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INSTITUTE of HYDROLOGY

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River Esk Hydrology

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Preface

This report describes the results of a study of the hydrology of the River Esk commissioned by British Nuclear Fuels Limited, Agreement No. H64235B. The main purpose of the study was to provide estimates of the return period of the 1978 and 1984 drought, to derive flow duration curves at specified locations and to provide estimates of regulation volumes and maximum regulating rates. The study was based on river flow data held on the UK Surface Water Archive at the Institute of Hydrology which was measured and processed by the Solway River Purification Board and the North West National Rivers Authority.

Contents

Figures

Tables

1. Introduction

The objectives of this study are to:

a) Assess the return period of low flows of various durations for the 1978 and 1984 drought.

b) Estimate the 100 year return period drought for pertinent durations.

2. Derive flow duration curves for the Esk at Netherby, Liddel Water at Rowenburnfoot and two ungauged locations on Liddel Water at Saughtree (NY560963) and Sandholm (NY494894).

3. Estimate the maximum regulated release rate and carry out a frequency analysis of annual total deficit volumes for periods when the river discharge is continuously below a given threshold discharge for the Esk at Netherby and at Metal Bridge.

The locations of the above points are shown in Figure 1. The assessment of the deficit volumes is dependant on abstraction rate and the maintained minimum acceptable flow. The analysis was carried out with abstraction rates of 20 50 100 and 150 Mld^{-1} and maintained flows of 15% of the mean flow for Netherby (321 $Ml.d^{-1}$) and 10% for Metal Bridge (276 $Ml.d^{-1}$).

2. Hydrometric data

The location of the flow measuring stations used in this study are shown in Figure 1 and are listed in Table 1. The main analysis was based on the

Table: 1 Flow records used in low flow analysis

Number	Name	NGR	Start	End	Area km^2	Mean Flow $M l.d^{-1}$
77001	Esk at Netherby	NY390718	1963	1988	841.7	2139[(1)]
77003	Liddel Water at Rowanburnfoot	NY415759	1973	1988	319.0	886[(2)]
77005	Lyne at Cliff Bridge	NY412662	1977	1988	191.0	477[(3)]

[(1)] Mean flow calculated from complete years 1965, 68, 73-78, 81-88.
[(2)] Mean flow calculated from complete years 1974-88.
[(3)] Mean flow calculated from complete years 1977, 84-88.

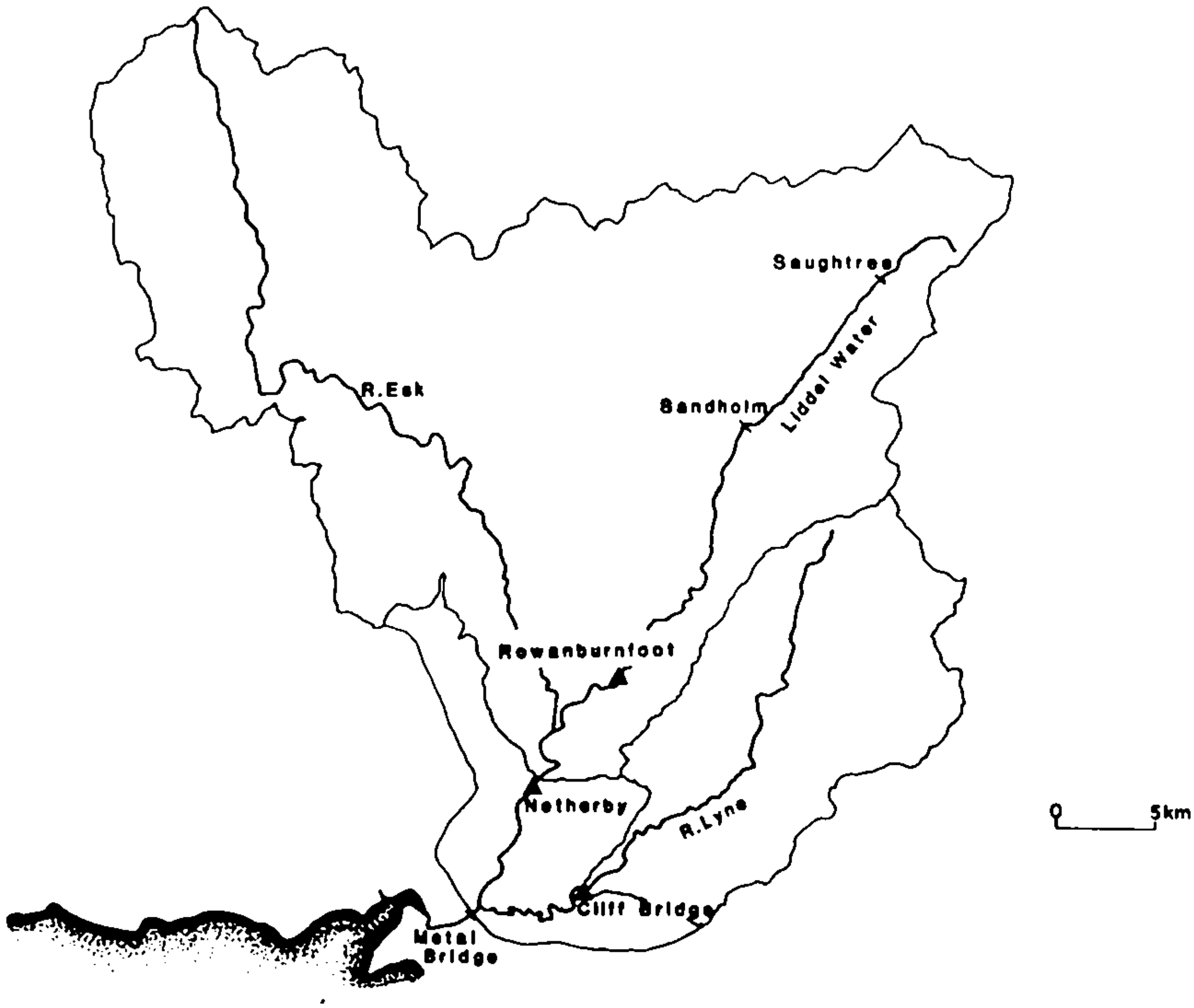


Figure 1 Location of flow measuring stations and ungauged sites.

record of gauged daily flows held on the Surface Water Archive for the Esk at Netherby and the Liddel Water at Rowanburnfoot. In addition, a synthetic set of daily flows was derived for the Esk at Metal Bridge, using data from the Esk at Netherby and the Lyne at Cliff Bridge.

The Esk at Netherby has velocity-area measurement of flows, which are contained over the full range. Flow data are archived from 1963. The Liddel Water at Rowanburnfoot is also a velocity-area station with data archived from 1973.

To derive the synthetic flow sequence for the Esk at Metal Bridge, the flows of the common period at Netherby (Q_n) and Cliff Bridge (Q_c) were correlated and, by regression analysis, the Cliff Bridge series extended to the period of the Netherby record using the following equation

$$Q_c = 0.133 \; Q_n^{1.066} \qquad R^2 = 0.88 \qquad fse = 1.49$$

The extended Cliff Bridge series was added to the gauged Netherby series. This represents flows from a combined area of 191.0 (Lyne at Cliff Bridge) + 841.7 (Esk at Netherby) = 1032.7 km^2. The additional catchment area to Metal Bridge was measured to be 97.0 km^2. The combined flow series was then adjusted by the areal ratio $\frac{1032.7 + 97.0}{1032.7}$ to derive the synthetic Esk at Metal Bridge series.

3. Analyses

3.1 RETURN PERIOD OF 1978 AND 1984 DROUGHT

The flow of the Esk at Netherby must support both the abstraction (20 50 100 150 Ml.d^{-1}) and the maintained minimum acceptable flow of 321 Mld^{-1} (15% of the mean flow). For periods when the sum of these (341 371 421 471 Ml.d^{-1}) is greater than the natural river flow then the river must be supported by upstream regulation releases. The approximate duration of this period of support during 1978 and 1984 was estimated for each of the four proposed abstraction rates by inspecting the daily mean flow hydrograph. For each of these durations an annual minimum frequency analysis was carried out by plotting discharge against W, the Weibull reduced variate (Institute of Hydrology 1980). Figure 2 shows the plot for each of the four critical durations. A graphical fit to the plotted points was used to estimate the return period of the annual minimum discharges of given duration which were recorded in 1978 and 1984. Return periods of the order of 10 years are estimated for 1978 and 25-50 years for 1984 (Table 2). These estimates are in agreement with the more extensive regional analysis of these droughts (Institute of Hydrology 1989). Figure 2 also enables the mean discharge over a given duration to be estimated for a given frequency of occurrence and these are shown in Table 3 for the critical durations between 60 and 150 days and a return period of 100 years.

Table: 2 Return period of 1978 and 1984 annual minima for Esk at Netherby.

	Abstraction Mℓ.d^{-1} 20	50	100	150
<u>1978</u>				
Critical duration, days	60	90	90	120
1978 minima, Mℓ.d^{-1}	274	327	327	383
Return period, years	10	10	10	10-25
<u>1984</u>				
Critical duration, days	120	120	150	150
1984 minima, Mℓ.d^{-1}	246	246	276	276
Return period, years	25-50	25-50	25-50	25-50

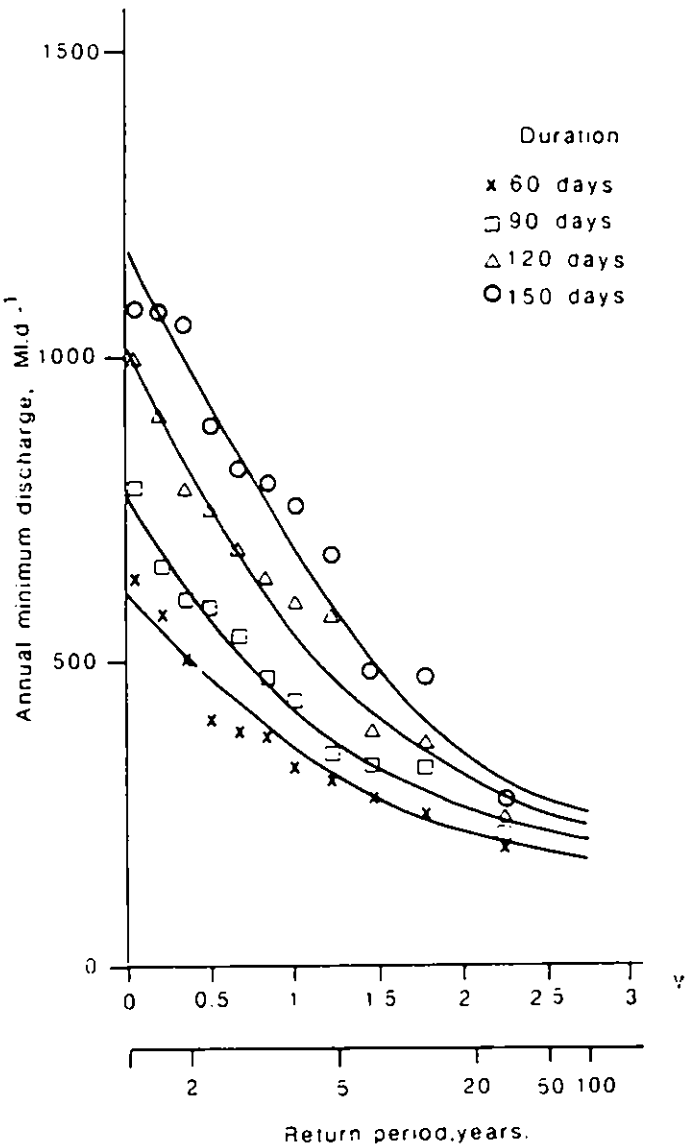


Figure 2 Annual minimum frequency analysis for the Esk at Netherby for 4 critical durations.

Table: 3 Annual minimum discharge with 100 year return period for given duration for Esk at Netherby

	Return period 100 years			
Duration, days	60	90	120	150
Flow, $M\ell.d^{-1}$	170	205	230	250

3.2 DERIVATION OF FLOW DURATION CURVES

Flow duration curves were derived (Institute of Hydrology 1980) from the daily flow series for the Esk at Netherby, the Liddel Water at Rowanburnfoot and the derived flow record for the Esk at Metal Bridge. These are shown on Figure 3 and tabulated on Table 4 together with synthetic curves for the Liddel Water at Sandholm and Saughtree. The latter were estimated using regional low flow estimation equations (Gustard *et al.,* 1987), the Base Flow map of Scotland and the following calculated catchment characteristics and flow indices

	Area km^2	Standard Annual Average Rainfall mm	Actual Evaporation mm	Base Flow Index	Mean Flow $Ml.d^{-1}$	95 percentile flow $Ml.d^{-1}$
Sandholm	177.8	1420	425	0.27	485	33.8
Saughtree	41.4	1350	425	0.20	105	4.12

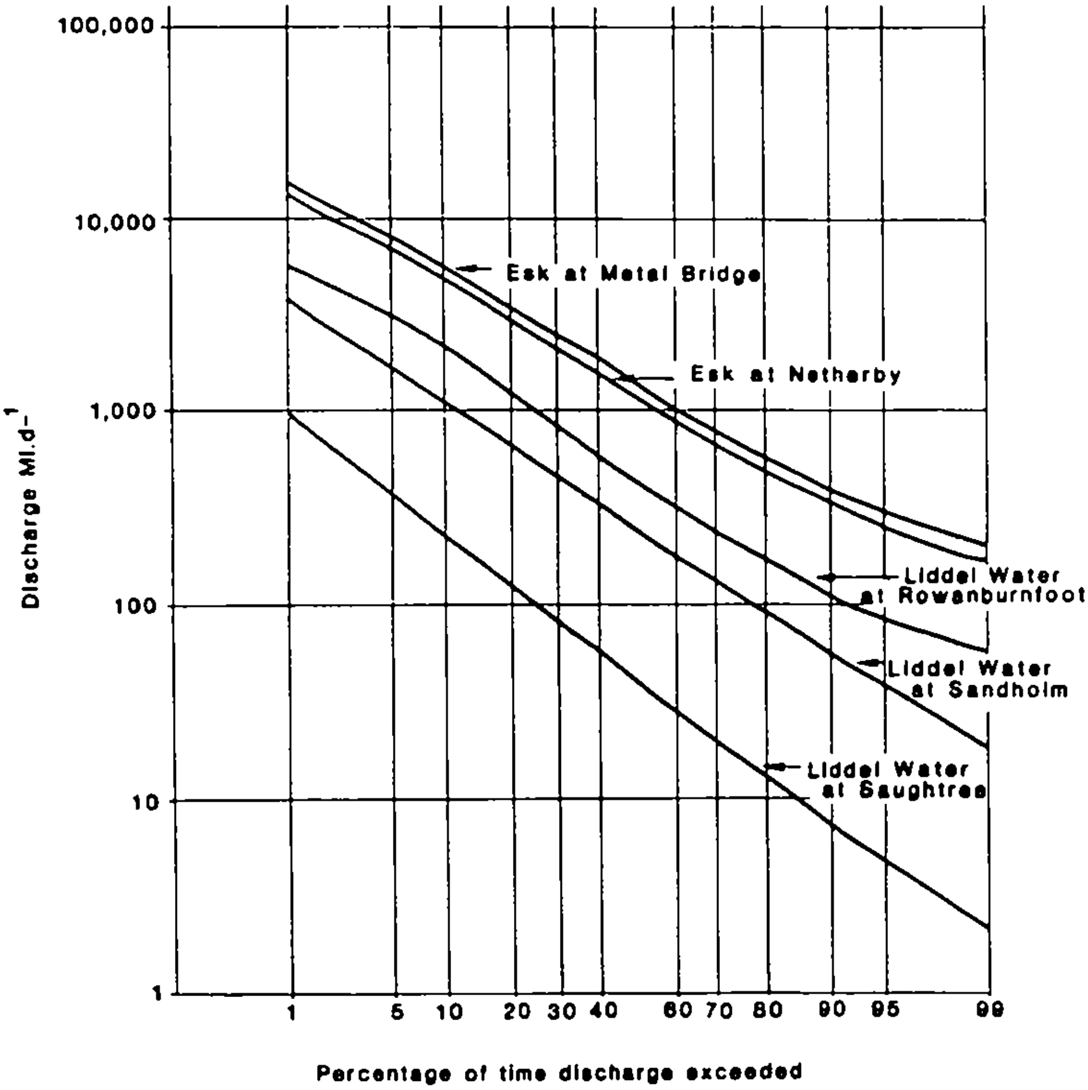


Figure 3 Flow duration curves.

Table: 4 Flow duration curve percentiles Ml.d⁻¹

	PERCENTILE							
	99	95	80	60	40	20	5	1
Esk at Metal Bridge	213	315	577	1064	1868	3740	9047	17310
Esk at Netherby	184	270	491	902	1581	3141	7512	14268
Liddel Water at Rowanburnfoot	64.6	89.8	171	324	606	1280	3272	6184
Liddel Water at Sandholm	19.4	40.5	95.8	183	330	659	1741	4084
Liddel Water at Saughtree	2.13	5.00	13.6	28.0	57.4	128	394	1068

3.3 MAXIMUM REGULATION RELEASE RATE

Figures 4a and 4b show the 1 day annual minima for the Esk at Netherby and at Metal Bridge from which the 20, 50 and 100 year return period annual minima have been estimated (Table 5a and 5b). The difference between these estimates and the sum of the abstraction rate and the minimum acceptable flow represent the maximum regulation release rate for the given frequency and abstraction rate. These are listed on Table 5a for Netherby and 5b for Metal Bridge. Figure 5 shows the maximum 1 day regulation release rate required to support the given abstraction and minimum acceptable flow for a return period of 50 years.

Table: 5(a) Maximum regulation release rate for Esk at Netherby.

		Abstraction, Ml.d⁻¹			
		20	50	100	150
Return period, years	Abstraction + minimum acceptable flow	341	371	421	471
20	1 day minima	158	158	158	158
	Regulation release rate	183	213	263	313
50	1 day minima	155	155	155	155
	Regulation release rate	186	216	266	316
100	1 day minima	153	153	153	153
	Regulation release rate	188	218	268	318

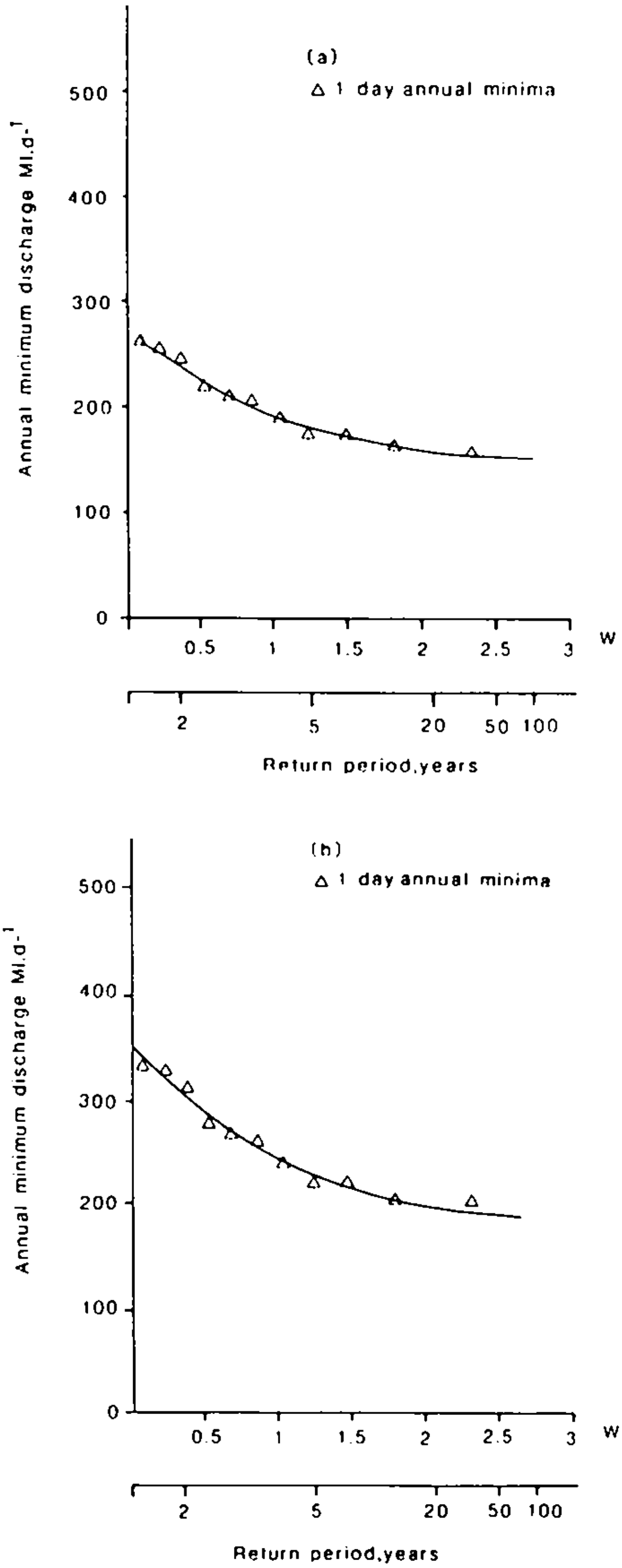


Figure 4 1 day annual minimum frequency analysis for (a) Esk at Netherby and (b) Esk at Metal Bridge.

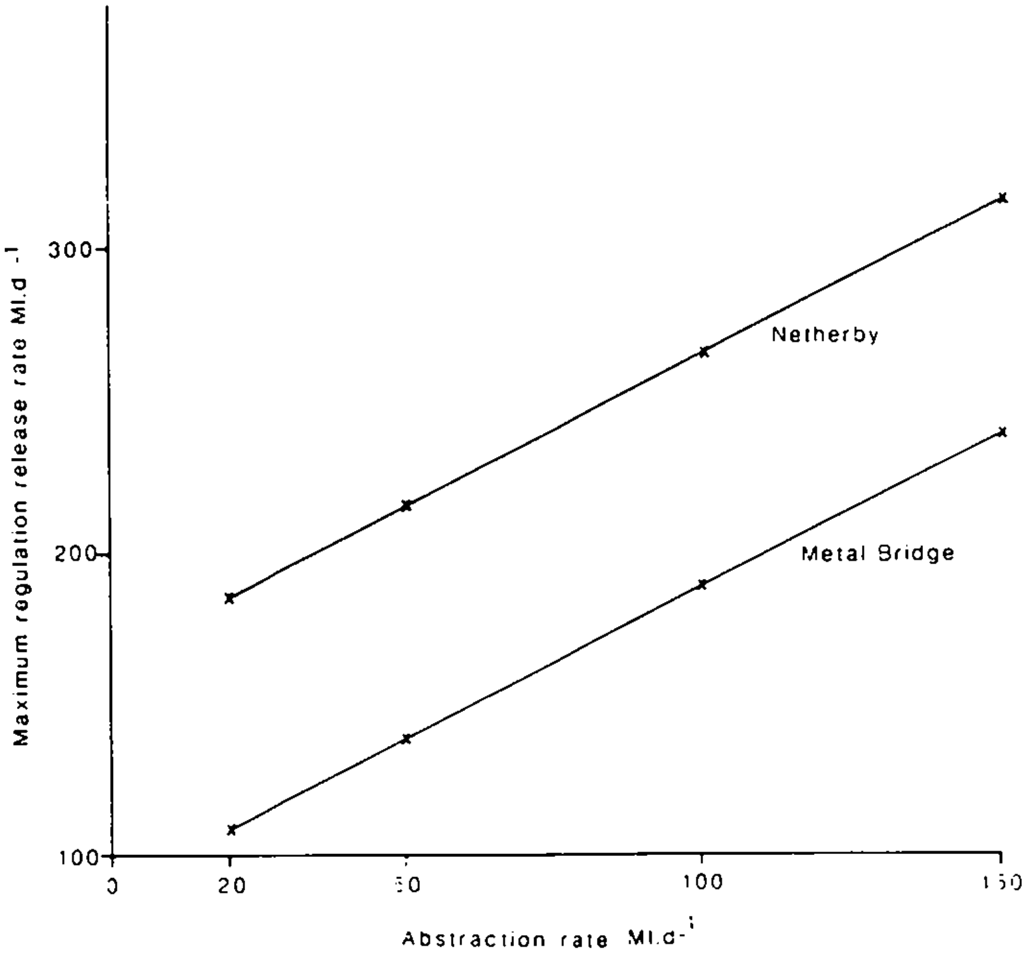


Figure 5 Maximum 1 day regulation release rate (maintained flow 15% of mean flow at Netherby and 10% of mean flow at Metal Bridge).

Table 5(b) Maximum regulation release rate for Esk at Metal Bridge

		Abstraction, Ml.d^{-1}			
		20	50	100	150
Return period, years	Abstraction + minimum acceptable flow	296	326	376	426
20	1 day minima	194	194	194	194
	Regulation release rate	102	132	182	232
50	1 day minima	188	188	188	188
	Regulation release rate	108	138	188	238
100	1 day minima	185	185	185	185
	Regulation release rate	111	141	191	241

3.4 FREQUENCY OF ANNUAL RELEASE VOLUMES

Figure 6 shows the definition of the annual total release volume V which is the sum of V_1, V_2 and V_3 and represents the volume of releases required to maintain the river flow at a given threshold. The threshold is the sum of the abstraction rate and the minimum acceptable flow. Figures 7a and 7b show a frequency plot of the total annual release volumes, using a normal probability plotting position (Institute of Hydrology 1980) and a logarithmic discharge axis. The year of occurrence shown for some of the data points illustrate that the 1984 drought was the most extreme for the period of record.

Tables 6a and 6b and Figures 8a and 8b are derived from Figure 7a and 7b by plotting the estimated total annual release volume against the abstraction.

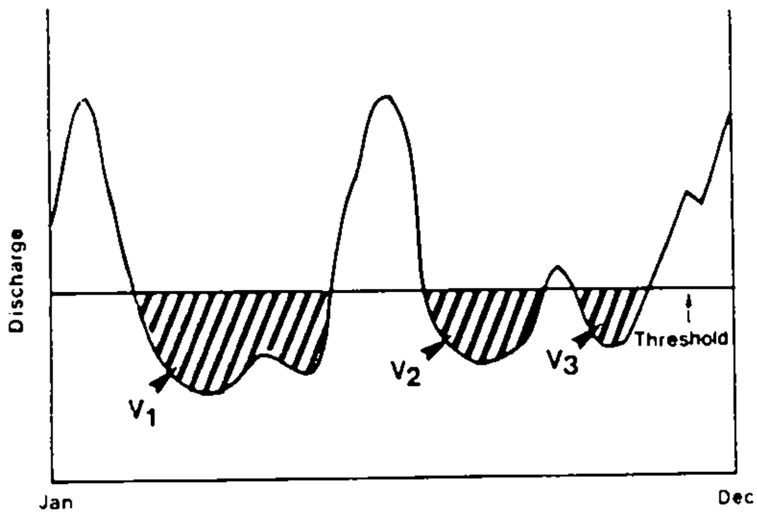
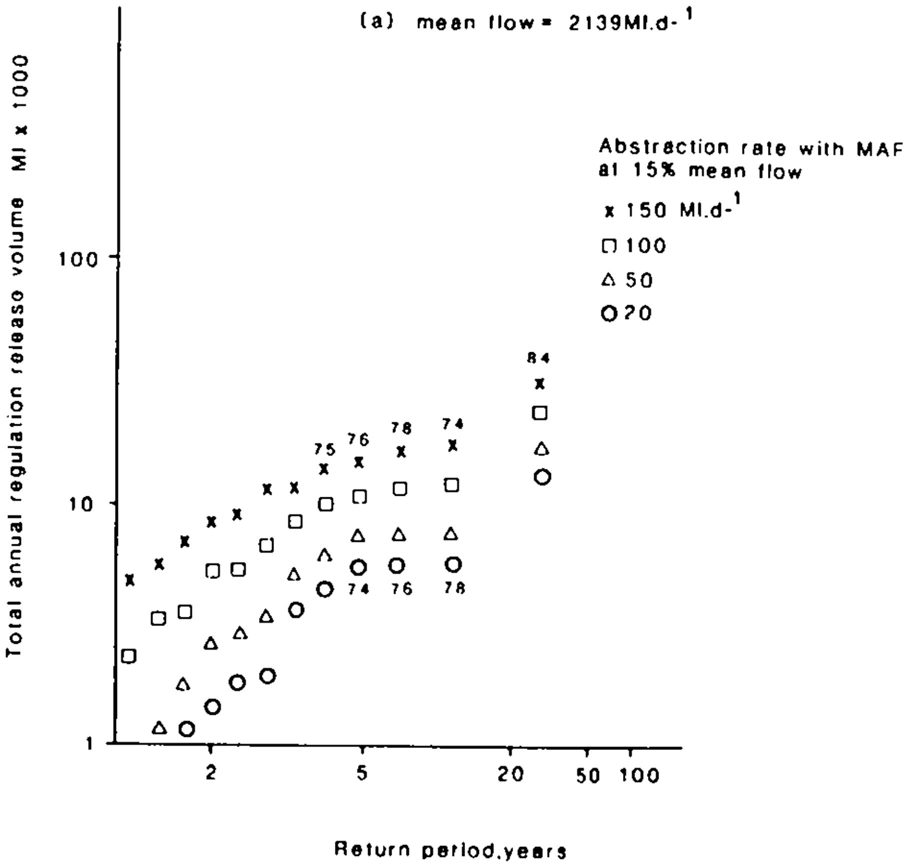


Figure 6 Definition of annual total release volume
$V = V_1 + V_2 + V_3$.

Table 6 Total annual regulation release volume, Mℓx1000
(a) Esk at Netherby.
(b) Esk at Metal Bridge

		Abstraction Mℓ.d.			
	Return period, years	20	50	100	150
(a)	20	11.9	15.3	20.3	29.2
	50	19.3	24.2	30.5	42.5
	100	24.9	30.5	36.5	50.9
(b)	20	2.87	4.31	8.98	13.4
	50	5.00	8.07	15.2	22.1
	100	6.76	10.1	19.4	27.7



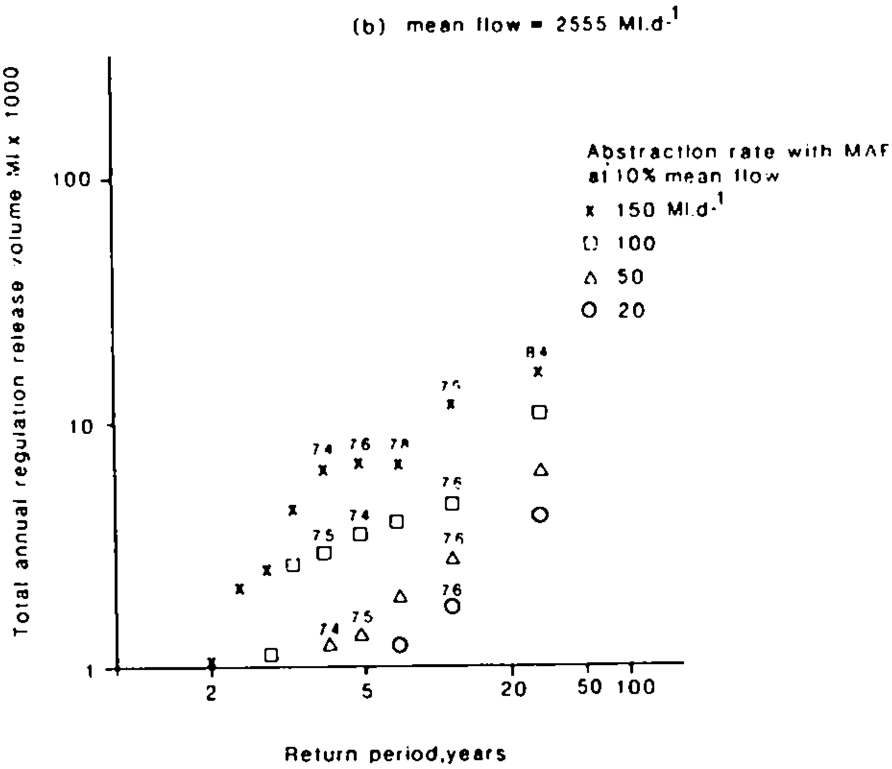


Figure 7 Annual regulation release volume required to meet abstraction rate and minimum acceptable flow (MAF) (a) Esk at Netherby and (b) Esk at Metal Bridge.

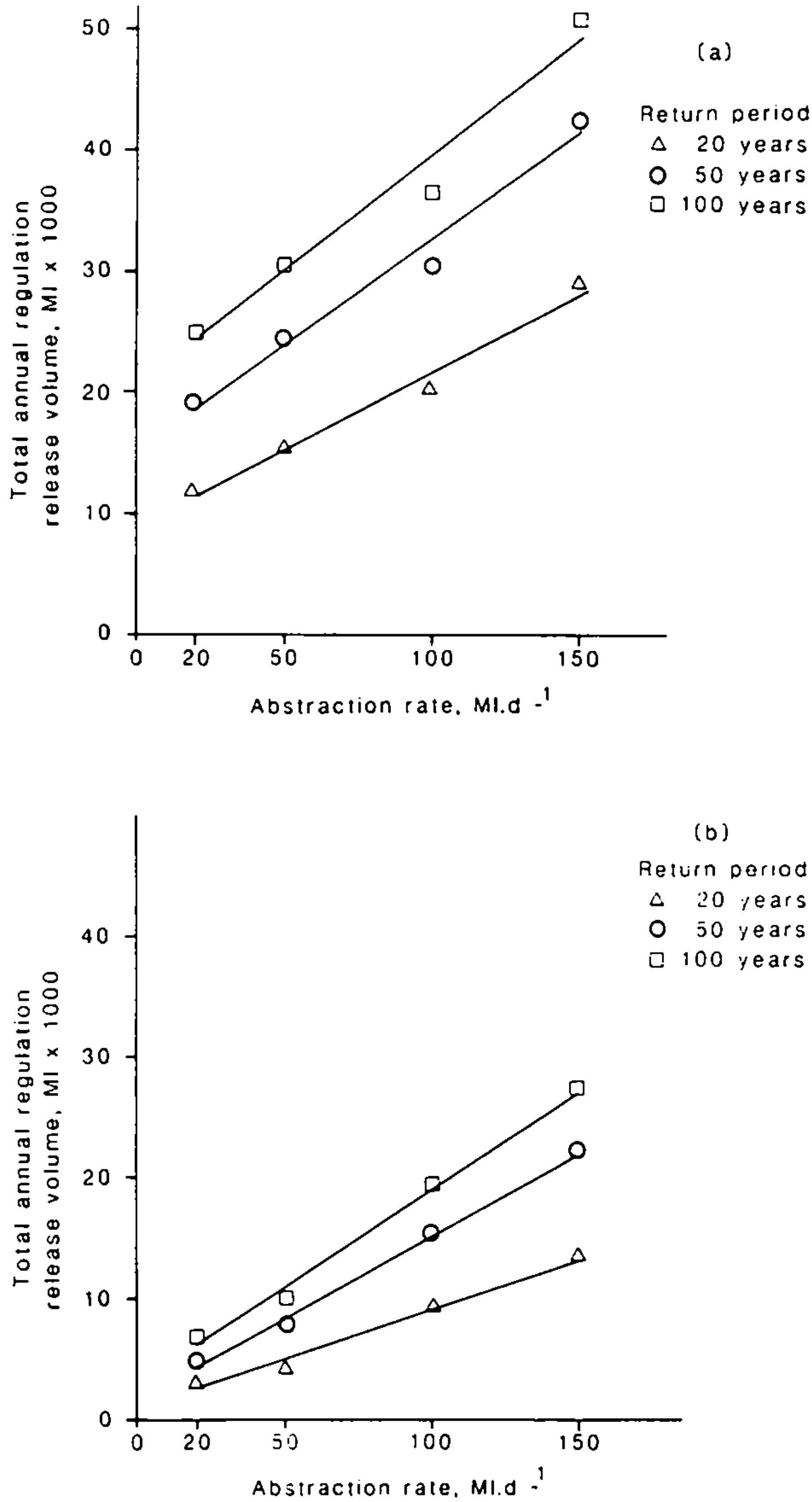


Figure 8 Total annual regulation release volume (maintained flow 15% of mean flow at Netherby and 10% of mean flow at metal Bridge)

rate for a return period of 20, 50 and 100 years. The Figure shows the release volume required for a given probability of failure in order to meet a given abstraction rate whilst maintaining the required prescribed flow (15% of the mean flow at Netherby and 10% of the mean at Metal Bridge).

4. Summary

The return period of the 1978 and 1984 droughts for the Esk at Netherby is estimated to be of the order of 10 and 25-50 years respectively for most of the critical durations. Annual minima discharges for different durations and a return period of 100 years are shown in Table 3. A frequency analysis of 1 day annual minima and of total annual regulation release volumes has been carried out for recorded flows for the Esk at Netherby and for a derived flow record for the Esk at Metal Bridge. This enables maximum transfer rates and total annual release volumes to be estimated for different abstraction rates and fixed minimum acceptable flows. These results are summarised in Table 5a, 5b, 6a and 6b. Regulation release rates range from 158 $Ml.d^{-1}$ (20 year return period, abstraction 20 $Ml.d^{-1}$) to 318 $Ml.d^{-1}$ (100 year return period, abstraction 150 $Ml.d^{-1}$) for the Esk at Netherby with the equivalent figures ranging from 102 $Ml.d^{-1}$ to 241 $Ml.d^{-1}$ for the Esk at Metal Bridge. The results were not very sensitive to different return periods of failure. The equivalent figures for the annual release volumes ranged from 11900 Ml to 50900 Ml for Netherby and from 2870 Ml to 27700 Ml for Metal Bridge.

The analysis carried out in this report is based primarily on the flow record of the Esk at Netherby which has a number of incomplete years of data between 1963 and 1988. Although the results presented provide adequate estimates for a feasibility study it is recommended that the analysis is repeated prior to detailed design work following the infilling of gaps in the record and if possible a historical extension to the time series.

References

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Institute of Hydrology (1989) Estimating the return periods of the 1978 and 1984 droughts on the River Annan at Brydekirk. Report prepared for Sir Frederick Snow and Partners.

Gustard, A. Marshall, D. C. W. & Sutcliffe, M. F. (1987) Low flow estimation in Scotland. Institute of Hydrology Report No. 101.

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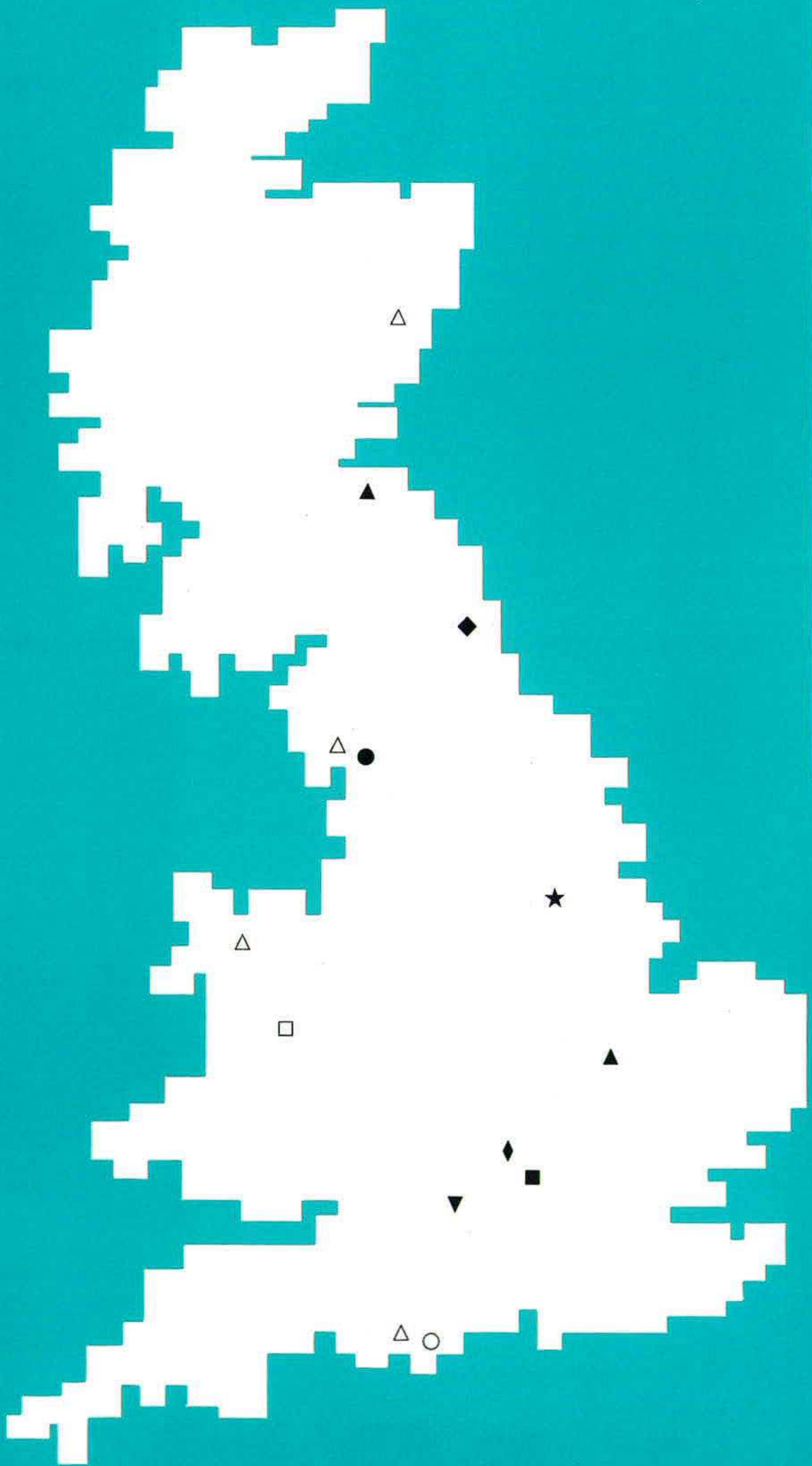

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