analysis technique, inflow sequence and reservoir characteristics, a series of reservoir simulations were carried out with different yields. Figure 6.11 show the relationship between yield and return period from which the 20 and 50 year T_F yields of 119.6 and 115.3 Ml/d can be read. The simulation was based on monthly data which would be expected to overestimate the

<u>Figure 6.11</u> Yield/failure relationship for Silent Valley



yield by about 2.5 Ml/d (2% ADF) compared with the daily based regional results. These yields thus support the corresponding yields of 112.12 and 107.67 Ml/d produced by the regional approach (Table 6.10).

(c) Simulation of Silent Valley reservoir-with rationing

The advantage of the simple definition of failure (i.e. reservoir empties once in 50 years with a constant yield) is that it can readily be used for the assessment of a larger number of sources with different yields, storage and runoff characteristics. However the method assumes that full output is maintained from a reservoir until it is empty. In practice output is of course reduced before the reservoir becomes empty because one cannot be certain that a particular drought will not develop into one that is more severe than the design standard. Inevitably restriction will be introduced which, after the event, will appear unnecessary, resulting in the frequency of conservation measures (rota cuts, standpipes) being greater than the quoted frequency of failure as defined by the above simple criterion. Furthermore, total failure rate will be less than the design failure rate.

An analysis was carried out to determine:-

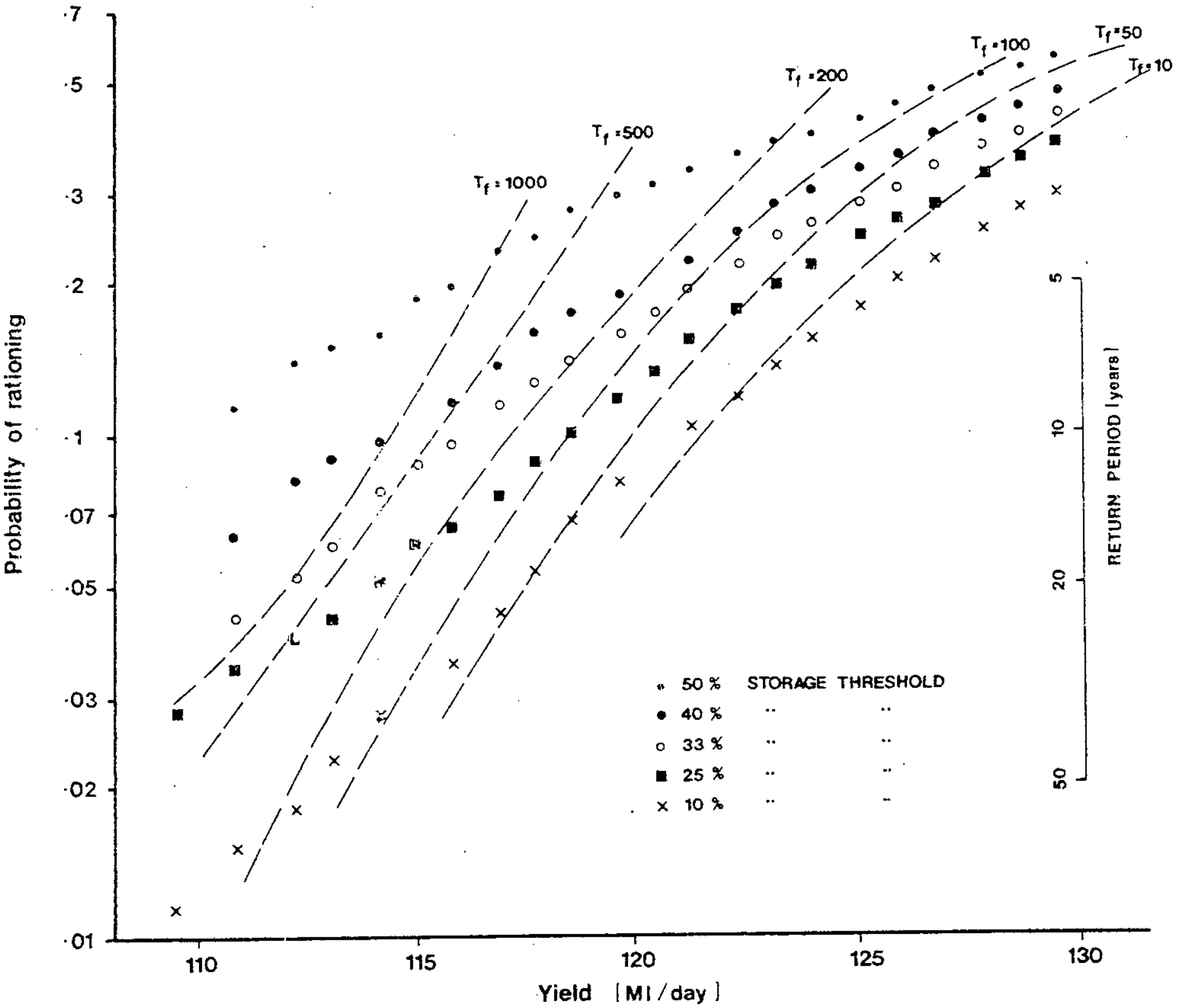
(a) the increase in yield by introducing rationing with a given return period T_R and given return period of total failure T_F.

(b) the effect of rationing on the frequency of total failure T_F.

The level of storage (50%, 40%, 33%, 25% and 10%) at which rationing is instigated was fixed for each simulation to provide a range of possible rationing schemes. A reduction in yield of 20% was assumed for all rationing periods.

Figure 6.12 summarises the results of a number of simulations and shows the relationship between the yield, T_R and T_F. It is made

Figure 6.12 Return period of rationing for given yields and probability of total failure



up of five series of plots each derived for a different storage threshold. Each series indicates an increasing yield as the probability of rationing T_R increases with a corresponding increase in return period of total failure T_F. Contours of T_F have been superimposed on Figure 6.12 and the contour $T_F = 50$ can be followed to show that a yield of 116.2 Ml/d can be met by the Silent Valley reservoirs with a T_R of 20 years. This is higher than the yield of 115.3 Ml/d shown on Figure 6.11 (section b) with the same T_F of 50 years but with no rationing.

The analysis can also be used to investigate the relationship between the return period of total failure T_F with and without rationing, but with the same yield. For example the yield for $T_F = 50$ and with no rationing is 115.3 Ml/d. From Figure 6.12 it can be seen that with this same yield of 115.3 Ml/d and assuming that rationing is introduced when the reservoir is 25% full that the return period of rationing would be 20 years; whilst the return period of total failure is much higher at 200 years. The figure can thus be used to provide guidance on the sensitivity of yield, frequency of rationing and frequency of failure to the introduction of simple rationing schemes which are dependent on reservoir contents.

This approach could be adopted for other reservoirs with different storage characteristics which may have a different sensitivity of yield to rationing. Figure 6.12 could be extended to assess the effect of conjunctive use of this source. The probability of rationing is then the probability of using the other source and the quantity of water required to make up the demand is controlled by the reduction in yield imposed by rationing. In this case a reduction of 20% was used but any other value could easily be incorporated. This type of analysis could also be carried out for the Woodburn complex so that the benefits of conjunctive use of the two largest sources in Northern Ireland could be assessed.

6.7 River Abstractions

(a) Background

In the first interim report a number of small abstractions with yields less than 2 Ml/d were identified. It is considered uneconomic to upgrade many of these schemes and furthermore for many abstractions, large and small, the flow characteristics of the river do not provide a constraint to abstraction. Of the remainder:-

(i) The Bann for Ballinrees. The yield is limited by the capacity of the intake, but abstraction may by constrained by downstream residual flows. However in view of the small abstraction rate, relative to the flow in the Lower Bann, this seems unlikely.

(ii) The River Douglas. Owing to the poor quality of the water, treatment would be necessary if it were to be utilised, however the quantity is too small to justify this economically.

(iii) Altnaheglish. Other consultants are working on a detailed study of the merits of using the Altnaheglish river and reservoir with the Glenedra river (and possible reservoir) in a number of different combinations. Detailed conjunctive use studies would be necessary and can be carried out if requested.

(iv) Faughan River. Binnies report of December 1969 put this into perspective and there is very little further to add.

(v) The Tievenny (H324859) abstraction on the River Derg is the only river source identified that requires yield estimation, the calculations are described below:-

The yield of this source was estimated by calculating the 95 percentile from the 10 day flow duration curve, Q95(10) and the 20 year and 50 year return period 10 day annual minimum flows. The calculations were based on the techniques described in the Low Flow Study Report (Institute of Hydrology 1980) incorporating the results from an analysis of local flow data from the gauging station 5 kilometers upstream at Castlederg (Station 201008, figure 6.1) and from Lough Erne inflows. Estimates were made for the Castlederg site and then transferred to the abstraction point.

(b) Flow Duration Curve

Using the Low Flow Study Report Number 2.1 (LFSR 2.1) a value of Q95(10) of 7.4% ADF was calculated from the observed Base Flow Index and catchment SAAR (Table 6.1). This value compares favourably with the value of 6.5% ADF from the short flow record from 1979-1980 at Castlederg.

(c) Annual minima

Using LFSR 2.2 and the same values of BFI and SAAR the 20 and 50 year return period annual minima were estimated as 2.1 %ADF and 1.5 %ADF respectively. An analysis of the flows in May 1980, the month with the lowest discharge in the Castlederg record, enabled additional estimates to be made. Inspection of the long Lough Erne inflows record (1900-1983) showed that this month was the annual minimum discharge with a return period of approximately 5 years. Although the flow regime of the Lough Erne inflows would be different from the smaller Derg catchment it is probable that the frequency of drought events on the two catchments would be similar. It was thus assumed that May 1980 was also the 5 year 1 month, annual minimum on the Derg. Using multiplying factors from LFSR 2.2 appropriate to the Derg catchment it was possible to estimate the 1 month, 20 and 50 year return period annual minima from this 5 year annual minimum. Furthermore, relationships between monthly and daily flow statistics (LFSR 2.2) enabled the 10 day annual minima to be calculated. Results from LFSR 2.2 indicated that the 10 day annual minima would be 54% of the 1 month annual minima. The ratio of the lowest 10 day average flow to the mean flow in May 1980 had a similar value of 50%. Using this monthly to daily adjustment of 50% the 20 and 50 year return period annual minima were estimated as 0.77 %ADF and 0.56 %ADF respectively. These values are lower than those estimated from BFI and SAAR but as they are derived from a greater use of local data they are the preferred values for yield calculation.

(d) Tievenny abstraction point

The above statistics are expressed as a %ADF and were converted to Ml/d using an estimate of average discharge at the abstraction point. This was affected by adjusting the 1979-80 gauged average discharge at Castlederg to the mean 1941-70 discharge based on the ratio of mean effective rainfall for the two periods. This discharge was increased by a factor of 1.11 (to allow for the larger catchment area to the abstraction point) to give an ADF of 1237 Ml/d and used to convert the flow statistics to units of Ml/d as shown in Table 6.11. The 20 and 50 year return period annual minima estimated using LFSR are higher than the observed discharges in May 1980 and are considered to be over estimates. The data based estimates are therefore the recommended design yields.

6.8 Severity of period 1970-1983

Although it is beyond the scope of this study to assess the return period of individual drought events some general results concerning the severity of river flow and rainfall in the period 1970-1983 may assist in assessing the frequency of water resource shortages in recent years. For each of the long flow sequences the date and volume of the maximum deficit (for a given yield) in this period was noted. Table 6.12 shows the date and rank of these maxima derived from comparisons with the deficits from earlier records. This table illustrates that for the higher yeilds the period contained some of the worst droughts in nearly 100 years of record.

A second approach was to apply a depth duration frequency analysis (Tabony 1977) to the Armagh rainfall record. For each duration, determined from the results of the reservoir simulation for Loch Erne inflows, the return period of the rainfall for a fixed starting month was estimated (Table 6.13). These results support the analysis of the flow data with return periods in excess of 100 years and some in excess of 500 years being attributed to the rainfall events.

The most recent flow data currently available is for the period up to September 1983 for the Lough Erne inflow series. This suggests that extreme low flows have also occurred in 1983. July 1983 is the lowest average monthly flow on record and the period July/August 1983

Table 6.11 Yield of river Derg abstraction at Tievenny

	Low Flow Study		Data Based	
	%ADF	Ml/d	%ADF	Ml/d
Q95 (10)	7.4	91.5	6.3	77.9
20 year return period †	2.1	28.9	0.76	9.4
50 year return period †	1.5	18.6	0.56	6.9

† 10 day annual minima

Table 6.12 Date and rank of highest deficit in period 1970-1983

Yield % ADF	Annalong 1895 -1979	Woodburn 1886-1980	L. Erne 1900-1983
90	Oct 73 (1)	July 76 (2)	Sep 78 (1)
70	Sep 73 (1)	Aug 75 (1)	Aug 76 (3)
50	Sep 72 (4)	Aug 75 (1)	Aug 75 (1)
30	Aug 72 (7)	Aug 75 (1)	Aug 75 (1)

Rank shown in brackets relates to long flow record ie rank (1) for Annalong is worst event from 1895-1979.

Table 6.13 Return period of Armagh rainfall for selected durations

Reservoir Yield	From start+ of reservoir depletion to maximum depletion		From start of reservoir depletion to full	
% ADF	Return Period	Period	Return Period	Period
90	500	1/71-8/76	100-200	1/71-2/81
80	200 - 500	1/75-8/76	50-100	1/75-2/78
60	> 1000	2/75-8/75	200-500	2/75-2/76
40	> 500	3/75-8/75	> 500	3/75-12/75

\+ Start of depletion is lagged by one month for rainfall return period based on Lough Erne reservoir simulation.

is the lowest 2 month average flow on record, equalling the average discharge of June/July 1976. The general conclusion is that the recent period has included some notable drought events of both long and short duration with return periods equal to or in excess of 100 years.

6.9 Lough Neagh

The water quality and quantity aspects of the water resources of Lough Neagh were considered in detail by the Lough Neagh Working Group (1971). Hydrological aspects of the study were based on a record from 1937-1971 of inflows into the Lower Bann catchment upstream of Movanagher weir, estimated from daily flow records at the weir and changes in storage in Lough Neagh. This exercise could now be updated using flow and level records up to 1983 and could be supplemented by a more detailed simulation of yield drawdown relationships. However the 1971 investigation highlighted the difficulties of measuring lake levels and these errors will remain in any further hydrological analysis. Furtheremore there is evidence that the frequency analysis used resulted in an underestimation of the probability of occurrence of cumulative inflows - that is design drawdowns for a given demand will recur less frequently than predicted. Section 12.9 of the report concluded "Ample supplies of water are available from Lough Neagh and the Lower River Bann Basins to meet all types of demand for the foreseeable future. Large quantities of water, up to about 450 tcmd (100 mgd) may be permanently exported from the 2 Basins with very little adverse effect on other interests. Investigations should, however, be carried out over the next decade to quantify the effects on any interests resulting from these exports."

Although we are unable to comment on the 'adverse effects' it is our view that in relation to the magnitude of the potential yield a further hydrological study would produce little change to the above conclusion. Although outside the scope of the current study it may be appropriate to review further water quality, fisheries or general environmental studies which have been completed since 1971. In this context the severe droughts of the period 1971-1976 may have provided further evidence to assess the environmental impact of increased abstractions. In this regard the general assessment of the frequency of recent droughts (Section 6.8) may be of value in appraising the Lough Neagh scheme.

6.10 Groundwater

The groundwater resources of Northern Ireland have been considered by reviewing published material and by discussion with the Geological Survey of Northern Ireland. The complex solid and drift geology of the province has resulted in all the aquifers being small in area and in yield. However there has been considerable recent groundwater development with pumping capacity increasing from 9 Ml/d in 1964, to 69 Ml/d in 1980 and to approximately 100 Ml/d in 1983. This represents 15% of the total public supply but is not wholly utlised.

Various aquifers of Carboniferous age which occur in the west of the Province give individual well yields of up to 3.5 Ml/d but relatively little development has taken place because of several factors, including low demand, availability of surface water, and quality problems from the chemistry of the groundwater.

Productive solid rock aquifers include the Permian and Triassic sandstones, in the Lagan Valley and to the west of Lough Neagh with recently commissioned borewells yielding a total of 10 Ml/d. The Cretaceous chalk is much thinner and of lower permeability than its English counterpart and its value as a resource is restricted primarily to the number of springs which issue from its base where it overlies impermeable strata. Although there may be some scope for development of the Tertiary Basalts this would be confined to the development of local boreholes with yields generally less than 1 Ml/d.

With the exception of upland areas the solid geology is covered by a veneer of drift deposits. Where this drift is composed of boulder clay recharge to underlying aquifers will be restricted. Bennett (1978) lists the evidence for the very low permeability of the boulder clay and this is substantiated by the low values of the Base Flow Index (Table 6.1) for catchments with a high proportion of boulder clay cover. In contrast, where the drift consists of fluvio glacial sands and gravels (in the Lagan valley and in the north and west of the region) the superficial deposits provide a local groundwater resource.

Individual borewell yields are up to 4.5 Ml/d and one group of three wells produces 10 Ml/d.

In conclusion local demands particularly in the north and west of the province may be met by further groundwater development from either solid or superficial aquifers. However groundwater development will not make a significant additional contribution to demands in the Belfast area.

6.11 Conclusions and recommendations

A regional storage yield relationship has been derived for Northern Ireland and used to estimate the yield of a number of reservoirs. The method is based primarily on three long flow records, Altnaheglish, Woodburn and Annalong, which show consistent storage yield relationships. Furthermore the curve is supported by a regional storage yield relationship derived independently for the NWWA area and from a curve derived in this study for South West Scotland.

Errors in yield estimation may arise from three sources. The first is the extent to which individual catchment storage yield relationships depart from the design curve. This departure will be proportionately small at high yields, which are controlled by the annual variability of rainfall, but will be larger for small yields and storages where the low flow characteristics of the river will assume greater importance. The second source of error is in estimating the average discharge of the reservoired catchment. This is dependent on the accuracy of published values of catchment area and rainfall, together with the accuracy of estimating losses. The latter will again be dependent on the characteristics of individual catchments. For example, no allowance has been made for catchments which are heavily forested and where the actual losses may be higher than estimated values; or for any groundwater leakage in the catchment. The third source of error is in estimating the efficiency of catchwaters and will only be significant for those reservoirs with large indirect catchment areas.

The estimated yield of the Silent Valley reservoir, using the regional approach, has been confirmed using a full simulation of reservoir behaviour but with a simple definition of failure. A more realistic simulation has also been carried out to examine the sensitivity of yield to different frequencies of rationing and total failure. We recommend that a full simulation is carried out for the other major reservoirs including the Woodburn complex. If requested this approach could also be used for conjunctive use studies.

The main emphasis of the hydrological aspects of the study has been on reservoir yield estimation with only the River Derg being considered for river abstractions. The hydrology of Lough Neagh has been reviewed and this indicated that water quantity would not be a constraint on future abstractions. Finally the review of groundwater abstractions indicated its current importance in the Lagan valley and for local supplies elsewhere; however its potential for making a major contribution to meet increasing demands in the Belfast area is limited.

ACKNOWLEDGEMENTS

We would like to thank North West Water Authority for permission to reproduce the regional storage yield relationship for north west England.

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Appendix I

Table 1 Red, Blue, Green and Control catchment runoff

YEAR	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
1960	91.95	83.82	74.68	61.21	15.75	10.92	50.29	65.79	51.31	79.25	129.54	67.31	781.82
1961	107.70	88.90	30.48	82.55	64.01	16.51	11.43	16.00	35.56	92.20	51.31	100.08	696.72
1962	82.80	56.90	27.43	45.97	23.11.	11.43	10.67	33.02	99.82	39.88	82.55	98.55	612.14
1963	30.99	62.23	71.63	45.72	49.53	39.12	42.42	49.53	46.48	89.92	144.78	48.77	721.11
1964	33.02	28.70	88.14	40.13	30.07	32.51	14.48	32.00	40.64	120.90	40.64	116.33	623.56
1965	113.53	38.11	56.74	78.08	37.03	25.70	31.36	32.71	46.51	51.39	82.48	162.44	757.08
1966	75.21	125.81	108.44	80.09	63.70	53.51	34.03	37.16	34.11	105.90	70.68	158.06	951.70
1967	105.43	76.12	77.25	37.78	41.15	34.29	20.62	32.14	83.79	105.57	124.59	79.54	818.27
1968	133.27	79.04	43.80	66.54	58.28	39.73	29.94	26.59	48.99	82.00	134.02	109.10	851.30
1969	118.95	94.80	82.80	79.83	81.35	53.74	33.40	28.83	16.70	17.56	36.60	69.23	708.89
1970	111.49	88.79	108.41	73.32	61.27	27.10	22.24	46.41	66.73	57.30	99.97	92.74	855.77

Table 2 Red, Blue, Green and Control monthly average catchment rainfall

YEAR	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	TOTAL
1960	124.2	99.6	83.6	94.2	53.8	63.0	230.4	142.7	93.0	176.3	135.1	79.2	1375.2
1961	134.1	106.2	48.5	140.7	93.7	67.8	69.1	105.9	120.9	145.8	67.3	102.9	1202.9
1962	132.8	60.2	48.8	72.9	73.7	45.7	68.1	147.3	194.6	51.3	119.6	130.6	1145.5
1963	47.5	39.1	94.2	68.3	101.9	121.1	96.0	134.4	88.1	149.1	190.2	28.4	1158.3
1964	53.3	25.9	108.2	66.0	65.0	86.4	48.8	128.0	104.6	169.2	73.7	128.0	1057.1
1965	109.5	17.1	88.0	94.7	64.3	65.3	105.2	84.9	119.0	76.4	187.0	141.3	1103.3
1966	68.2	173.9	100.5	107.8	111.5	107.5	77.8	110.8	102.5	131.2	100.1	184.9	1376.6
1967	119.8	78.1	100.7	65.5	84.5	67.0	76.2	124.2	168.1	168.1	143.1	96.1	1291.7
1968	142.1	86.1	52.2	88.8	98.7	83.4	73.7	76.9	133.6	124.7	168.2	116.2	1244.5
1969	136.9	82.2	88.2	103.0	108.3	83.9	82.6	49.6	33.6	60.2	103.9	114.5	1046.6
1970	121.3	91.6	119.5	97.6	68.7	48.0	83.3	140.5	158.7	106.3	144.5	86.0	1265.8

Table 3 Correlation matrix for Annalong record extension

FLOW	1	1.0000								
LOGFLOW	2	0.9256	1.0000							
EVAP	3	-0.3865	-0.4061	1.0000						
RR	4	0.8658	0.8307	-0.5116	1.0000					
RRL1	5	0.3122	0.3648	-0.5156	0.2876	1.0000				
RRL2	6	0.2522	0.2808	-0.4151	0.2315	0.3142	1.0000			
SMD	7	-0.3912	-0.4461	0.4242	-0.3591	-0.3993	-0.3349	1.0000		
SMDL1	8	-0.1198	-0.1562	0.2803	-0.0973	-0.3458	-0.4398	0.3805	1.0000	
SMDL2	9	0.0794	0.0972	0.0492	0.1391	-0.0042	-0.2793	0.1700	0.3737	1.0000
		1	2	3	4	5	6	7	8	9

Table 4 Correlation matrix for Woodburn complex record extension

FLOW	1	1.0000								
LOGFLOW	2	0.9449	1.0000							
EVAP	3	-0.6638	-0.6536	1.0000						
KR	4	0.8310	0.7981	-0.5935	1.0000					
KRL1	5	0.5850	0.6135	-0.6782	0.4118	1.0000				
KRL2	6	0.4067	0.4245	-0.5636	0.1799	0.4126	1.0000			
SMD	7	-0.6040	-0.6173	0.5894	-0.4568	-0.5539	-0.4800	1.0000		
SMDL1	8	-0.4513	-0.4555	0.4657	-0.1910	-0.4627	-0.5576	0.3918	1.0000	
SMDL2	9	-0.1218	-0.0933	0.2153	0.1123	-0.1874	-0.4541	0.1492	0.3926	1.0000
		1	2	3	4	5	6	7	8	9

Institute of Hydrology Wallingford Oxfordshire OX10 8BB UK
Telephone Wallingford (STD 0491) 38800 Telegrams Hycycle Wallingford Telex 849365 Hydrol G

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