LOW FLOW STUDIES

Report No 2.2

Flow frequency curve estimation manual

PREFACE

This report describes the procedure for estimation of the flow frequency curve for both gauged and ungauged catchments. It forms one of a series of reports which document the work of the Low Flow Study carried out at the Institute of Hydrology and funded by the Department of the Environment.

The complete series of reports is as follows:

Report No 1	*Research Report*
Report No 2	*Manuals for estimating low flow measures at gauged or ungauged sites*
Report No 3	*A manual describing the techniques for extracting catchment characteristics*
Report No 4	*River basin and regional monographs describing the relationship between the base flow index and catchment geology*

The first report outlines the scope of the Low Flow Study; it describes the analysis of the flow data, the derivation of the relationship between low flows and catchment characteristics and summarizes the estimation technique. The second report series takes the form of calculation sheets which describe the underlying principles of each low flow measure and enable the user to estimate them from flow data or catchment characteristics; procedures are also given for incorporating local gauged data at various stages in the estimation technique. Report No 3 describes the techniques for calculating catchment characteristics. Report No 4 consists of a series of regional monographs which detail the relationships between the base flow index and catchment geology and enables the index to be estimated at an ungauged site.

CONTENTS

ILLUSTRATIONS

FIGURES

TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

ADF	average flow in cumecs
BFI	base flow index
D	duration (in days unless specified to be in months)
GRADMAM	rate of change of MAM(D)/MAM(10) with D
GRADQ95	rate of change of Q95(D)/Q95(10) with D
MAM(D)	mean annual D day minimum
MAM(10)	mean annual 10 day minimum
AMP(D)	annual minimum D day flow of annual exceedence probability P
Q95(D)	D day average flow exceeded by 95% of D day average discharges
Q95(10)	10 day average flow exceeded by 95% of 10 day average discharges
QP(D)	D day average flow exceeded by P% of D day discharges
SAAR	standard period (1941-1970) annual average rainfall in mm
TC	type curve for flow duration curve and flow frequency curve

Introduction

The flow frequency curve provides a graphical technique for estimating the probability that a year will contain an annual minima less than a given discharge. The probability is commonly expressed in terms of a return period, that is, the average interval in years between the occurrence of an event of a specified or more extreme severity. The curve can be drawn from daily or monthly flow data or from minima of any consecutive D day or month period. It is frequently used for assessing the severity of extreme events and has applications in economic studies where the risk of any event occurring in a given design period can be calculated from the curve and used in cost benefit analysis.

This estimation manual describes methods for drawing the flow frequency curve where adequate flow data are available (greater than 20 years), or where flow data can be used in conjunction with generalized techniques (2-20 years of data) and finally for the case where data are absent. A section is also given for methods of incorporating short or discontinuous data at or close to the site of interest. The frequency relationships of Section 3.4 are also useful to check curves based on greater than 20 years of data because they are developed by pooling data from a large number of catchments.

To help explain the technique, this manual includes a worked example, the River Pang at Pangbourne, for which all the calculations have been completed. This is laid out on right-hand pages. Details of three other catchments which can be used for practice are laid out on the left-hand side, set in italic type.

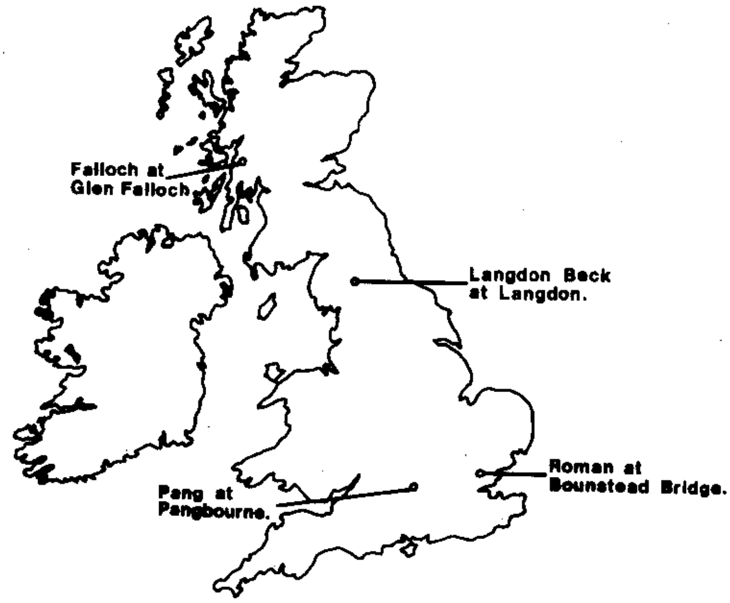


FIGURE 1.1 LOCATION OF ALL THE EXAMPLE CATCHMENTS

CALCULATION SHEETS
ON THIS SIDE

1.1 GENERAL INFORMATION FOR EXAMPLE CATCHMENTS

a. *The River Falloch at Glen Falloch is in hydrometric area 85. The site of interest is at grid reference NN321197 and the area of the catchment is 80.3 km² which includes the Dubh Eas catchment.*

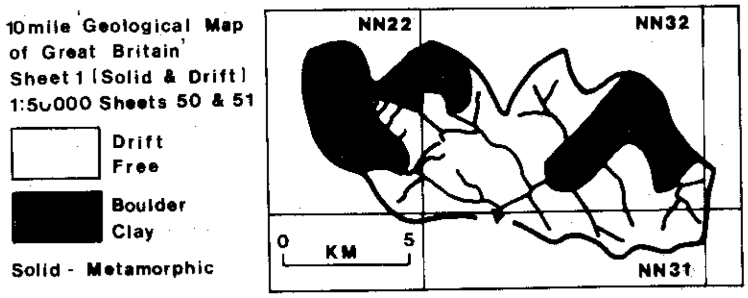


FIGURE 1.2b GEOLOGY AND KEY TO MAPS OF THE FALLOCH CATCHMENT

b. *The Langdon Beck at Langdon is in hydrometric area 25. The site of interest is at grid reference NY 852309 and the area of the catchment is 13.0 km².*

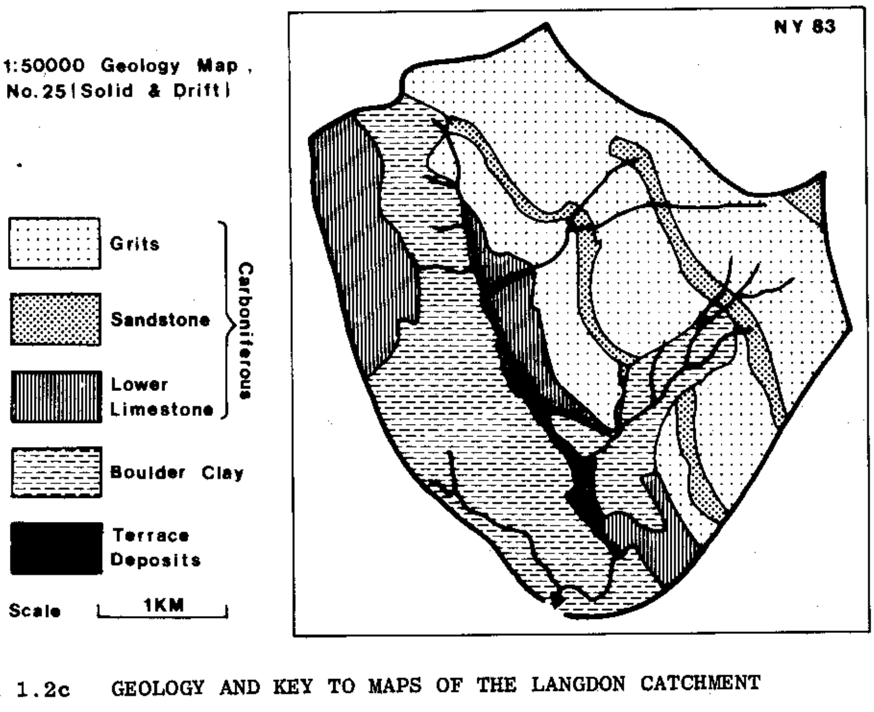


FIGURE 1.2c GEOLOGY AND KEY TO MAPS OF THE LANGDON CATCHMENT

1 Basic data

1.1 GENERAL INFORMATION

The River Pang at Pangbourne is in hydrometric area 39. The site of interest is at Grid Reference SU 634766 and the catchment area is 171 km^2.

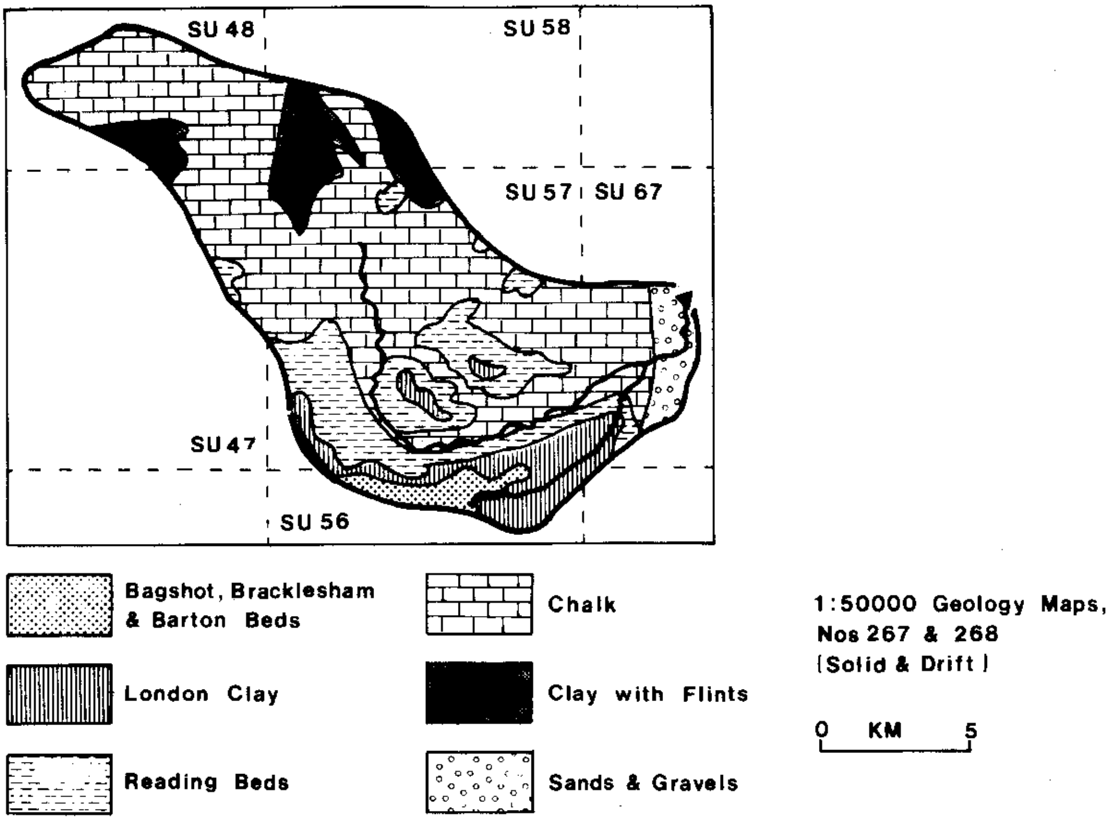
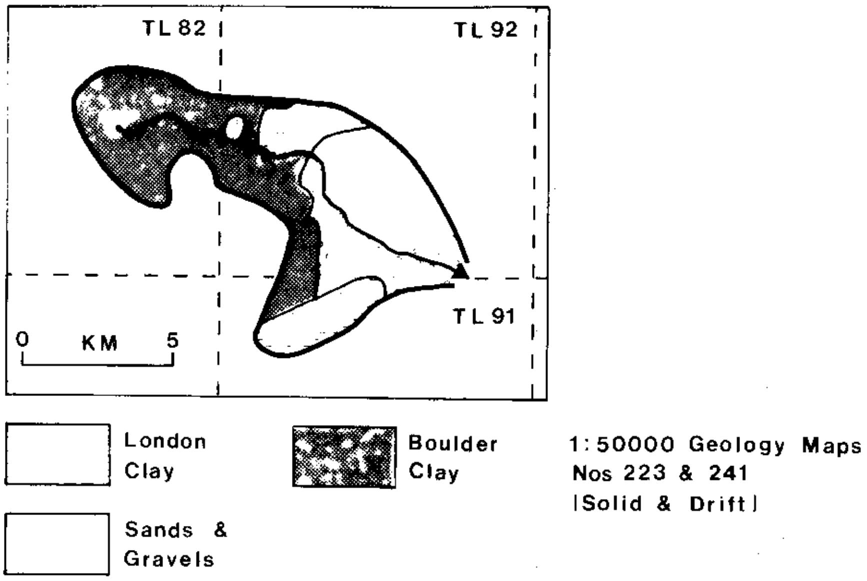


FIGURE 1.2a GEOLOGY AND KEY TO MAPS OF THE PANG CATCHMENT

c. *The Roman River at Bounstead Bridge is in hydrometric area 37. The site of interest is at grid reference TL 985205 and the area of the catchment is 52.6 km^2.*



1.2 FLOW DATA FOR DRAWING THE FLOW FREQUENCY CURVE

Tables 1.1b, c and d contain the daily flow data that are assembled into Table 2.4b and from which the flow frequency curve is prepared.

TABLE 1.1b

85003 FALLOCH AT GLEN FALLOCH

YEAR 1971 NUMBER OF DAYS WITH DATA= 365 MEAN= 5.148 MINIMUM = .246 MAXIMUM = 88.025 (CUMECS)

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	.523	1.201	3.798	1.499	.669	2.925	3.361	4.555	12.784	2.178	18.490	1.876
2	.827	16.631	3.171	1.208	.573	2.243	3.121	5.867	9.575	1.860	7.093	1.056
3	.900	6.465	2.039	.982	.491	1.783	2.711	2.063	3.498	1.179	20.051	16.939
4	.447	2.730	1.482	.901	.425	1.476	8.262	2.603	3.263	.897	9.466	6.059
5	.389	1.708	2.906	.981	.372	1.276	3.306	4.396	1.424	2.440	4.971	1.559
6	41.633	1.502	2.796	.853	3.263	1.135	2.548	5.002	1.005	9.883	5.338	1.169
7	20.491	1.730	1.951	.763	6.055	1.019	1.385	4.221	.787	7.270	19.247	1.073
8	11.116	1.849	1.435	.678	3.753	.933	1.195	4.921	.619	7.257	5.406	3.892
9	51.426	2.523	1.681	.609	3.136	.890	1.090	3.627	.507	13.764	2.038	7.993
10	4.051	7.501	1.304	.581	2.896	.859	.927	1.679	.423	60.302	2.424	2.777
11	1.949	11.562	13.382	.549	2.004	.993	1.219	1.219	.376	6.909	2.075	4.559
12	1.445	43.923	18.529	.517	1.830	1.406	.988	.971	.341	3.071	3.171	11.906
13	1.229	7.303	4.281	.490	1.414	1.182	.816	1.119	.331	1.754	2.636	4.407
14	1.113	10.356	2.059	.448	1.218	1.066	.843	.759	.692	1.322	2.820	13.988
15	1.045	3.921	1.405	.465	3.143	.978	.993	.550	.712	20.526	20.448	6.176
16	1.016	2.257	1.128	.904	7.515	.946	.812	.478	.561	8.682	4.321	3.120
17	5.371	2.525	.944	6.186	5.869	.889	.705	.423	1.705	30.352	3.419	2.606
18	18.602	2.136	.784	4.386	3.301	.829	.672	.363	1.147	11.888	1.842	24.959
19	17.318	9.664	.739	2.433	2.553	.787	.872	.315	1.494	17.033	1.288	20.524
20	7.278	18.016	.693	1.362	2.296	.769	.736	.281	1.816	10.569	1.458	49.229
21	7.506	5.244	.610	1.124	1.807	6.382	1.736	.261	2.528	88.025	1.329	10.630
22	4.806	2.596	.539	.929	1.529	3.261	1.774	.246	1.447	20.263	1.595	4.547
23	9.278	12.616	3.235	24.445	7.220	2.424	3.409	.304	1.684	7.383	2.759	14.974
24	22.228	5.053	12.195	3.987	4.728	8.844	6.176	.337	.942	6.161	6.002	5.337
25	13.200	3.247	5.693	1.553	2.865	10.823	11.107	.313	.685	2.318	6.904	5.786
26	4.517	2.114	4.248	1.072	6.293	17.571	5.655	3.283	3.148	1.663	8.121	8.323
27	2.752	2.532	3.151	.844	12.472	11.225	4.968	6.141	1.818	1.335	7.009	2.795
28	2.513	2.081	9.884	.696	4.721	4.841	2.593	8.473	1.407	1.099	2.475	1.253
29	2.241		8.268	.823	3.960	3.212	1.861	3.235	5.329	1.109	6.203	.913
30	1.530		2.481	.896	16.655	2.715	1.432	12.120	4.268	4.484	2.854	.661
31	1.179		1.788		4.298		10.547	14.832		4.483		.573

1.2 FLOW DATA FOR DRAWING THE FLOW FREQUENCY CURVE

Table 1.1a contains the daily flow data of the type from which the annual minima of various durations on Table 2.1a have been extracted and which are subsequently used in the analysis for the gauged catchment case.

TABLE 1.1a 39027 PANG AT PANGBOURNE

YEAR 1971 NUMBER OF DAYS WITH DATA= 365 MEAN= .805 MINIMUM = .408 MAXIMUM = 2.960 (CUMECS)

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	.513	1.110	.749	.860	.993	.705	1.090	.819	.652	.519	.464	.567
2	.494	1.260	.899	.848	.955	.674	1.060	.797	.654	.495	.455	.557
3	.480	1.460	.826	.820	.900	.672	1.040	.804	.654	.544	.459	.538
4	.471	1.340	.776	.826	.855	.652	1.020	.789	.643	.499	.457	.521
5	.463	.904	.761	.839	.854	.667	1.030	.811	.632	.488	.558	.508
6	.467	.834	.748	.817	.878	.663	1.010	.817	.613	.481	.544	.506
7	.666	.816	.721	.811	.879	.670	.996	.780	.602	.474	.520	.496
8	.713	.789	.755	.819	.821	.689	1.010	.752	.602	.474	.513	.494
9	.588	.803	.750	.901	.811	1.170	.980	.749	.603	.487	.491	.509
10	.554	.765	.741	.888	.790	1.110	.964	.759	.607	.476	.484	.492
11	.541	.771	.714	.791	.783	2.960	.946	.739	.595	.473	.477	.484
12	.520	.769	.718	.829	.768	2.080	.929	.749	.590	.496	.486	.470
13	.503	.769	.722	.815	.775	1.480	.895	.758	.582	.573	.477	.465
14	.524	.794	.733	.815	.735	1.900	.800	.785	.594	.610	.456	.463
15	.546	.987	1.200	.802	.775	2.190	.796	.753	[illegible]	.532	.444	.463
16	.622	.874	.968	.800	.793	1.580	.783	.719	.580	.655	.438	.455
17	.665	.907	1.190	.768	.742	1.330	.787	.693	.548	.769	.408	.452
18	.630	.889	2.290	.766	.726	1.650	.791	.702	.582	.612	.466	.454
19	.822	.793	1.700	.743	.710	2.710	.773	.851	.568	.576	.461	.665
20	.997	.854	1.390	.766	.708	2.230	.793	.834	.561	.566	.516	.589
21	1.620	.821	1.210	.761	.692	1.740	.824	.816	.540	.538	.689	.521
22	1.570	.783	1.090	.768	.706	1.490	.846	.764	.540	.516	.549	.603
23	2.080	.783	1.010	1.030	.773	1.360	.805	.724	.549	.474	.593	.626
24	1.740	.766	.991	1.520	.756	1.280	.844	.727	.548	.487	.547	.561
25	1.870	.761	.947	1.220	.875	1.230	.833	.689	.551	.481	.518	.516
26	1.910	.754	.938	1.670	.763	1.220	.797	.716	.559	.470	.534	.536
27	1.520	.745	.900	1.700	.791	1.210	.836	.707	.555	.473	.625	.558
28	1.200	.727	.883	1.300	.829	1.240	.829	.692	.551	.455	.893	.589
29	.987		.895	1.110	.795	1.140	.806	.670	.531	.480	.621	.552
30	1.180		.865	1.040	.773	1.120	.827	.654	.545	.468	.596	.529
31	1.210		.861		.728		.847	.658		.473		.518

TABLE 1.1c

25011 [illegible] BECK [illegible]

YEAR 1971 NUMBER OF DAYS WITH DATA= 365 MEAN= .332 MINIMUM = .024 MAXIMUM = 6.252 (CUMECS)

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	.105	.098	.100	.114	.067	.040	.122	.120	.120	.031	.065	.124
2	.126	.252	.143	.096	.059	.133	.079	.104	.186	.030	.069	.114
3	.221	.410	.109	.095	.051	.041	.069	.823	.204	.030	.073	.123
4	.182	.171	.150	.191	.046	.030	.053	1.297	.134	.032	.544	.191
5	.108	.135	.131	.124	.040	.031	.045	.436	.088	.030	1.067	.133
6	2.292	.118	.159	.109	.056	.043	.039	.433	.066	.027	.459	.111
7	6.252	.109	.545	.082	.063	.057	.035	.531	.054	.029	1.406	.097
8	1.758	.099	.941	.082	.050	.045	.033	.508	.048	.034	.477	.127
9	.950	.086	.449	.066	.043	.043	.033	.495	.043	.091	.184	.111
10	.282	.075	.378	.059	.053	.038	.032	.145	.040	.098	.141	.095
11	.165	.109	.461	.052	.046	.657	.029	.131	.038	.136	.132	.080
12	.132	4.061	.268	.048	.040	.266	.028	.100	.036	.074	.118	.184
13	.122	.860	.191	.046	.038	.162	.026	4.703	.035	.072	.114	.374
14	.119	.733	.374	.043	.036	.165	.026	3.750	.038	.055	.096	.288
15	.110	.422	.210	.041	.034	.096	.025	.460	.040	.102	.100	.202
16	.101	.242	.147	.049	.036	.131	.025	.200	.036	.357	.144	.162
17	.098	.184	.226	.047	.037	.101	.024	.130	.035	1.273	1.114	.151
18	.618	.452	2.194	.045	.038	.259	.024	.096	.033	3.435	.348	.140
19	1.086	.670	2.331	.039	.033	.054	.025	.075	.032	2.696	.154	1.367
20	.657	1.851	1.037	.038	.033	.928	.026	.060	.031	.742	.354	.501
21	2.053	.605	.554	.035	.030	.837	.034	.052	.030	.965	.697	.262
22	.377	.234	.382	.034	.033	.363	.033	.049	.030	.404	.332	.168
23	.504	.176	.751	1.777	.113	.144	.049	.048	.030	.223	.424	.144
24	1.923	.172	1.575	2.456	.146	.094	.193	.046	.030	.175	.798	.136
25	.894	.152	.468	.320	.087	.094	.376	.041	.029	.136	2.559	.136
26	.360	.128	.440	.180	.051	.138	.215	.038	.034	.110	.501	.118
27	.411	.111	.242	.138	.043	.111	.149	.035	.038	.095	1.326	.201
28	.463	.103	.187	.104	.037	.134	.089	.048	.033	.079	.321	.140
29	.273		.154	.094	.037	.917	.059	1.707	.037	.071	.174	.112
30	.191		.146	.080	.052	.231	.046	.545	.036	.077	.138	.099
31	.137		.115		.050		.057	.225		.072		.261

TABLE 1.1d

37021 ROMAN AT BOUNDSTEAD

YEAR 1971 NUMBER OF DAYS WITH DATA= 365 MEAN= .204 MINIMUM = .067 MAXIMUM = 1.879 (CUMECS)

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	.530	.673	.294	.219	.161	.113	.115	.090	.091	.091	.097	.185
2	.432	.356	.366	.208	.153	.105	.114	.092	.088	.092	.101	.163
3	.366	.424	.333	.190	.143	.099	.109	.154	.090	.092	.100	.121
4	.327	.420	.303	.194	.140	.097	.108	.106	.090	.092	.098	.146
5	.192	.401	.278	.183	.137	.104	.103	.153	.090	.093	.128	.143
6	.238	.385	.275	.180	.134	.106	.104	.107	.089	.089	.115	.152
7	.836	.362	.258	.174	.225	.105	.099	.131	.087	.091	.118	.138
8	.884	.352	.260	.170	.164	.099	.099	.107	.084	.091	.108	.135
9	.452	.332	.248	.181	.146	.103	.089	.100	.083	.090	.102	.139
10	.443	.332	.220	.152	.142	.172	.084	.110	.085	.095	.101	.133
11	.422	.314	.224	.161	.133	.138	.082	.100	.090	.092	.097	.130
12	.319	.304	.226	.161	.124	.118	.095	.099	.085	.135	.105	.127
13	.271	.303	.226	.163	.114	.113	.091	.105	.086	.220	.108	.128
14	.176	.290	.228	.168	.117	.446	.091	.111	.089	.088	.102	.125
15	.305	.281	.235	.166	.140	.290	.088	.096	.087	.108	.095	.123
16	.252	.264	.220	.183	.166	.125	.103	.094	.085	.120	.104	.123
17	.252	.300	.257	.165	.142	.141	.067	.092	.085	.148	.100	.121
18	.691	.507	.371	.165	.134	.253	.087	.093	.086	.133	.175	.119
19	.446	.449	.355	.158	.124	.299	.092	.095	.082	.127	.132	.177
20	.544	.434	.350	.158	.119	.407	.088	.159	.087	.077	.178	.148
21	.816	.404	.356	.155	.115	.253	.096	.131	.085	.107	.278	.137
22	.758	.344	.356	.153	.122	.123	.097	.114	.065	.104	.226	.165
23	1.679	.306	.221	.275	.133	.141	.096	.110	.098	.101	.214	.249
24	1.518	.307	.260	.232	.132	.132	.099	.103	.102	.101	.183	.203
25	1.067	.247	.254	.252	.157	.124	.117	.097	.091	.099	.161	.171
26	1.399	.234	.245	.225	.141	.154	.103	.100	.107	.100	.186	.161
27	1.400	.246	.221	.161	.151	.073	.102	.093	.149	.097	.179	.149
28	.699	.250	.226	.167	.141	.133	.117	.092	.102	.097	.491	.143
29	.700		.225	.165	.129	.116	.105	.094	.094	.097	.317	.144
30	.795		.211	.164	.146	.111	.103	.093	.091	.097	.286	.173
31	.652		.250		.124		.084	.093		.095		.176

1.3 PLOTTING FLOW FREQUENCY CURVE FROM DAILY FLOW DATA

The steps for preparing flow frequency curves from the data of Tables 1.1b to 1.1d are described in Section 2 of this manual and curves for the example catchments are shown in Figure 2.2b.

1.3 PLOTTING FLOW FREQUENCY CURVE FROM DAILY FLOW DATA

Figure 1.3 shows a flow frequency curve for the River Pang for annual minima of 1, 10, 60 and 180 days. The curve has been plotted using the Institute of Hydrology data processing system.

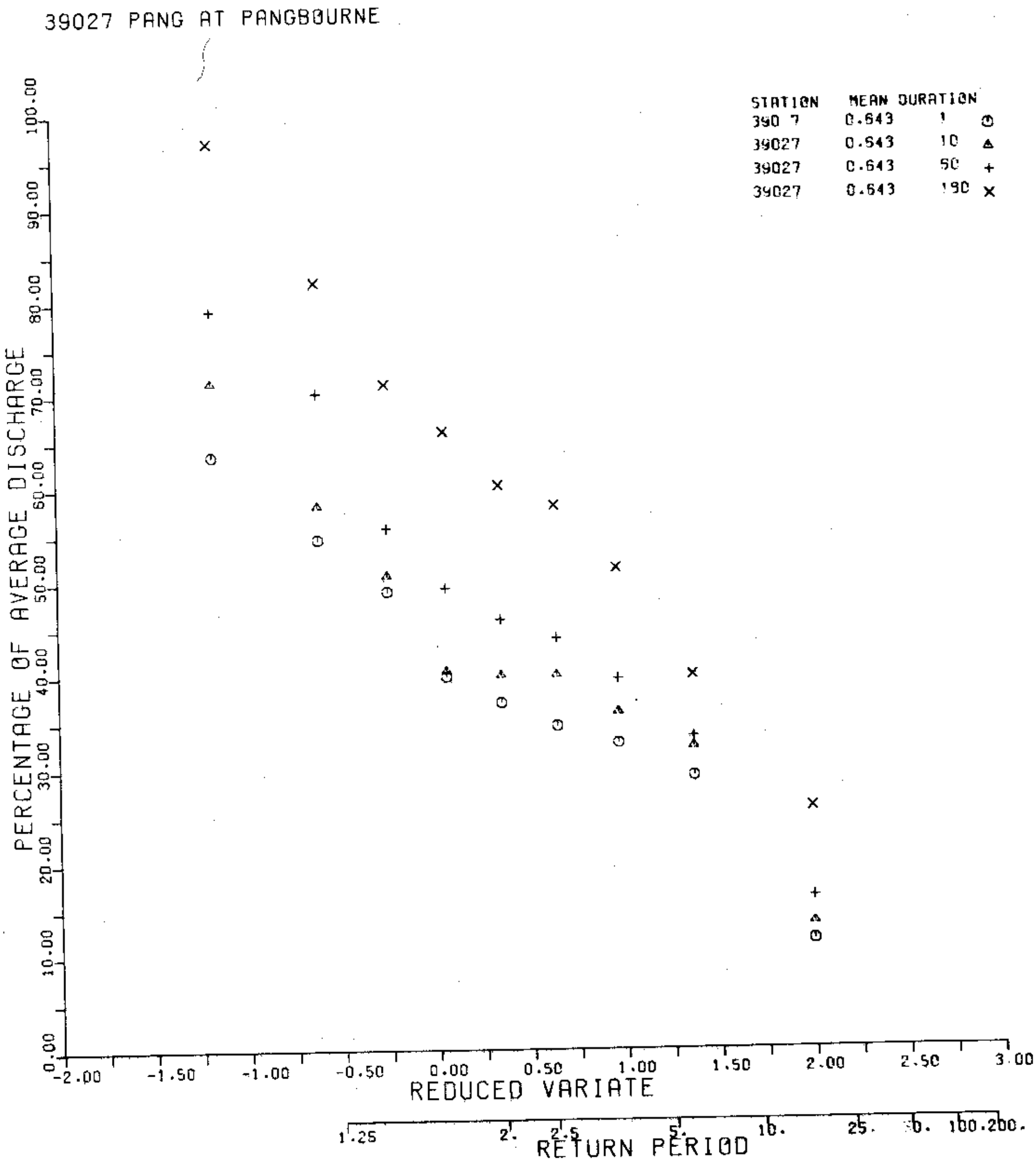


FIGURE 1.3 AUTOMATED FLOW FREQUENCY PLOT FOR RIVER PANG

1.4 OUTLINE OF ESTIMATION PROCEDURE

The basic recommendations for drawing flow frequency curves are given opposite. For purposes of illustration a departure is made from these recommendations. Thus although all the example catchments have only eight years of data, Section 2 describes how to construct flow frequency curves based on the data alone and not as suggested by a combination of data and national type curves.

1.4 OUTLINE OF ESTIMATION PROCEDURE

The procedure for estimating the flow frequency curve depends on the availability of data at or near the site of interest. Figure 1.4 outlines three basic approaches and the corresponding sections of this manual to use. It can be seen from the figure that the technique based on catchment characteristics refers to the Catchment Characteristic estimation manual - Report No. 3 of this series.

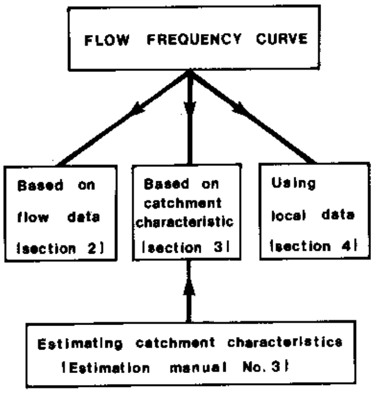


FIGURE 1.4 **OUTLINE OF ESTIMATION PROCEDURE**

Which of the three procedures to use or combinations thereof, depends on the amount of data available. Suggested guidelines are summarised in Table 1.2 and described below.

> 20 yrs Use the data in cumec units to construct the flow frequency curve directly (Section 2). If return periods in excess of twice the length of record are being estimated then the type curves of Section 3 can be used for extending the curve beyond the range of the data.

10-20 yrs The minimum for the appropriate duration can be calculated from the data and the type curves (Section 3) used to estimate the discharge for a given frequency. In addition, the curve can be plotted by dividing the daily flow data by the average flow (ADF) over the period of record and the discharge scale expressed as a % ADF. This overcomes to a great extent departures due to wet or dry years. The conversion to long term average flow is described in Section 2.5 of Report No. 3.

5-10 yrs Divide the daily or monthly flow by the average daily flow (ADF) over the period of record before analysis. This overcomes to a great extent the departures due to wet or dry years. The value of the mean annual minimum as a % ADF is then used in conjunction with the type curves of Section 3. The conversion to the long term flow frequency curve is made using an estimate of long term average flow (Section 2.5, Report 3).

< 2yrs Use Sections 3 and 4 of this manual and refer to Report 3 for use of short records for calculating the Base Flow Index and ADF.

TABLE 1.2 **Technique to use for given record length**

Yrs of record	Technique	Section of report to use
> 20	Plot data in cumecs	2
> 10	MAM(10) cumecs and type curves (check by plot)	2 & 3
2-10	MAM(D) as % ADF from data and type curves	2 & 3
< 2	BFI from data or use of short record directly	3 & 4
No data	BFI from geology	3

The worked example for the Pang departs from these guidelines in that only ten years of data are available - less than that recommended for construction of the entire curve. It is stressed however that although Table 1.2 summarizes the appropriate technique, each design problem should be viewed on its merits and more than one of the suggested procedures may be appropriate.

2.1 ASSEMBLY OF DATA

Although, strictly, the length of records are too short for this type of analysis, (Section 1.4), they can be used for demonstration purposes and for comparison with the ungauged case procedure (Section 3).

The annual minima have been provided for all the years except 1971. The minimum for this year can be entered into Tables 2.1b-2.1d by using the mean daily discharge from Table 1.1b (Falloch), 1.1c (Langdon), 1.1d (Roman). The long term average discharges from daily flow data are as follows:

Falloch	:	*4.913 cumecs*
Langdon	:	*0.388 cumecs*
Roman	:	*0.183 cumecs*

TABLE 2.1b Annual minima for the Falloch

	Duration	1971	1972	1973	1974	1975	1976	1977	1978
Cumecs	1		0·161	0·224	0·119	0·065	0·037	0·032	0·089
	10		0·283	0·681	0·137	0·101	0·045	0·047	0·114
	30		0·622	1·133	0·300	0·378	0·115	0·119	0·489
	60		0·753	1·704	1·205	0·857	0·379	0·343	0·596
	90		1·612	2·701	1·464	1·013	1·085	0·937	0·775
	180		3·157	3·202	2·231	1·464	2·620	2·992	2·798
% ADF	1		3·3	4·6	2·4	1·3	0·8	0·7	1·8
	10		5·8	7·8	2·8	2·1	0·9	1·0	2·3
	30		12·7	23·1	6·1	7·7	2·3	2·4	10·0
	60		15·3	34·7	24·5	17·4	7·7	7·0	12·1
	90		32·8	55·0	29·8	20·6	22·1	19·1	15·8
	180		64·3	65·2	45·4	29·8	53·3	60·9	57·0

2 The gauged catchment case

2.1 ASSEMBLY OF DATA

From the average flow data calculate the long term average discharge (ADF). For the River Pang this is 0.643 cumecs.

For each calendar year of record extract the minimum discharge over D consecutive days where D is the duration of interest. In this example, we use D = 1, 10, 30, 60, 90 and 180 days. It cannot be assumed that the lowest flows over short periods are contained within the long periods. It will be more convenient in searching for annual minima to sum the daily flow values and work initially in cumec-day units, and then divide by D to yield cumec units. If comparisons with other rivers or with the procedure recommended for the ungauged case are required, divide again by ADF/100 to yield units of % ADF. This is the case shown here.

If a year contains missing data then the true annual minima may not be recorded and that year may have to be omitted from the calculation. The rule adopted in the Low Flow Study was that if 10 days data are missing from the record during the period March to October, then the year is considered as a missing year from the point of view of the flow frequency curve. This accounts for why, on Figure 1.3 for example, only 9 points have been plotted for the 10 years of data. This rule was designed for large-scale automatic data processing and for manual processing the criteria can be adjusted in the light of information from neighbouring stations, if, for example, they indicated that the minimum could not have occurred in the gap.

Although strictly speaking the Pang's record length is insufficient for this analysis, we will make use of it for demonstration purposes and because it will allow comparisons to be made with other procedures.

TABLE 2.1a **Annual minima for the Pang**

	Duration	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978
Cumecs	1	·315	·210	·408	·238	·187	·222	·256	·074	·351	·152
	10	·326	·231	·459	·257	·207	·257	·260	·086	·374	·165
	30	·342	·233	·478	·270	·211	·270	·290	·089	·391	·216
	60	·358	·254	·509	·282	·214	·295	·317	·104	·451	·266
	90	·374	·274	·520	·292	·216	·329	·336	·114	·467	·346
	180	·457	·330	·624	·373	·256	·424	·387	·165	·528	·535
% ADF	1	49·0	32·7	63·5	37·0	29·1	34·5	39·8	11·5	54·6	23·6
	10	50·7	35·9	71·4	40·0	32·2	40·0	40·4	13·4	58·2	25·7
	30	53·2	36·2	74·3	42·0	32·8	42·0	45·1	13·8	60·8	33·6
	60	55·7	39·5	79·2	43·9	33·3	45·9	49·3	16·2	70·1	41·4
	90	58·2	42·6	80·9	45·4	33·6	51·2	52·3	17·7	72·6	53·8
	180	71·1	51·3	97·0	58·0	39·8	65·9	60·2	25·7	82·1	83·2

TABLE 2.1c **Annual minima for the Langdon**

	Duration	1970	1971	1972	1973	1974	1975	1976	1977
Cumecs	1	0·021		0·022	0·023	0·020	0·018	0·013	0·023
	10	0·022		0·022	0·028	0·025	0·019	0·014	0·025
	30	0·026		0·026	0·038	0·040	0·027	0·017	0·037
	60	0·046		0·028	0·087	0·040	0·056	0·030	0·044
	90	0·073		0·033	0·171	0·054	0·100	0·033	0·107
	180	0·219		0·168	0·212	0·118	0·154	0·190	0·231
% ADF	1	5·4		5·7	5·9	5·2	4·6	3·4	5·9
	10	5·7		5·7	7·2	6·4	4·9	3·6	6·4
	30	6·7		6·7	9·8	10·3	7·0	4·4	9·6
	60	11·9		7·2	22·4	10·3	14·4	7·7	11·3
	90	18·8		8·5	44·1	13·9	25·8	8·5	27·6
	180	56·4		43·3	54·6	30·4	40·4	49·0	59·5

TABLE 2.1d **Annual minima for the Roman**

	Duration	1970	1971	1972	1973	1974	1975	1976	1977
Cumecs	1	0·052		0·048	0·038	0·036	0·062	0·037	0·043
	10	0·088		0·067	0·045	0·046	0·079	0·045	0·066
	30	0·092		0·076	0·049	0·052	0·088	0·050	0·070
	60	0·096		0·082	0·057	0·054	0·091	0·056	0·074
	90	0·096		0·085	0·064	0·055	0·095	0·057	0·082
	180	0·106		0·090	0·072	0066	0·113	0·067	0·086
% ADF	1	28·4		26·2	20·8	19·7	33·9	20·2	23·5
	10	45·4		36·6	24·6	25·1	43·2	24·6	36·1
	30	50·3		41·5	26·8	23·4	48·1	27·3	38·3
	60	52·5		44·8	31·1	29·5	49·7	30·6	40·4
	90	52·5		46·4	35·0	30·1	51·9	31·1	44·8
	180	57·8		49·2	39·3	36·1	61·7	36·6	47·0

2.2 PREPARATION OF PROBABILITY PAPER

Using the values of T, evaluate the corresponding values of W

T	2.5	5	10	25	50	100
$(T-1)/T$						
$(-\ln(T-1)/T)^{\frac{1}{4}}$						
W						

Make up a W scale and a subsidiay scale of return period values at the appropriate W points using the graph paper provided (Figure 2.1b).

2.3 PLOTTING ANNUAL MINIMA

The following table may be completed using the % ADF data of Section 2.1 by ranking the data from highest (i=1) to lowest.

TABLE 2.2b Ranked annual minima for Falloch, Langdon, Roman

	Rank i									
	1	2	3	4	5	6	7	8	9	10
1 day minima										
10 day minima										
30 day minima										
60 day minima										
90 day minima										
180 day minima										
P										
$(-\ln P)^{\frac{1}{4}}$										
W										

2.2 PREPARATION OF PROBABILITY PAPER

The annual minimum values of the previous section are to be plotted on special probability paper which has been found to linearise low flow data in many cases. In fact, the paper linearises a 'standardised Weibull variate', W, so the horizontal axis is marked primarily by a linear axis from -1.0 to +3.0. To increase the usefulness of the paper however, it is helpful to also mark a return period scale. The conversion to a return period scale is:

$$T = \left[1-\exp\left[-\{1-W/4\}^4\right]\right]^{-1}$$

or

$$W = 4\left[1-\{-\ln\left[(T-1)/T\right]\}^{\frac{1}{4}}\right]$$

The vertical axis is labelled linearly as discharge either in cumecs or, as in this example, in % ADF. A third alternative is to express the discharge as a multiple of the mean annual minimum MAM(D). In this latter form the frequency curve can be compared directly with the low flow frequency type curves (Section 3.3).

2.3 PLOTTING ANNUAL MINIMA

The exceedence probability P is calculated for each ranked minimum i and N is the total number of annual minima

$$P = (i-0.44)/N+0.12)$$

$$W = 4\left[1-\{-\ln P\}^{\frac{1}{4}}\right]$$

(obtained from Low Flow Study Report No. 1 with Weibull parameter, γ=4.0).

For the Pang data the following table is constructed by ranking the flows from highest (i=1) to lowest:

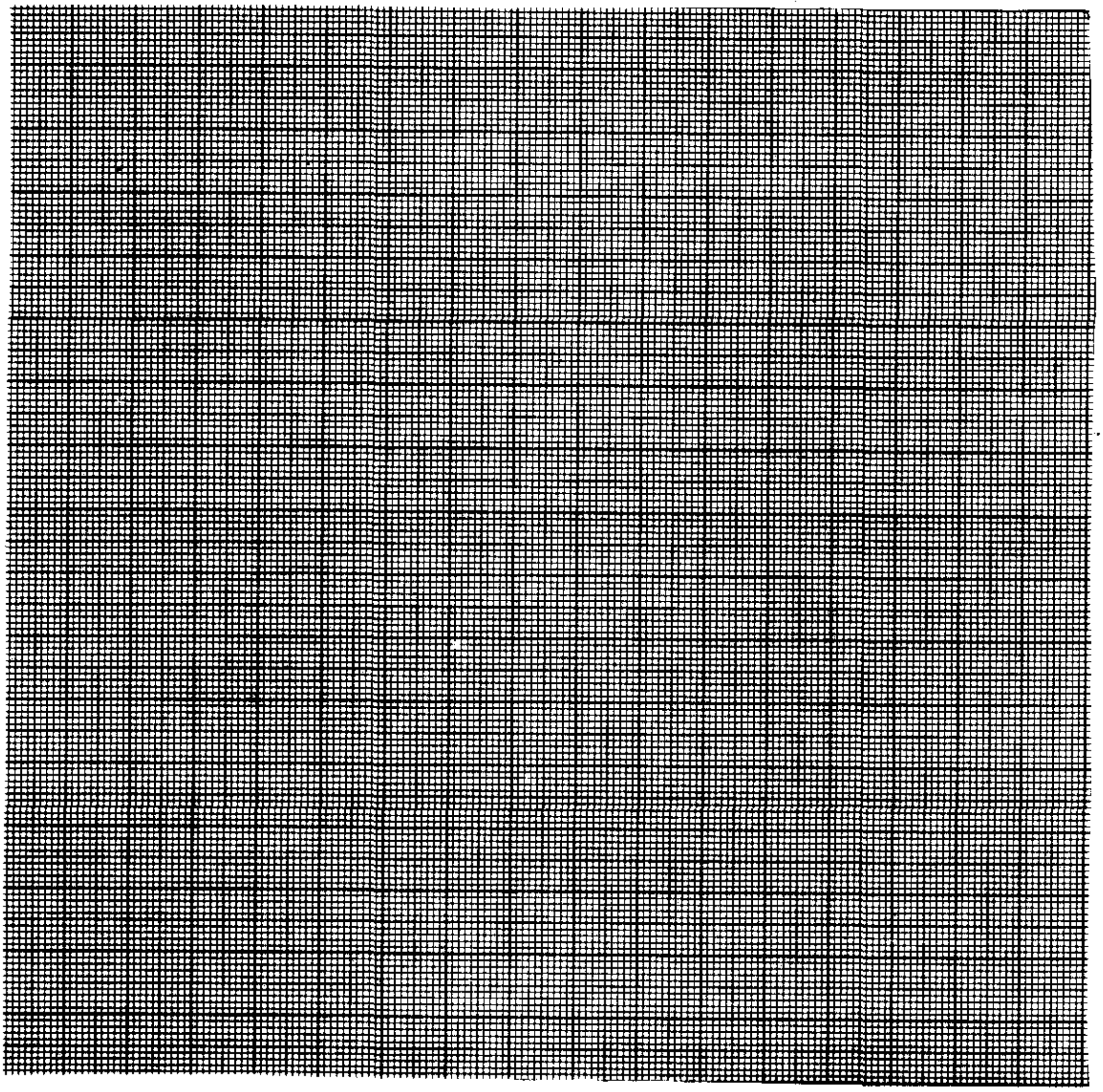
TABLE 2.2a Ranked annual minima for Pang

	Rank i									
	1	2	3	4	5	6	7	8	9	10
1 day minima	63.5	54.6	49.0	39.8	37.0	34.5	32.7	29.1	23.6	11.5
10 day minima	71.4	58.2	50.7	40.4	40.0	40.0	35.9	32.2	25.7	13.4
30 day minima	74.3	60.8	53.2	45.1	42.0	42.0	36.2	33.6	32.8	13.8
60 day minima	79.2	70.1	55.7	49.3	45.9	43.9	41.4	39.5	33.3	16.2
90 day minima	80.9	72.6	58.2	53.8	52.3	51.2	45.4	42.6	33.6	17.7
180 day minima	97.0	83.2	82.1	71.1	65.9	60.2	58.0	51.3	39.8	25.7
P	0.055	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95
$(-\ln P)^{\frac{1}{4}}$	1.3	1.17	1.08	1.01	0.94	0.88	0.81	0.73	0.64	0.49
W	-1.2	-0.68	-0.33	-0.04	0.22	0.48	0.75	1.06	1.44	2.05

Plot the ranked flow against the corresponding Weibull reduced variate W on Figure 2.1b

FIGURE 2.1b FLOW FREQUENCY DIAGRAM FOR FALLOCH, LANGDON, ROMAN

DISCHARGE as % of ADF

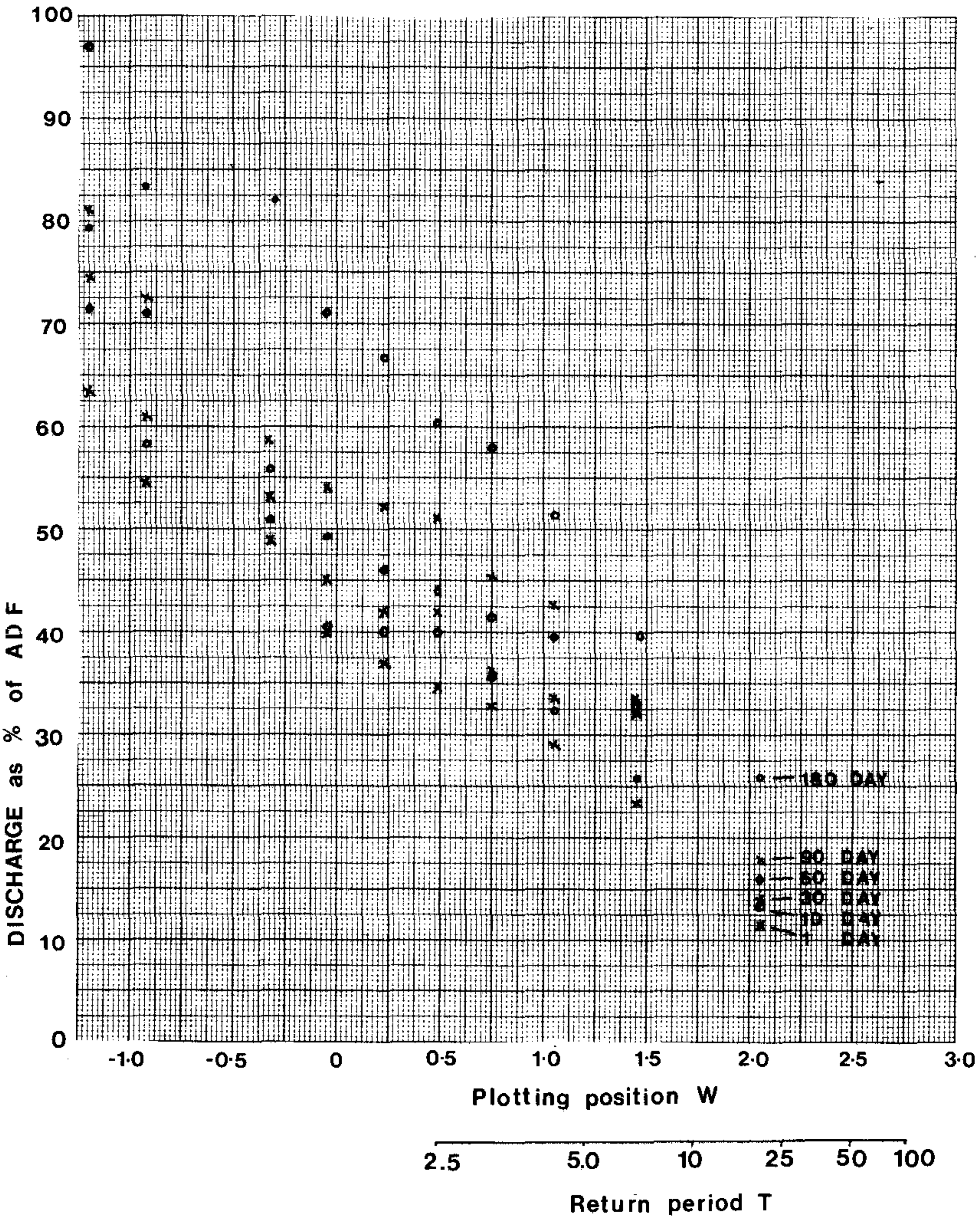


DISCHARGE in CUMECS

Fit by eye, lines through the right most plotted points. Maintain a smooth transition between the slopes of different durations. It will normally be found that the steeper slopes occur with the longer durations.

The ranked flows are plotted against the corresponding W value on Figure 2.1a

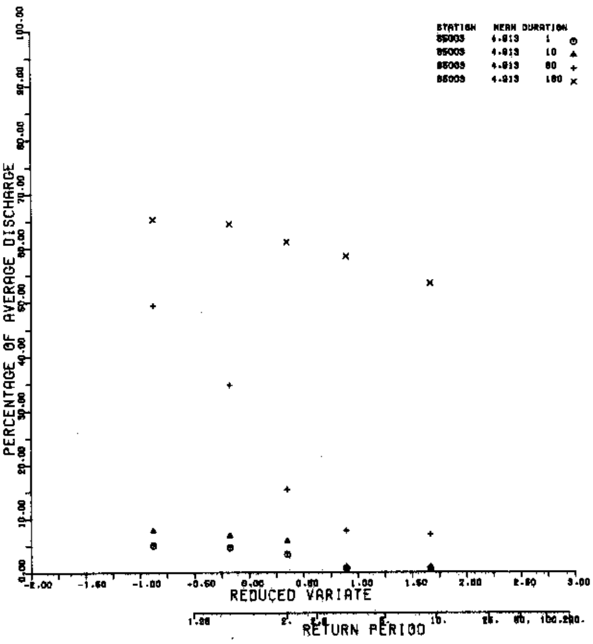
FIGURE 2.1a FLOW FREQUENCY DIAGRAM FOR PANG



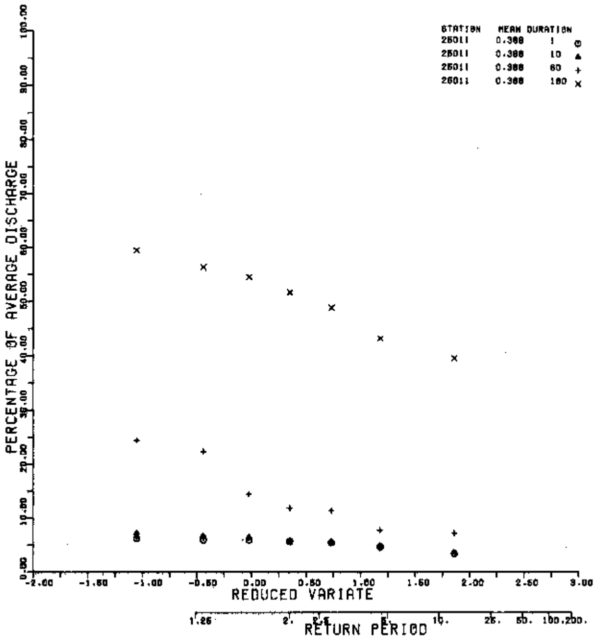
Eye-fitted lines should be sketched through the sets of points bearing in mind the expectation of a smooth transition from one duration to another in terms of slope and position of the line on the paper. It is not normally useful to use the points to the left of the W = 0 point as these commonly describe a much steeper line indicating that they derive from a separate distribution.

2.4 CURVES FOR DIFFERENT DURATIONS

85003 FALLOCH AT GLEN FALLOCH



25011 LANGDON BECK AT LANGDON



37021 ROMAN AT BOUNSTEAD

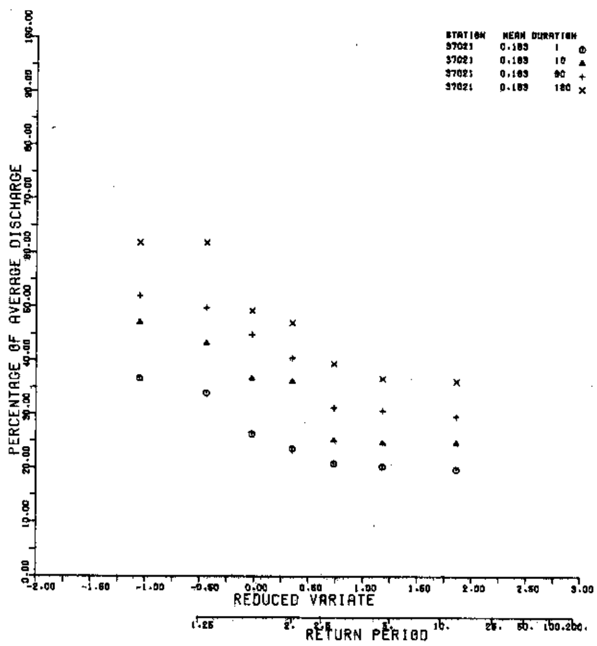


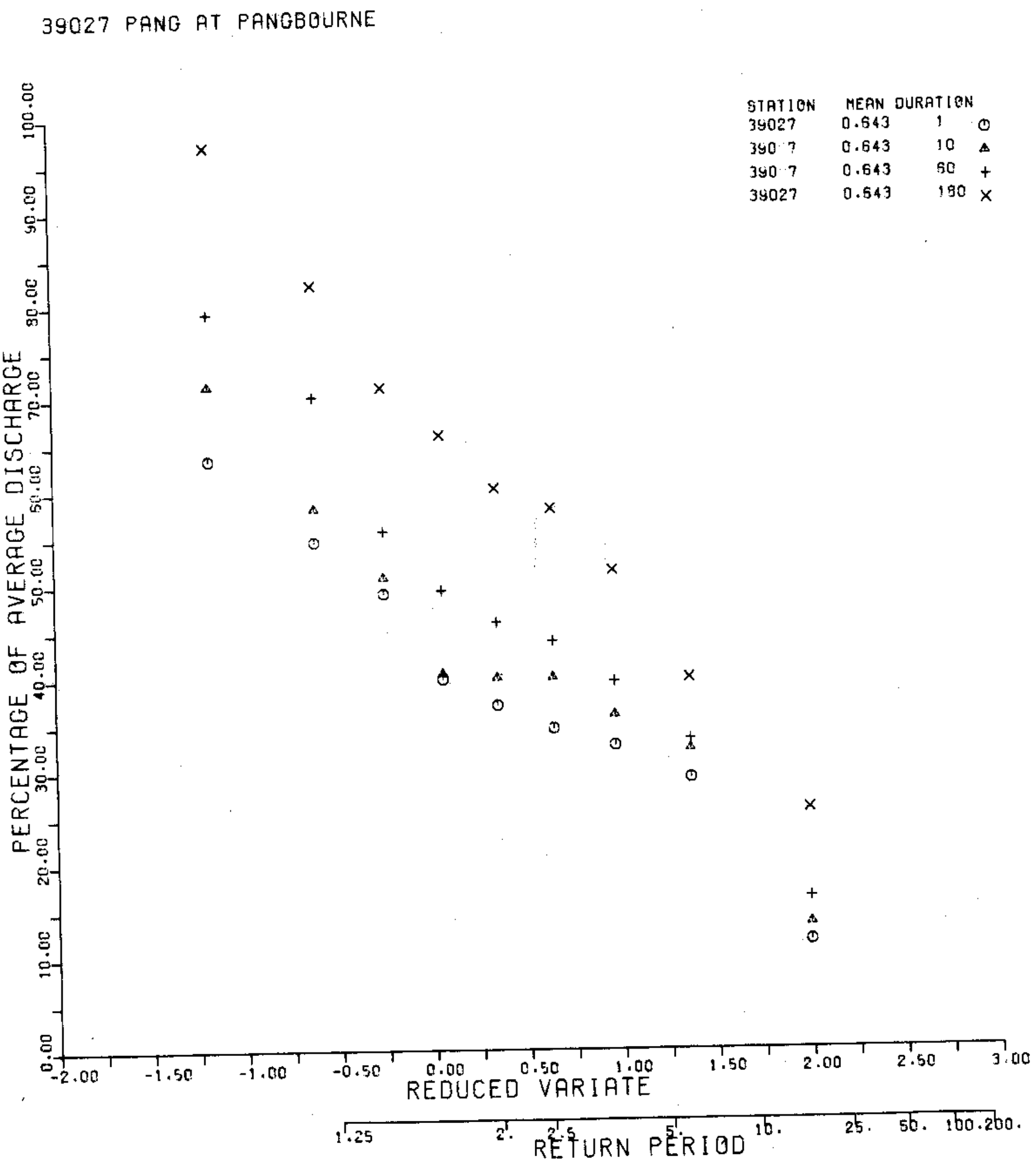
FIGURE 2.2b

FLOW FREQUENCY CURVE FOR FALLOCH, LANGDON, ROMAN FOR DIFFERENT DURATIONS

2.4 CURVES FOR DIFFERENT DURATIONS

The flow frequency curves below and opposite were plotted using the automatic plotting system. It can be seen that there is a considerable difference between curves from different stations and for different durations for the same station. Permeable catchments have frequency curves which differ little between durations whilst flashy catchments have a much greater spacing between their curves. This can best be shown by contrasting the frequency curves of the Falloch and Pang.

FIGURE 2.2a FLOW FREQUENCY CURVE FOR PANG



3.1 INTRODUCTION

The basic steps in the estimation procedure are explained opposite. The flow frequency curve will be estimated using BFI from catchment geology (Report No. 3) to construct the entire curve. Alternative procedures would be to use BFI from 8 months of flow data (Report No. 3, Section 3.1), or calculate MAM(D) from Section 2 of this report and enter the procedure at stage (c) opposite. If the entire D day curve is not required, then steps (c), or (b) and (c) can be omitted as appropriate.

3 The ungauged catchment case

3.1 INTRODUCTION

This section describes how the flow frequency curve of any duration can be estimated at the ungauged site. The method is based on the relationship between the flow frequency curve and catchment characteristics. The latter include catchment rainfall and a baseflowindex (BFI) which can be estimated from catchment geology and are described in Estimation manual No. 3. The method can be used, however, in conjunction with flow data either by using estimates of BFI from data in preference to geology-based estimates, or by using estimates of the mean annual minimum from data and using the Type Curves of Section 3.4.

The procedure for estimating the entire low flow frequency curve for any duration D is divided into the following three components which are illustrated by Figure 3.1.

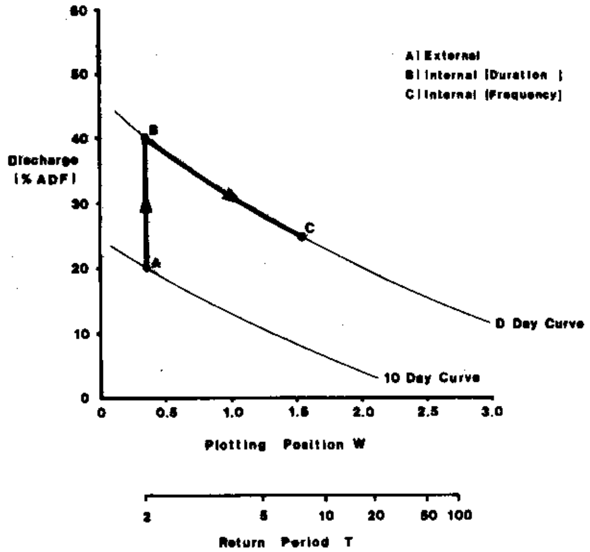


FIGURE 3.1

ESTIMATION PROCEDURE FOR UNGAUGED CASE

(a) estimation of the 10-day mean annual minimum flow expressed as a %ADF, MAM(10) This locates point A on the diagram (where the mean of the annual minimum series plots at a return period of approximately two years) which has a discharge of 20% ADF. This calculation is explained in Section 3.2 and is referred to as the External relationship (with catchment characteristics).

(b) estimation of the mean annual minimum for durations D other than the 10-day duration to give MAM(D). This locates point B on the diagram which in Figure 3.1 has a value of MAM(D) of 40% ADF. This is described in Section 3.3 and is referred to as an Internal duration relationship.

(c) estimation of the annual minimum of other return periods or probabilities to give AMP(D). This locates point C on the diagram which has a value of AMP(D) of 25%. This is described in Section 3.4 and is referred to as an Internal frequency relationship.

If only the mean annual D-day minimum MAM(D) is required, then step (c) can be omitted. Similarly, if only MAM(10) is required, then both steps (b) and (c) can be omitted. The procedure can frequently be entered at step (b) using a value of MAM(D) from data and using the frequency relationship to estimate AMP(D).

3.2 EXTERNAL RELATIONSHIP

The example catchment is in hydrometric area ________ and therefore in regression region ____________. Substituting the catchment characteristic values into the appropriate equation,

$$\sqrt{MAM(10)} = \_\_\_\_\_\_\_\_ \sqrt{\quad\quad} + \_\_\_\_\_\_\_\_ \sqrt{\quad\quad} - \_\_\_\_\_\_\_\_$$

MAM(10) = *% ADF*

3.2 EXTERNAL RELATIONSHIP

Table 3.1 shows the regression equation used in the various regions of the country shown in Figure 3.2. The equation gives an estimate of the ten day mean annual minimum, MAM(10), in units of %ADF. SAAR is the 1941-70 standard annual average rainfall in mm and BFI is the catchment's base flow index which is estimated at the ungauged site from catchment geology. This is explained in Sections 2.5 and 3 of Report No. 3.

TABLE 3.1 **Regional estimation equations for 10 day mean annual minima**

Region	Hydrometric area	Equation $\sqrt{MAM(10)}$ =
1	1-19, 84-97, 104-108	$8.50 \sqrt{BFI} - 1.22$
2	20-25, 27, 68-83, 103	$8.50 \sqrt{BFI} - 1.57$
3	45-67, 102, 201-223	$8.50 \sqrt{BFI} - 2.01$
4	26, 28-33	$11.2 \sqrt{BFI} + .0982 \sqrt{SAAR} - 6.81$
5	34-44, 101	$9.69 \sqrt{BFI} - 2.58$

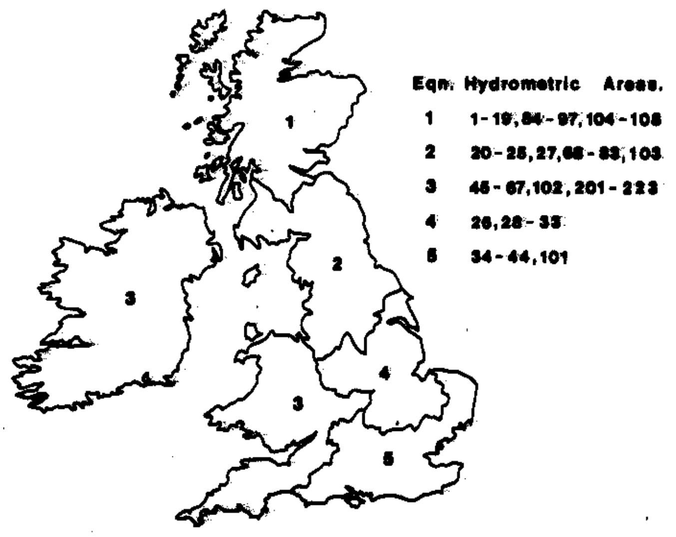


FIGURE 3.2 ESTIMATION EQUATIONS TO USE IN DIFFERENT REGIONS

The Pang is located within hydrometric area 39, therefore use the regression equation given for region 5 and a BFI of 0.90 estimated from the geology of the catchment (Report No. 3)

$$\sqrt{MAM(10)} = 9.69 \sqrt{BFI} - 2.58$$

$$= 6.61$$

$$MAM(10) = 43.73 \text{ \% ADF}$$

3.3 INTERNAL RELATIONSHIP (DURATION)

For the _________ *catchment SAAR =* _______ *and MAM(10) =* _______*, therefore:*

$\log_{10}$GRADMAM = ______$\sqrt{\quad}$ - ______ $\sqrt{\quad}$ - ______

= _______

GRADMAM = ______

The following can be completed using the MAM(D) expression opposite

D	1	10	30	60	90	180	
1+(D-10)GRADMAM	___	___	___	___	___	___	
MAM(D)	___	___	___	___	___	___	% ADF

3.4 INTERNAL RELATIONSHIP (FREQUENCY)

For the ________*catchment, MAM(10) is* ______*%ADF so the following type curves are read from Table 3.2 for the various durations.*

D	1	10	30	60	90	180
Type curve	___	___	___	___	___	___

3.3 INTERNAL RELATIONSHIP (DURATION)

Having estimated the value of MAM(10) the next step (if required) is to estimate the mean annual minimum for the duration of interest. This process of obtaining MAM(D) from MAM(10) is in two steps: The first is to obtain the gradient or rate of change of MAM(D)/MAM(10) with D,(GRADMAM); the second is to use this gradient to calculate MAM(D).

The gradient is obtained from the regression:

$$\log_{10}(\text{GRADMAM}) = 0.00842\sqrt{\text{SAAR}} - 0.137\sqrt{\text{MAM(10)}} - 1.61$$

For the Pang:

SAAR = 722, MAM(10) from Section 3.1 is 43·73 % ADF

GRADMAM = 0·005132

The variable GRADMAM is then substituted into the equation:

$$\text{MAM(D)} = \{1 + (\text{D}-10).\text{GRADMAM}\}\text{MAM(10)}$$

to give the value of MAM(D) for any required duration, D, in % ADF units which for the Pang gives the following values of MAM(D):

	1	10	30	60	90	180	
MAM(D)	41·71	43·73	48·218	54·95	61·684	81·882	% ADF

3.4 INTERNAL RELATIONSHIP (FREQUENCY)

The process of obtaining the low flow of any return period consists of multiplying the mean annual minimum by a factor that is read off a particular type curve. Table 3.2 enables the type curve to be found for the particular duration D and value of MAM(10). For the Pang the following values are found.

D	1	10	30	60	90	180
Type curve	10	9	8	7	6	5

Factors to be applied to MAM(D) are read from Figure 3.3 and entered on the table below:

Return period		*Duration days* 1	10	30	60	90	180
2.5	*Factor*						
	% ADF						
5	*Factor*						
	% ADF						
10	*Factor*						
	% ADF						
25	*Factor*						
	% ADF						
50	*Factor*						
	% ADF						
100	*Factor*						
	% ADF						

Plot these points on Figure 3.4 overleaf.

TABLE 3.2 **Curve number for required duration and 10 day mean annual minima**

MAM(10) as percentage of average daily flow	Duration D in days: 1	10	30	60	90	180
5	1	1	1	1	2	3
10	2	2	2	2	2	3
15	4	4	3	2	2	4
20	5	5	3	2	2	4
25	6	6	4	2	3	5
30	8	8	6	4	4	5
40	10	9	8	6	6	5
50	10	10	9	8	7	6
60	10	10	10	9	8	7

FIGURE 3.3 **FLOW FREQUENCY TYPE CURVES**

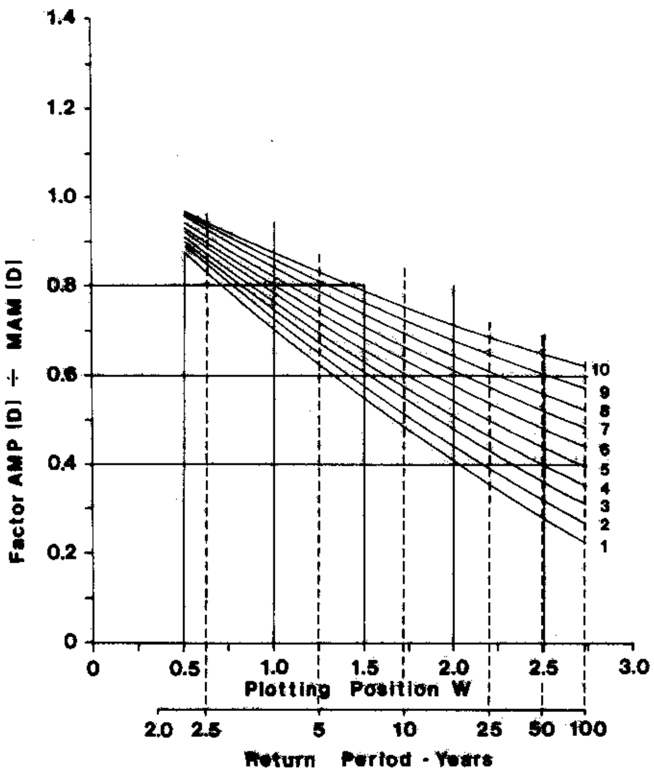


Figure 3.3 shows a family of standardised type flow frequency curves which enable the discharge of any return period AMP(D) to be estimated from the mean annual minimum MAM(D).

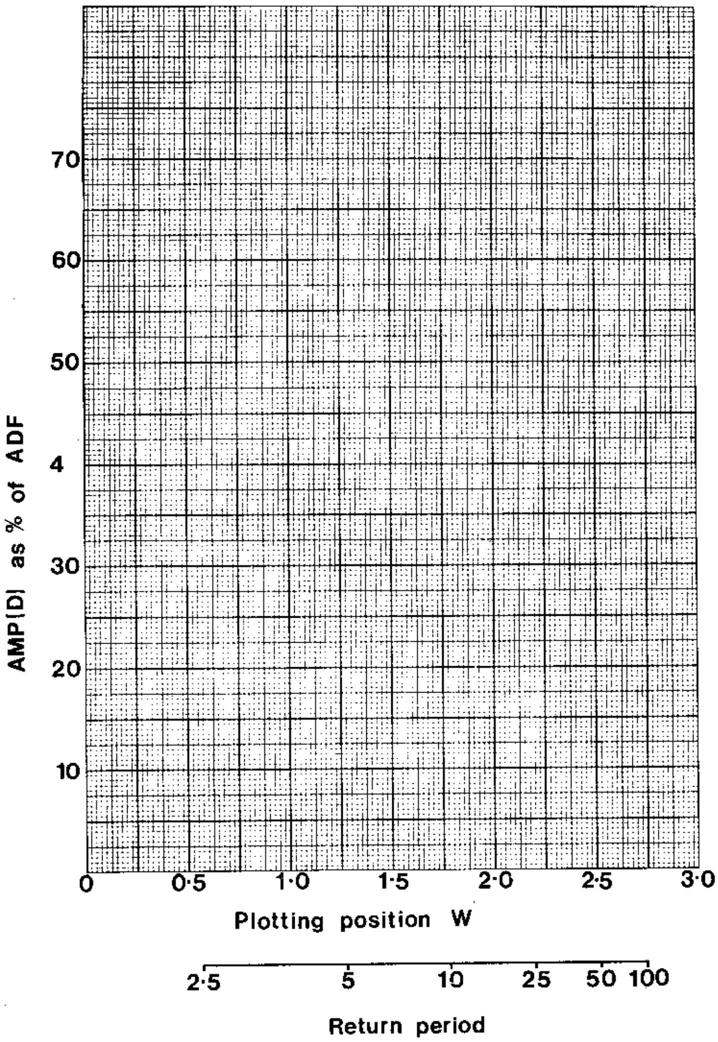


FIGURE 3.4b FLOW FREQUENCY CURVE FOR FALLOCH, LANGDON, ROMAN FROM CATCHMENT CHARACTERISTICS

3.5 CONVERTING TO ABSOLUTE UNITS

Using Report No. 3 calculate the average flow (ADF) from rainfall and evaporation data. Label Figure 3.4b in cumec units.

Factors are read from Figure 3.3, eg for D = 60 days for which Type Curve 7 is appropriate, the following factors and hence AMP(D) values were obtained:

Return period	2.5	5	10	25	50	100
Factor	0.92	0.75	0.66	0.57	0.52	0.47
AMP(60) % ADF	50.55	41.21	36.27	31.32	28.57	25.83

These values are plotted as shown on Figure 3.4a

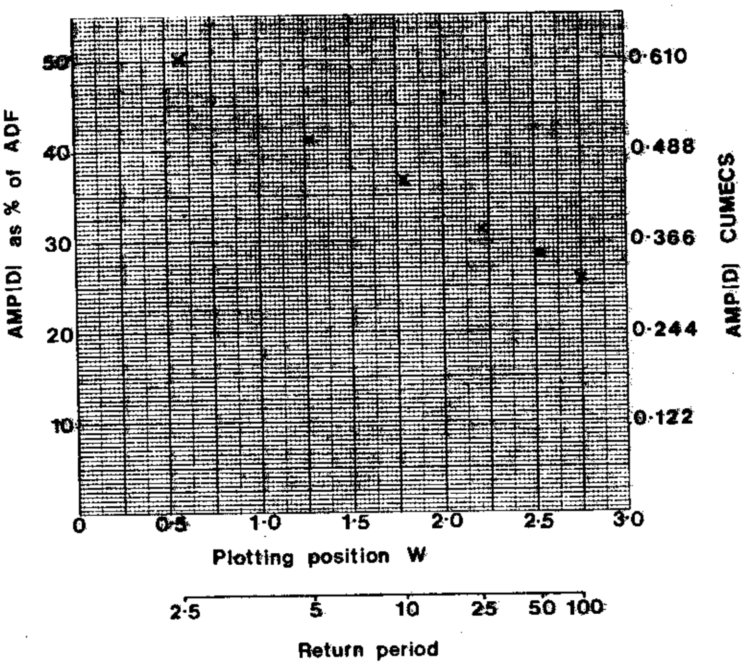


FIGURE 3.4a **FLOW FREQUENCY CURVE FOR PANG FOR D = 60 DAYS FROM CATCHMENT CHARACTERISTICS**

3.5 CONVERTING TO ABSOLUTE UNITS

Each step of the estimation procedure expresses discharge in terms of the % ADF. The final stage in the estimation procedure requires the estimation of the average discharge to the site of interest. A number of different techniques for doing this are described in Report No. 3; they are based on one of two approaches. The first uses rainfall and evaporation data, the second is based on recorded flow data at or near the site of interest.

From Report No. 3, the average flow for the Pang estimated from catchment characteristics is 1.22 cumecs. The scale of figure 3.4a is then calibrated in cumecs where, 100% ADF = 1.22 cumecs, 10% ADF = 0.122 cumecs, etc.

4.1 USING RELATIONSHIP BETWEEN THE FLOW DURATION CURVE AND FLOW FREQUENCY CURVE

Values of Q95(1) have been obtained for each of the example catchments as follows:

________ *(F)* __________ *(L)* ____________ *(R)* *% ADF*

The first step is to convert these to Q95(10) values.

$\log_{10}$ *GRADQ95* =

GRADQ95 =

Q95(10) = __________

The second step is the linking relationship between the flow duration and flow frequency curves.

MAM(10) =

= *% ADF*

As a check on the results, Figure 4.1 may be used. This is an overall average and omits the effect of climate. The value obtained from Figure 4.1 is ________ *% ADF.*

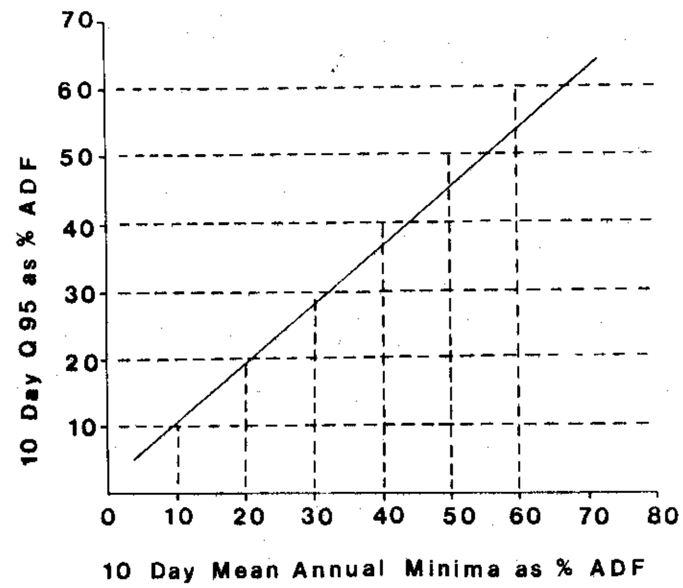


FIGURE 4.1 APPROXIMATE FLOW DURATION : FLOW FREQUENCY RELATION

4 Use of local data

In this chapter a number of methods of incorporating short or discontinuous data sources are demonstrated.

4.1 USING RELATIONSHIP BETWEEN THE FLOW DURATION CURVE AND FLOW FREQUENCY CURVE

If the flow duration curve has previously been obtained, perhaps from current meterings (see Section 4.2) or from a period of record that is too short to enable the flow frequency curve to be estimated adequately, the following linking relationship between the 95 percentile from the 10 day flow duration curve Q95(10) and the 10-day mean annual minima, MAM(10) can be used:

$$\sqrt{MAM(10)} = 1.07\sqrt{Q95(10)} - .0320\sqrt{SAAR} + .741$$

As this relationship has been established between the 10 day duration statistics, it may initially be necessary to convert from the 1 day to the 10 day flow duration curve. For the Pang, a value of 43.65% ADF had previously been found for Q95(1). Using principles from the Flow duration curve manual, 2.1 , Section 3.3, the following relationships are used:

$$Q95(10) = Q95(1)/\{1-9 \times GRADQ95\}$$

where $\log_{10}GRADQ95 = .0230\sqrt{SAAR} - .204\sqrt{Q95(1)} - 2.11$

This is an adequate approximation for present purposes.

For the Pang:

$$\log_{10}GRADQ95 = .023\sqrt{722} - .204\sqrt{43.65} - 2.11 = -2.8398$$

$$GRADQ95 = 0.001446$$

$$Q95(10) = 44.23 \text{ \% ADF}$$

Substituting this value of Q95(10) in the above equation for the Pang, gives:

$$MAM(10) = 48.31 \text{ \% ADF}$$

From this point on the internal relationships of Section 3.3 and 3.4 are used to obtain annual minima of other durations and frequencies.

4.2 USE OF CURRENT METERINGS

1. Use the current meterings as described in Report 2.1, Section 4, to obtain an estimate of Q95(1).

2. Use the method of Section 4.1 to obtain the flow frequency curve from the flow duration curve.

4.3 USE OF A SHORT PERIOD OF CONTINUOUS DATA

One year or less

Establish a correlation between the daily discharges of the station of interest (Q_I), and a long term analogue station (Q_A). If, for example,

$$Q_I = a + b\ Q_A$$

where a and b can be estimated from the common period of record, to every Q_A value there corresponds a Q_I value. The method consists simply of relabelling the flow axis of the analogue catchment's flow frequency curve.

One year of record

Use section 3.1 of Report No. 3, to obtain BFI thus by-passing the need for a geology map-based estimate. Then use the procedure of Section 3.

Two years of record

Obtain the flow duration curve standardised by the short period ADF (Section 2 of Report 2.1). Use the method of Section 4.1 to convert to flow frequency curve.

Greater than two years

Calculate MAM(D) from data and use the type curves of section 3.4. Express data as % ADF if less than 10 years, but directly in cumecs for longer flow records. When more than 10 years of data are available the minima can be plotted and compared with the type curves.

4.4 USE OF MONTHLY DATA

The example cases have between 5 and 10 years of record. Monthly data can be used to obtain MAM(1 month) and thus MAM(45 days).

4.2 USE OF CURRENT METERINGS

A method entirely analogous to that described for the flow duration curve is not possible because the likely span of frequencies on the current metering days is likely to be very narrow. The method recommended here is to use the current meterings, firstly to obtain an improved estimate of the flow duration curve (see Section 4 of Report 2.1). Having obtained estimates of Q95(1) the linking relationship between flow duration and flow frequency curves may be used (see Section 4.1 of this report).

4.3 USE OF A SHORT PERIOD OF CONTINUOUS DATA

A correlation between two records, one with one year or less data, the other a long term analogue catchment (ie, similar BFI), can be established. The correlation can be expressed graphically or by means of regression. The flow frequency curve of the analogue station can then be 'relabelled' using the equivalent flows of the short period station from the correlation.

One year's data are best used to refine the Base Flow Index estimate. An example of its use is given in the Catchment Characteristic estimation manual, Report No. 3, Section 3.1.

Two years' data are sufficient to obtain a flow duration curve, at least in terms of % ADF. The method is described in Section 2 of Report 2.1. The method of Section 4.1 can be used to convert to the flow frequency curve and a long term ADF estimate used to convert from % ADF to discharge units.

If between 2 and 10 years of data are available, it is recommended to use these data to estimate MAM(D) and then to use the type curves of Section 3.4 for the frequency relationship. Between 10 and 20 years of data, MAM(D) can be calculated in cumecs and used together with the type curves and compared with a plot of the raw data.

4.4 USE OF MONTHLY DATA

Monthly runoff values can be used where daily flow data are not available or reliable. Use can be made of the monthly flow data to obtain flow frequency curves if 20 years or more data are available, or a mean annual minimum MAM(1 month) in cumecs if 10 years or more are available. If less than 10 years are available, MAM(1 month) expressed as % ADF is more reliable. Type curves can be used for the frequency relationship when the record is less than 20 years.

In all cases the relationship between monthly-based and daily-based statistics is used. This takes account of the fact that daily data give the opportunity to find lower minima in any year than calendar month data. A study showed that the monthly mean annual minima is equal to the D day annual minima where D is 15 days longer than the number of days in monthly based statistics.

Thus the mean annual minimum 1 month data is equivalent to the mean annual minimum 45 days data and similarly for other durations.

MAM(1 month) = MAM(45)

MAM(3 month) = MAM(107)

For the Pang:

MAM(1 month) = 49.44 % ADF ∴ MAM(45) = 49.44 % ADF