LOW FLOW STUDIES

REPORT No. 2. 3

RUNOFF ACCUMULATION TIME: DESCRIPTION AND ESTIMATION MANUAL

PREFACE

This report describes the procedure for estimating runoff accumulation times on 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	*Low flow estimation in Scotland*

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 contains the results of a low flow study of Scottish rivers, commissioned by the Scottish Development Department.

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LIST OF SYMBOLS AND ABBREVIATIONS

ARV	annual runoff volume
ADF	average flow in cumecs
BFI	base flow index
SAAR	standard period (1941 - 1970) annual average rainfall
Q95(10)	10 day average flow exceeded by 95% of 10 day average discharges
MCM	Million cubic metres
P	non exceedance probability in %
p	non exceedance probability as fraction

INTRODUCTION AND SUMMARY

The time required to accumulate a given volume of water at a point on a river is of interest for several reasons. One of the most obvious applications concerns reservoir filling. A depleted reservoir (or indeed a newly constructed reservoir) will take time to fill and a knowledge of how long filling may take is helpful when deciding whether to allow it to fill naturally or to use artificial means. The results and methods given in this report equally apply to other water resource planning problems. For example, the operating rule for water resource systems e.g. the conjunctive use of surface and groundwater supplies, are based principally upon the probabilities of specified volumes of water being available at different times of the year. Typical practical circumstances where the information presented in this manual would apply are quoted in Sections 1.3 and 1.5.

The following brief orientation to the runoff accumulation time curves may assist the reader in assimilating a rather complex quantity. Some of the difficulty may be removed by emphasising that the variable of interest is a TIME; in fact the time required to accumulate a given volume of runoff. It will be found convenient to express runoff volume in terms of the annual average runoff volume (ARV). For example the expected time to accumulate the annual runoff volume (100% ARV) is one year but in a dry year it will take longer than 365 days whilst in wet years this volume will be accumulated in a shorter time. The frequency of exceeding or not exceeding some threshold accumulation time is, in essence, the object of this manual.

While it is relatively simple to understand runoff accumulation times for a volume of 100% ARV (or indeed 200% or 300% ARV) the situation with fractions of ARV merits some further explanation. Let us consider the accumulation time for 50% ARV. An initial estimate for this would be 6 months, however, the 6 month period April to September on average produces much less runoff than 50% ARV and in consequence the average accumulation time starting in April is much longer than 6 months. For an October start when the runoff occurs during the wet winter period the expected accumulation time for 50% ARV will be less than 6 months. The shape of the curve; runoff accumulation time versus start month appears sinusoidal. The details of the curve i.e. the position of its maximum, its amplitude and asymmetry, and variation from catchment to catchment is the subject of this manual. As well as treating average accumulation times, results of the probability distribution of larger or shorter accumulation times are presented.

Section 2 of this manual describes how the runoff accumulation times for a given start month and probability of occurrence can be estimated from flow data. Section 3 outlines techniques for achieving the same goal in the case where there are no data available, by utilising a knowledge of a catchment's physical and climatological characteristics.

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. It will of course be realised that the positioning of hypothetical reservoirs, abstractions etc at points on the example rivers is purely illustrative and carries no implication for the suitability or otherwise of these streams for water resource exploitation.

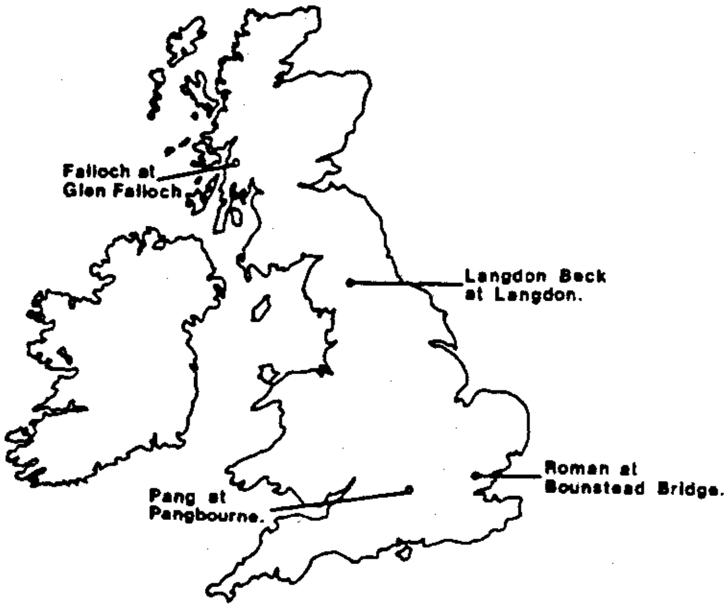

FIGURE 1.1 LOCATION OF ALL THE EXAMPLE CATCHMENTS

1.1 GENERAL INFORMATION

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 if 80.3 km² which includes the Dubh Eas catchment.*

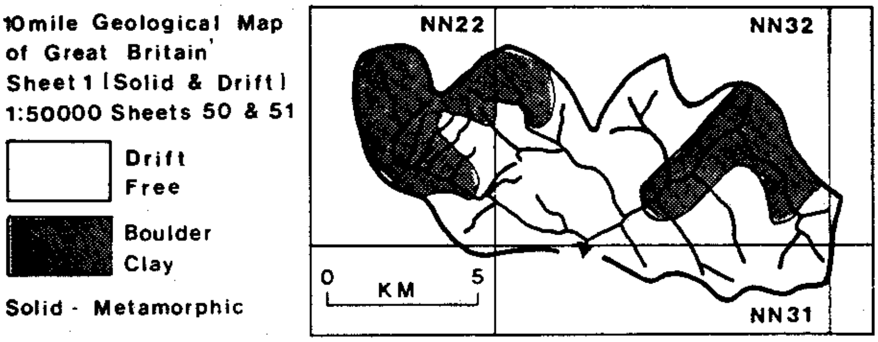

FIGURE 1.2b GEOLOGY AND KEY TO MAPS OF THE FALLOCH CATCHMENT

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

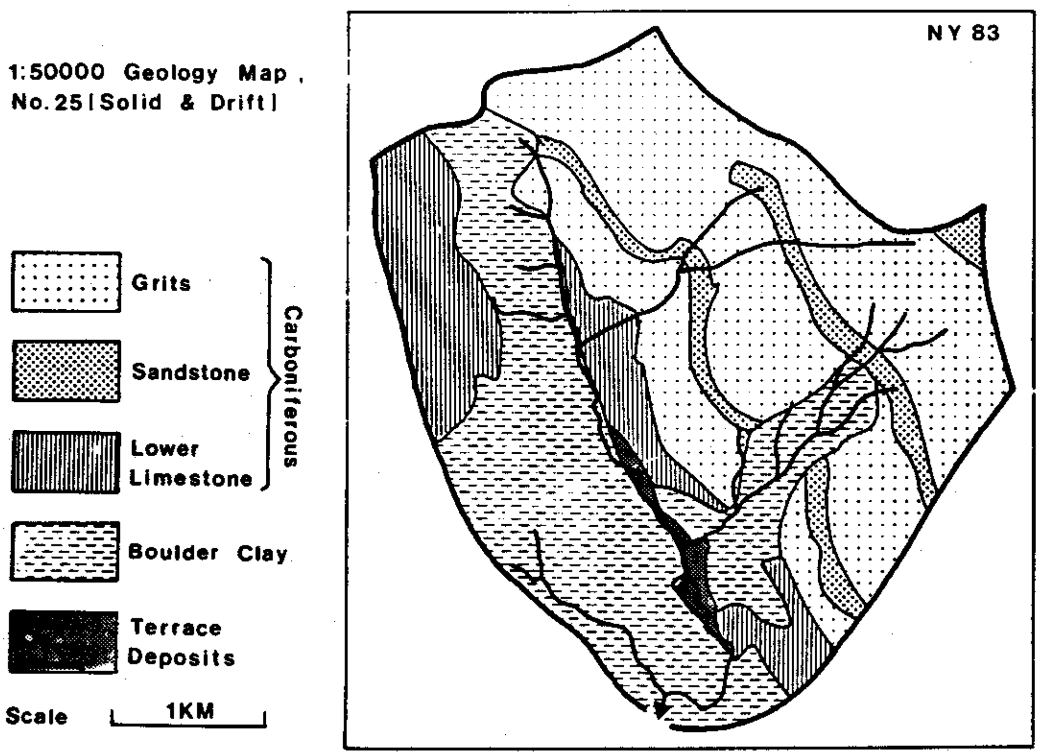

FIGURE 1.2c GEOLOGY AND KEY TO MAPS OF THE LANGDON CATCHMENT

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.

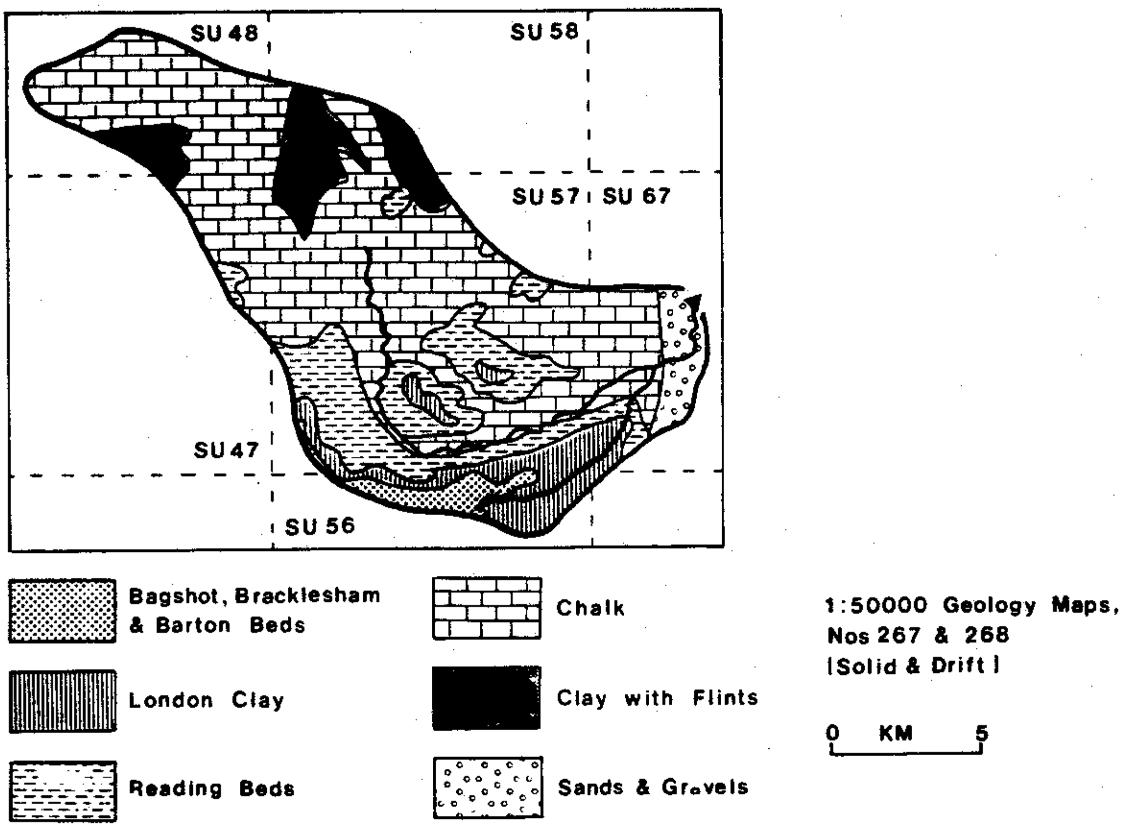

FIGURE 1.2a GEOLOGY AND KEY TO MAPS OF THE PANG CATCHMENT

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.

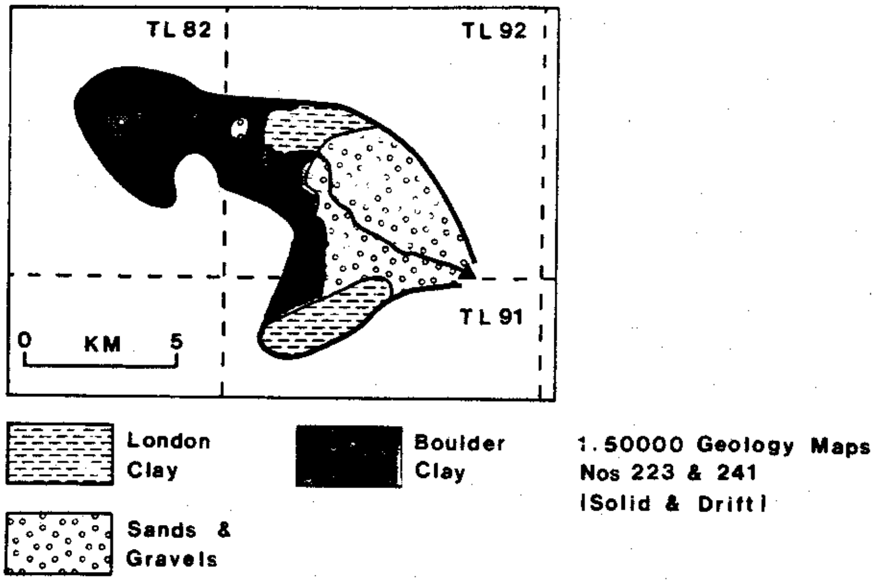

FIGURE 1.2d GEOLOGY AND KEY TO MAPS OF THE ROMAN CATCHMENT

1.2 FLOW DATA FOR CONSTRUCTING THE RUNOFF ACCUMULATION TIME CURVE

Tables 1.1b, c and d contain the daily flow data from which the times to accumulate 25% starting on the 1st of each month, can be determined. These times are then inserted into tables 2.1b.

TABLE 1.1b

05003 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	1.490	.669	2.925	3.361	4.555	12.784	2.178	18.490	1.876
2	.627	16.031	3.171	1.208	.573	2.243	3.121	5.867	9.575	1.660	7.093	1.056
3	.988	6.465	2.039	.982	.491	1.783	2.711	2.063	3.498	1.179	20.051	16.939
4	.647	2.730	1.482	.961	.425	1.476	8.262	2.603	3.263	.897	9.466	6.059
5	.389	1.708	2.966	.981	.372	1.276	3.306	4.396	1.424	2.440	4.971	1.559
6	41.633	1.582	2.796	.853	3.263	1.135	2.548	5.882	1.005	9.883	9.338	1.169
7	28.491	1.738	1.951	.763	6.055	1.019	1.385	4.221	.787	7.270	19.247	1.073
8	11.116	1.848	1.435	.678	3.753	.933	1.195	4.921	.619	7.257	5.406	3.892
9	51.426	2.523	1.681	.889	3.136	.898	1.098	3.627	.507	13.704	2.038	7.993
10	4.051	7.581	1.304	.581	2.896	.859	.927	1.879	.423	60.302	2.424	2.777
11	1.949	11.962	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	1.838	1.486	.988	.971	.361	3.071	3.171	11.906
13	1.229	7.363	4.281	.498	1.414	1.182	.816	1.119	.331	1.754	2.836	4.407
14	1.113	10.356	2.059	.468	1.218	1.066	.843	.759	.692	1.322	2.828	13.988
15	1.065	3.921	1.405	.465	3.143	.978	.993	.550	.712	20.526	28.448	6.176
16	1.818	2.257	1.128	.986	7.515	.948	.812	.478	.561	8.682	4.321	3.120
17	5.371	2.528	.944	6.186	5.869	.889	.705	.423	1.705	30.352	3.418	2.606
18	10.682	2.136	.784	4.386	3.361	.829	.472	.363	1.167	11.888	1.862	24.959
19	17.318	9.864	.739	2.433	2.553	.787	.872	.315	1.496	17.033	1.288	20.524
20	7.278	18.816	.693	1.362	2.296	.769	.736	.281	1.816	10.569	1.458	49.229
21	7.508	5.244	.618	1.124	1.897	6.382	1.736	.261	2.528	88.025	1.329	18.638
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	12.816	3.235	24.465	7.228	2.424	3.409	.306	1.684	7.383	2.759	14.976
24	22.228	5.053	12.195	3.987	4.728	8.844	4.176	.337	.942	6.161	6.002	5.337
25	13.288	3.247	5.693	1.553	2.865	10.823	11.187	.313	.685	2.318	6.906	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	11.229	4.968	6.141	1.816	1.335	7.889	2.795
28	2.513	8.881	9.884	.696	4.721	4.841	2.593	8.673	1.607	1.899	2.479	1.253
29	2.241		8.268	.823	3.968	3.212	1.861	3.235	5.329	1.189	6.203	.913
30	1.536		2.481	.896	16.655	2.715	1.432	12.128	4.268	4.404	2.854	.661
31	1.179		1.708		4.298		16.567	14.832		4.483		.573

1.2 FLOW DATA FOR CONSTRUCTING THE RUNOFF ACCUMULATION TIME CURVE

TABLE 1.1a

39027 PANG AT PANGBOURNE

YEAR 1976 NUMBER OF DAYS WITH DATA= 365 MEAN= .517 MINIMUM = .210 MAXIMUM = 1.550 (CUMECS)

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	.422	.883	.733	.665	.596	.666	.398	.318	.277	.223	.248	.758
2	.426	.941	.737	.633	.577	.439	.357	.278	.309	.214	.292	.691
3	.421	.879	.711	.637	.580	.449	.350	.286	.278	.227	.341	.672
4	.398	.851	.818	.630	.502	.468	.359	.281	.308	.226	.264	.627
5	.389	.797	.765	.657	.588	.468	.347	.298	.289	.247	.269	.696
6	.395	.756	.768	.777	.568	.431	.341	.317	.314	.259	.238	.685
7	.384	.776	.788	.724	.628	.426	.312	.323	.261	.244	.443	.832
8	.379	.781	.759	.690	.572	.404	.371	.313	.287	.233	.368	.583
9	.593	.805	.788	.675	.619	.424	.347	.316	.348	.262	.279	.583
10	.775	.729	.698	.669	.634	.420	.332	.319	.282	.232	.276	.578
11	1.028	.786	.978	.693	.608	.431	.335	.315	.293	.229	.274	.591
12	.748	.813	.987	.863	.641	.414	.316	.305	.308	.232	.355	.534
13	.638	.769	.859	.806	.624	.407	.308	.296	.322	.232	.331	.552
14	.988	.788	.798	.748	.593	.367	.359	.299	.294	.246	.768	.538
15	.748	.867	.734	.715	.596	.387	.354	.328	.312	.238	.647	.511
16	.788	.673	.741	.786	.563	.389	.352	.313	.278	.232	.499	.582
17	.628	.879	.745	.735	.564	.403	.359	.291	.263	.229	.539	.568
18	.657	.967	.759	.718	.545	.408	.348	.381	.270	.259	.791	.585
19	.633	1.088	.697	.689	.581	.382	.379	.427	.268	.210	.926	.494
20	.628	.975	.708	.669	.586	.378	.355	.384	.268	.232	.863	.486
21	.665	1.040	.896	.692	.528	.355	.347	.359	.258	.232	.571	.479
22	.784	1.048	.686	.672	.536	.411	.348	.349	.259	.238	.586	.473
23	1.550	.962	.732	.644	.418	.391	.348	.368	.268	.237	1.898	.481
24	1.188	.858	.734	.615	.487	.443	.357	.348	.268	.224	.708	.477
25	.937	.806	.692	.669	.468	.379	.352	.328	.261	.275	.626	.465
26	.998	.761	.678	.647	.538	.373	.358	.318	.268	.225	.532	.468
27	.828	.748	.638	.622	.491	.378	.333	.315	.271	.221	.518	.461
28	.786	.731	.648	.622	.517	.359	.349	.311	.257	.221	.555	.476
29	.856		.658	.685	.486	.358	.348	.306	.247	.249	1.468	.506
30	1.288		.669	.687	.475	.378	.328	.293	.236	.213	.971	.639
31	.916		.678		.485		.291	.288		.221		.846

TABLE 1.1c

25011 LANGDON BECK LANGDON

YEAR 1971 NUMBER OF DAYS WITH DATA= 365 MEAN= .132 MINIMUM = .024 MAXIMUM = 6.252 (CUMECS)

DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	.185	.098	.100	.104	.067	.040	.122	.120	.128	.031	.065	.124
2	.128	.252	.143	.096	.059	.033	.079	.184	.186	.030	.069	.114
3	.221	.410	.109	.095	.051	.031	.059	.823	.204	.030	.073	.123
4	.182	.171	.100	.101	.046	.030	.053	1.297	.134	.032	.544	.191
5	.188	.135	.101	.128	.048	.031	.045	.436	.088	.030	1.067	.133
6	2.292	.118	.199	.180	.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	.841	.082	.058	.045	.033	.588	.048	.034	.477	.127
9	.958	.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	.057	.029	.131	.030	.136	.132	.080
12	.132	4.861	.268	.048	.048	.266	.028	.109	.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	3.758	.038	.055	.096	.288
15	.118	.422	.210	.041	.034	.096	.025	.460	.040	.102	.100	.202
16	.101	.242	.147	.049	.036	.331	.025	.208	.034	.357	.144	.162
17	.098	.184	.226	.047	.037	.161	.024	.136	.035	1.273	1.114	.151
18	.618	.452	2.194	.045	.038	.259	.024	.096	.033	3.435	.348	.140
19	1.088	.678	2.331	.039	.233	.054	.025	.075	.032	2.696	.154	1.367
20	.657	1.851	1.037	.038	.033	.928	.026	.060	.031	.742	.364	.501
21	2.053	.605	.954	.035	.038	.037	.034	.052	.030	.965	.697	.282
22	.372	.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	.148	.094	.193	.046	.030	.175	.798	.136
25	.894	.162	.468	.328	.087	.094	.376	.041	.029	.136	2.559	.136
26	.348	.128	.440	.188	.051	.138	.215	.038	.034	.110	.501	.118
27	.411	.111	.262	.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	.034	.077	.138	.099
31	.137		.115		.058		.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	.538	.678	.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	.198	.143	.099	.109	.154	.090	.092	.100	.121
4	.327	.420	.303	.194	.148	.097	.108	.106	.090	.092	.098	.146
5	.192	.461	.278	.183	.137	.104	.103	.153	.098	.093	.128	.143
6	.238	.305	.275	.180	.134	.106	.104	.107	.089	.089	.115	.152
7	.836	.362	.258	.176	.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	.148	.103	.089	.100	.083	.090	.102	.139
10	.463	.332	.220	.192	.142	.172	.084	.110	.085	.095	.101	.133
11	.422	.314	.224	.161	.133	.138	.082	.100	.098	.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	.298	.228	.168	.117	.446	.091	.111	.089	.088	.102	.125
15	.305	.281	.235	.166	.148	.290	.088	.098	.087	.108	.095	.123
16	.252	.284	.228	.183	.166	.125	.183	.094	.085	.120	.104	.123
17	.252	.380	.257	.165	.142	.141	.067	.092	.085	.148	.100	.121
18	.891	.507	.371	.160	.134	.253	.087	.093	.086	.133	.175	.119
19	.446	.449	.355	.158	.124	.299	.092	.095	.082	.127	.132	.177
20	.544	.434	.358	.158	.119	.467	.088	.159	.087	.077	.178	.148
21	.816	.484	.356	.155	.115	.253	.096	.131	.085	.107	.278	.137
22	.798	.364	.366	.153	.122	.123	.097	.114	.085	.104	.226	.165
23	1.879	.386	.221	.275	.133	.141	.096	.118	.098	.101	.216	.249
24	1.518	.307	.268	.232	.132	.132	.099	.103	.182	.101	.183	.203
25	1.067	.267	.254	.252	.167	.124	.117	.097	.091	.099	.161	.171
26	1.398	.234	.245	.225	.161	.164	.183	.108	.187	.108	.186	.161
27	1.408	.246	.221	.161	.151	.073	.182	.093	.149	.097	.179	.169
28	.899	.268	.226	.167	.141	.133	.117	.092	.182	.097	.491	.143
29	.708		.225	.165	.129	.118	.105	.096	.094	.097	.317	.144
30	.799		.211	.164	.146	.111	.103	.093	.091	.097	.286	.173
31	.882		.286		.124		.084	.093		.095		.176

1.3 AN EXAMPLE OF A RUNOFF ACCUMULATION TIME CURVE OBTAINED FROM DATA

The steps for preparing runoff accumulation time curves from the data of Tables 1.1b to 1.1d are described in section 2.

1.3 AN EXAMPLE OF A RUNOFF ACCUMULATION TIME CURVE OBTAINED FROM DATA

Figure 1.3 shows frequency curves of the time taken to accumulate a runoff volume equivalent to 25% ARV for the river Pang. It can also be used to give the start and finish dates associated with given levels of probability. This diagram represents the end product of the techniques outlined in sections 2 and 3 and can be produced for any given runoff volume.

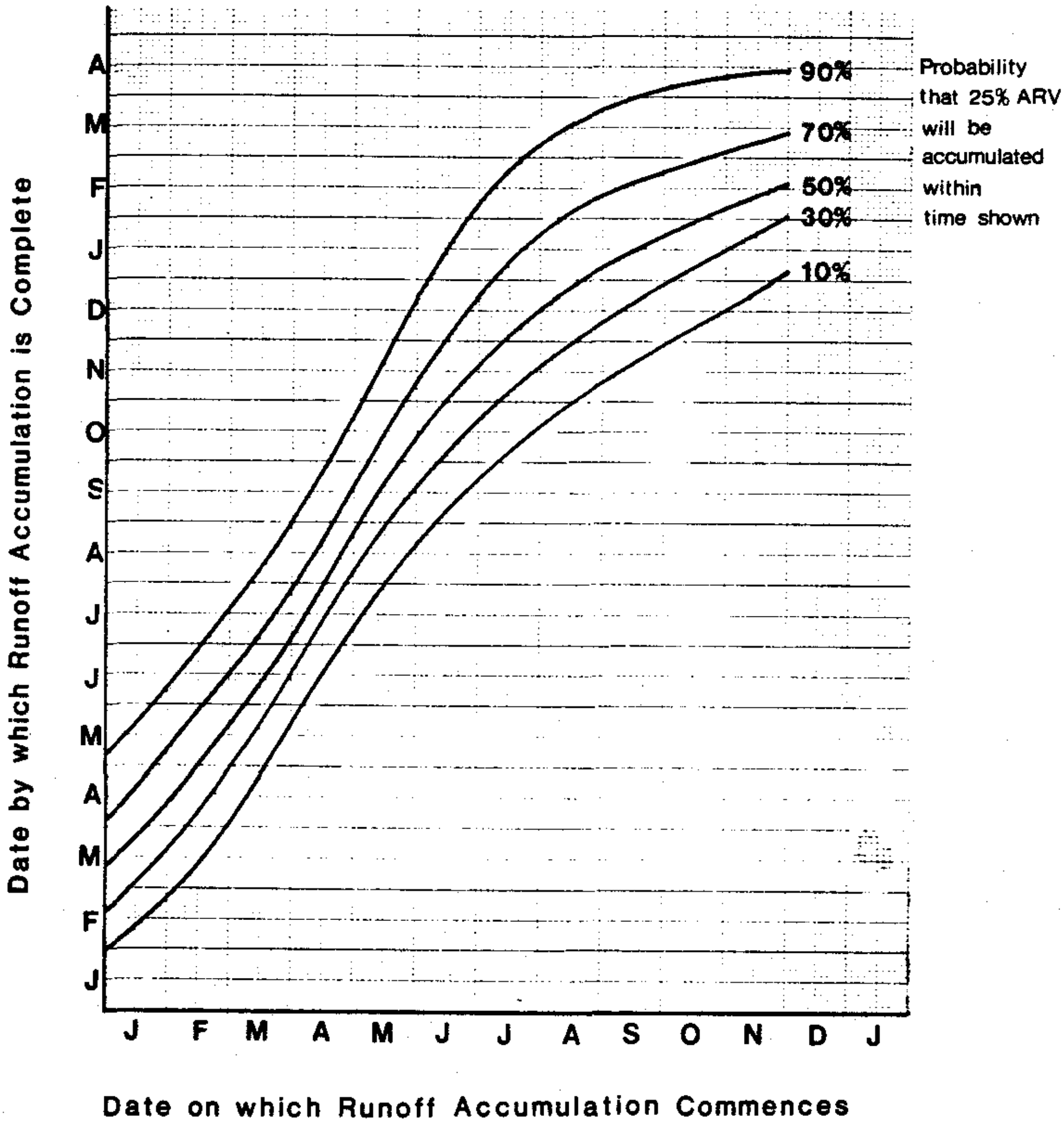

FIGURE 1.3 RUNOFF ACCUMULATION TIME CURVES FOR THE RIVER PANG (25% ARV)

As an example of the use of Fig 1.3, suppose that it is proposed to use an aquifer conjunctively with a surface supply from the river Pang. A contribution from the surface supply of 5.1 MCM (equivalent to 25% of the average annual runoff) is required during the period between June and mid-November when the aquifer is normally depleted. For design purposes what is required is an assessment of the risk that 5.1 MCM will be unavailable from the river. Figure 1.3 is entered with start date 1st June and completion date 15th November. This diagram which has been prepared for the 25% ARV case, indicates that in just over 70% of years, the 5.1 MCM requirement will be available. The risk of non-availability of water is hence given by the complement, i.e. 30%, and this value is the basis of management decisions on the suitability of this surface supply.

A further example of the use of Fig 1.3 is illustrated in Section 1.5 where the siting of a hypothetical new reservoir on a river is considered, and the time needed to fill it is to be calculated.

1.4 OUTLINE OF ESTIMATION PROCEDURE

The basic recommendations for constructing the runoff accumulation time curve are given opposite. All the example catchments have 8 years of data and for such a short record we would normally recommend the use of the generalised procedure of Section 3 for much of the procedure but supplemented by data-based estimate of Q95(10), ADF, and hence ARV. Nevertheless for purposes of illustration in Section 2 we depart from these recommendations and construct accumulation time curves based on the data alone. Similarly in Section 3 we ignore the presence of the gauging stations and work entirely from catchment characteristics.

1.4 OUTLINE OF ESTIMATION PROCEDURE

The procedure for estimating the runoff accumulation time curve depends on the availability of data at or near the site of interest. Fig 1.4 outlines three basic approaches and the corresponding section of this manual to use. The technique based on catchment characteristics refers to the Catchment Characteristic estimation manual - Report No 3 of this series.

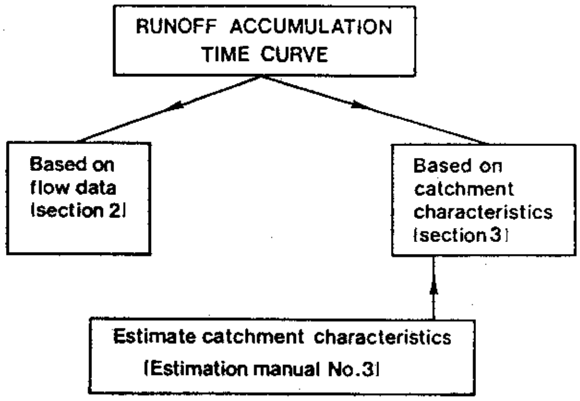

FIGURE 1.4 OUTLINE OF ESTIMATION PROCEDURE

Which of these three procedures to use, individually or in combination, depends on the amount of data available. There are three main elements to the calculation which depend strongly on the data availability: the calculation of ARV; the seasonal pattern of behaviour of the mean accumulation time; and the frequency distribution of accumulation times about its mean.

In each case there is a gradation between almost total reliance on the flow data and total reliance on catchment characteristic based derivation. This gradation is based primarily on the length of record but other issues such as quality of the data and the conformity with similar surrounding catchments affect the decision on the method to follow. In view of this uncertainty the thresholds listed below must be accepted as approximate guidelines.

More than 20 years. With records of this length the Section 2 method applies in its entirety. A frequency diagram for runoff accumulation times can be extended to a return period equivalent of twice the record length e.g. if N = 20 the 2½% and 97½% curves can be derived. It may be necessary to smooth some of the trend lines to reduce the more obvious discontinuities due to sampling error. The Table 3.3 frequency curve numbers will assist with this smoothing.

Between 10 and 20 years. This record length is adequate for ARV calculation and indeed the average runoff accumulation time. However some care should be exercised in the case of the accumulation time to ensure that it displays a single cycle about the year whose peak and amplitude are close to that anticipated from section 3.3. The average accumulation times of Table 3.1 are preferred to those derived from the data such as in Figure 2.1a at the 10 year record level with increasing reliance (at least at probabilities in the 5% to 95% range) at the 20 year record level, on the data. It will be necessary to standardise the runoff to % ARV form in order to make comparisons with the frequency curves of Figure 3.3 and to use Section 2 of Manual 2.1 to calculate Q95(10).

Below 10 years. Below 10 years record length the advice of Manual 2.1 Sections 1.4 and 4, should be followed for ARV and Q95(10) estimation. In particular the flow data may be applied to estimate annual catchment losses (rainfall - runoff) and this can be subtracted from the mapped annual average rainfall value. Section 3 methods must be used to estimate both the seasonal behaviour of average accumulation time and its frequency distribution. However the data-based estimate of the average accumulation times should be compared with the catchment characteristics based estimates (Table 3.1) which may be modified either by striking an average between the two estimates or if the evidence is overriding (e.g. strong regional conformity, or known anomalous behaviour) then it may substitute for the section 3 method.

The worked example for the river Pang in Section 2 adopts the data approach of "More than 20 years of data being available" in order to simplify and illustrate the general data-based procedure. Likewise in Section 3 the position is taken that no data at all are available at the site.

1.5 RESERVOIR FILLING PROBLEM FOR EVALUATION IN SECTIONS 2 AND 3

A similar reservoir filling problem is set for the three practical example catchments as described opposite for the river Pang. Because there is a considerable amount of repetitive work involved in the construction of the complete runoff accumulation time curve, the calculations have already been carried out for all months except July. Your practical example is concerned therefore solely with accumulation times commencing on 1st July. The reservoir volumes for the example catchments are listed below along with the corresponding long term average daily flows.

	Reservoir volume	*ADF*
Falloch	*38.8 MCM*	*4.91 cumecs*
Langdon	*3.07 MCM*	*0.39 cumecs*
Roman	*1.44 MCM*	*0.18 cumecs*

1.5 RESERVOIR FILLING PROBLEM FOR EVALUATION IN CHAPTERS 2 AND 3

In this worked example the runoff accumulation time for a July start is calculated; in chapter 2 using gauged data, and in chapter 3 using catchment characteristics. This incidentally permits us to complete the diagram for any start date. For illustration consider a hypothetical reservoir to be built on the river Pang at Pangbourne. The probability of the reservoir not filling during a specified period starting 1st July is required. The reservoir volume is 5.1 MCM (which equates to 25% ARV). The completion date is scheduled for 1st July and it is hoped that it can be brought into use by 1st December when existing water supplies are scheduled to be closed. The question to be answered in chapters 2 and 3 is "what is the chance that the existing water supplies will have to be maintained after 1st December because the Pang reservoir has not filled?".

Although the example has been couched in terms of a reservoir filling problem the example could have been expressed to answer questions relating to (1) energy loss during a shut-down period in a hydro-power scheme (2) operational decisions on reservoir management during a low flow period (3) capability of a surface water source to augment a groundwater or reservoir supply.

2. THE GAUGED CATCHMENT CASE

2.1 OUTLINE OF PROCEDURE

The runoff accumulation time frequency diagram is to be used for a reservoir filling problem. Use the formulae opposite to re-express the volume of the example reservoirs in cumec day and % ARV terms.

Reservoir	*Inflow ADF*	*Volume MCM*	*(1) Volume cumec-day*	*(2) % ARV*
Falloch	*4.913*	*38.8*	--------	----
Langdon	*0.388*	*3.07*	--------	----
Roman	*0.183*	*1.44*	--------	----

Volume in (1) cumec-day units = *MCM* x *11.574*

$$(2)\ \%\ ARV\ units = \frac{cumec\text{-}days \times 100}{ADF \times 365}$$

2. THE GAUGED CATCHMENT CASE

2.1 OUTLINE OF PROCEDURE

The use of flow data to construct the runoff accumulation time frequency diagram involves several distinct steps. This section covers each of these steps adopting the procedure that would be appropriate to a 20 year record i.e. the use of data for all steps of the analysis but expressed wherever appropriate in standardised form. Standardisation permits intercatchment comparisons and particularly comparisons with the results of Section 3 for the catchment. This can be regarded as representing the average behaviour for catchments in the same climatic and hydrogeological zone.

A preliminary step is to express the reservoir volume in units of cumec days. This is needed in order to calculate runoff accumulation times (equivalent to reservoir filling times) from daily flow listings. For the Pang reservoir (5.07 MCM) this works out to be 58.68 cumec days. The general formula is 1 MCM $\equiv$ 11.574 cumec days. Another preliminary step is to express the volume as a percentage of annual runoff volume.

The general formulae are

1 cumec day = (0.274/ADF)% ARV
1 MCM = (3.168/ADF) % ARV

The basic method of estimating the average discharge (ADF) for the Pang catchment is to sum the daily flow values for the entire length of record, and divide by the length of record in days. A single year's data for the Pang example catchment is given in table 1.1a however, this is an insufficient length of record to compute ADF. The ADF used in this example has been calculated from the nine years of data available, and was found to be 0.643 cumecs. A better method to use in the case of shorter records, utilising knowledge of a catchment's rainfall and evaporation, is outlined in section 2.5 of Manual 3. The standardised reservoir volume works out to be 25% ARV.

The first computation step is shown in Section 2.2 and is to evaluate the runoff accumulation time for each month of record. Section 2.3 describes how the average accumulation time (for a given start month) can be plotted against start month to show the seasonal variation in average filling times. This may be compared with the results from section 3 which enable the same curve to be estimated from catchment hydrogeology and climate. Section 2.4 and 2.5 describe how the runoff accumulation frequency diagram may be derived to enable rarer accumulation times for a given start month to be estimated.

2.2 RUNOFF ACCUMULATION TIME FOR EACH MONTH OF RECORD

Calculation of accumulation time

Tables 2.1b c and d show the accumulation times for the example reservoirs for each month of record except July 1971. The daily and hence monthly flow data of Table 1.1b, c and d should be used to complete the July 1971 entry.

TABLE 2.1b Runoff accumulation times for Falloch reservoir (_ _ _ _ cumec days)

	Start month											
Year	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
1971	57	114	146	152	148	131		81	62	39	70	70
1972	101	115	96	81	100	154	149	121	100	71	52	59
1973	76	100	119	130	127	118	130	103	83	72	51	44
1974	24	159	183	166	138	122	96	78	64	55	52	50
1975	138	204	177	164	150	120	95	93	68	89	67	49
1976	41	66	82	121	157	155	139	118	87	66	84	94
1977	69	59	52	161	153	131	102	80	53	39	83	83
1978	45	66	159	166	140	113	86	58	45	38	36	34
Average	69	110	127	143	139	131		92	70	59	62	60

TABLE 2.1c Runoff accumulation times for Langdon reservoir (_ _ _ _ cumec days)

	Start month											
Year	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
1970	52	68	71	142	158	134	115	88	63	51	66	73
1971	55	100	156	164	170	140		102	123	100	78	70
1972	53	64	87	94	192	179	156	126	101	71	40	74
1973	111	114	142	128	162	161	131	131	112	91	70	47
1974	32	143	185	192	162	131	126	104	74	60	43	27
1975	43	199	207	179	157	157	137	122	93	96	79	73
1976	61	93	193	179	159	136	107	79	50	63	85	64
1977	37	37	60	147	156	151	128	98	71	53	51	68
Average	56	102	142	152	165	149		106	86	73	64	62

2.2 RUNOFF ACCUMULATION TIME FOR EACH MONTH OF RECORD

Commencing at the start of the 1st day of each month in turn, daily flows are summed until the required runoff volume has been accumulated. For example, consider the filling time starting July 1st 1970. Recall that the required runoff volume is 58.67 cumec days (Section 2.1). First calculate the month in which filling will occur. Table 1.1a shows the monthly runoff volumes for July, August, September, October and November 1970 to be 10.726, 9.827, 8.400, 7.223 and 16.290 cumec days. The total runoff to the beginning of December 1971 is 52.466 cumec days which is below 58.67. The runoff during December is seen to overfill the reservoir so the next step is to inspect the daily runoff. Further summation shows that 58.67 is accumulated on December 9th 1970. The filling time for this particular year, volume and start date is thus;

$$31 + 31 + 30 + 31 + 30 + 9 = 162 \text{ days}$$

and this is entered in Table 2.1a. The same calculation is carried out for July starts in each year of record thus completing the July column. The process is repeated for all the other months to complete Table 2.1a. Table 3.5 will assist with the whole month part of the filling time calculation.

Table 2.1a Runoff accumulation times for Pang reservoir

	Start month											
Year	J	F	M	A	M	J	J	A	S	O	N	D
1969	38	39	36	50	64	90	120	137	138	122	105	88
1970	75	76	88	116	154	175	162	152	138	115	88	75
1971	65	63	61	69	55	49	74	95	109	108	95	82
1972	67	59	62	75	100	146	160	148	139	127	115	109
1973	134	146	150	164	187	212	199	183	161	135	107	83
1974	62	57	82	117	149	144	136	111	82	56	41	54
1975	44	43	45	55	74	113	148	164	178	194	221	272
1976	280	272	261	249	231	205	183	154	128	109	94	78
1977	59	52	63	77	102	100	110	107	108	99	83	66
Average	92	90	94	108	124	137	144	139	131	118	105	101

TABLE 2.1d Runoff accumulation times for Roman reservoir (_ _ _ _ cumec days)

	Start month											
Year	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
1970	*45*	*53*	*65*	*75*	*149*	*165*	*142*	*121*	*96*	*81*	*59*	*48*
1971	*27*	*52*	*81*	*112*	*135*	*147*		*140*	*126*	*102*	*79*	*57*
1972	*33*	*46*	*75*	*138*	*170*	*183*	*181*	*176*	*172*	*182*	*180*	*173*
1973	*184*	*203*	*210*	*204*	*211*	*224*	*218*	*196*	*169*	*157*	*136*	*123*
1974	*120*	*141*	*203*	*190*	*170*	*144*	*128*	*105*	*78*	*49*	*21*	*50*
1975	*27*	*36*	*21*	*36*	*80*	*159*	*150*	*129*	*119*	*111*	*106*	*128*
1976	*159*	*199*	*221*	*224*	*214*	*198*	*176*	*153*	*126*	*101*	*75*	*55*
1977	*39*	*35*	*78*	*138*	*162*	*189*	*178*	*163*	*144*	*120*	*93*	*67*
Average	*79*	*96*	*119*	*140*	*161*	*176*		*148*	*129*	*113*	*94*	*88*

2.3 SEASONAL VARIATION OF AVERAGE ACCUMULATION TIME

Plot the average monthly accumulation times from Table 2.1b-d on Figure 2.1b. This is not strictly part of the estimation procedure for the frequency diagram - for longer records the median is estimated graphically from Figure 2.2b.

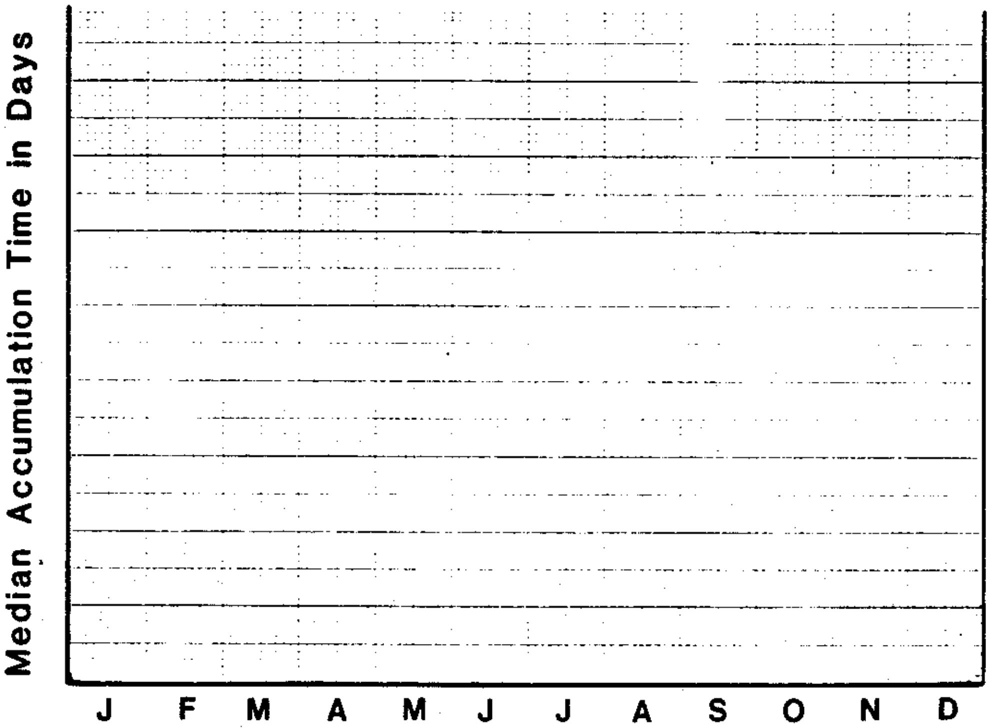

FIGURE 2.1b SEASONAL PATTERN OF MEDIAN ACCUMULATION TIME

2.3 SEASONAL VARIATION OF AVERAGE ACCUMULATION TIME

It is helpful at this stage to average the column entries of Table 2.1a in order to study the seasonal pattern of variation. The monthly averages are plotted on Fig 2.1a which illustrates the way in which the time to fill the required volume from the Pang, varies around the year. As an alternative a graphical estimate of the mean may be obtained from the frequency relationship described in Section 2.4.

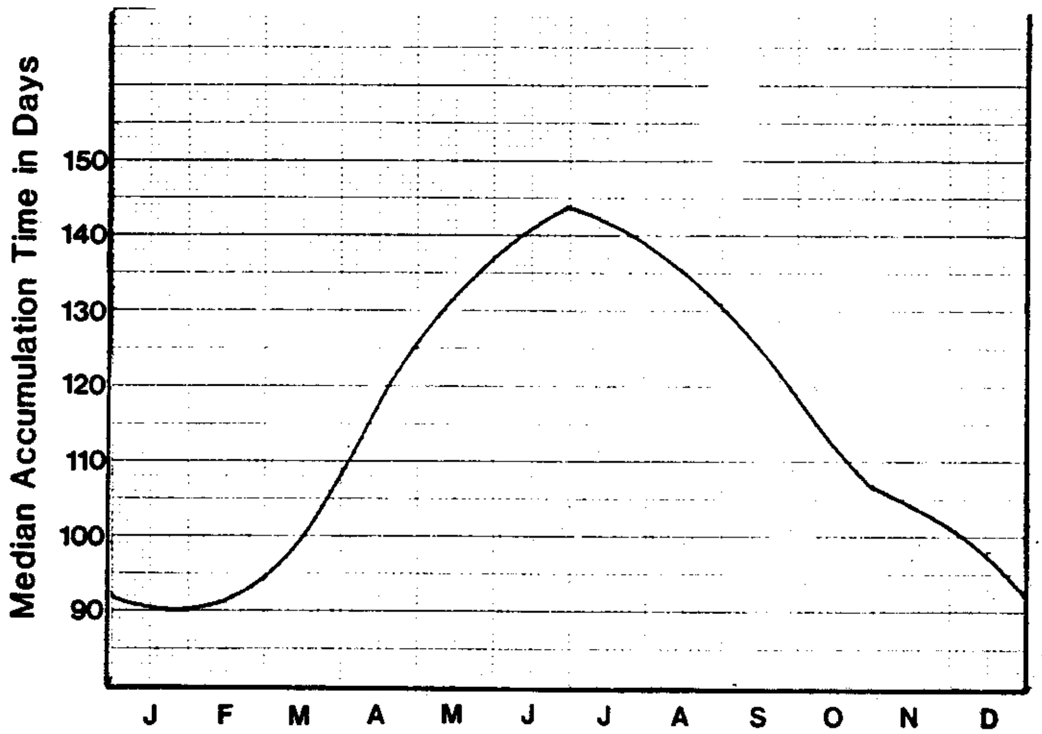

FIGURE 2.1a SEASONAL PATTERN OF MEDIAN ACCUMULATION TIME FOR PANG RESERVOIR

2.4 FREQUENCY DISTRIBUTION OF RUNOFF ACCUMULATION TIMES

Plotting the frequency distribution

All three of the practical example catchments have eight years of data. The Normal variate plotting position values have been calculated for this record length and are given in Table 2.3b. For other cases the appropriate plotting positions are calculated by reference opposite. Complete Table 2.3b using the data contained in Tables 2.1b to 2.1d.

Table 2.3b Ranked runoff accumulation times for July starts for Falloch, Langdon, Roman

	Rank	Year	Accumulation time (days)	$X_{i,N}$
low	1			− 1.44
	2			− 0.85
	3			− 0.47
	4			− 0.15
	5			+ 0.15
	6			+ 0.47
	7			+ 0.85
high	8			+ 1.44

Plot the ranked filling times against the plotting positions of Table 2.3b on Figure 2.2b and draw an eye guided line or curve through the points. Strictly this is too short a record for this treatment (see section 1.4) but we proceed as if it were adequate for data-based analysis.

2.4 FREQUENCY DISTRIBUTION OF RUNOFF ACCUMULATION TIMES

Preparation of probability paper

The frequencies of more rapid or slower accumulation, obtained from the basic accumulation time data of Table 2.1a are plotted on Normal probability paper. If Normal probability paper is not available, then ordinary graph paper may be used. The abscissa is marked out in terms of a standard Normal variate, t. The relationship between the probability of the accumulation volume being attained in a shorter time and abscissa, is shown on Table 2.2. Both probability and standard Normal variate scales are marked on Fig 2.2a.

Table 2.2 Probability and standard Normal variate equivalents

Probability % P%	Normal variate x	Probability P%	Normal variate x
99.5	2.575	40	- 0.255
99	2.325	30	- 0.550
98	2.055	20	- 0.840
95	1.645	10	- 1.280
90	1.280	5	- 1.645
80	0.840	2	- 2.055
70	0.550	1	- 2.325
60	0.255	0.5	- 2.575
50	0.000		

Statistical tables can be used to convert other non-exceedance probability values, p, to standard Normal variates x. If tables are not available, the normal variate x is given to a sufficient degree of accuracy by:

$$x = \text{signum}\,(p - \tfrac{1}{2})\{1.238t(1 + 0.0262t)\} \qquad \ldots\ldots \quad 2.1$$

where signum $(p - \frac{1}{2}) = +1$ where $p > \frac{1}{2}$; and -1 where $p < \frac{1}{2}$

and $t = \{-\ln 4p(1-p)\}^{\frac{1}{2}}$.

Plotting the frequency distribution

The accumulation times from each column of Table 2.1a are ranked from lowest (i=1) to highest (i=N) each of the ranked accumulation times is associated with a plotting position $x_{i,N}$. Plotting positions for sample sizes up to N = 50 are listed in table XX of Fisher & Yates (1963), reproduced as Table 1.13 in Vol I F.S.R., 1975. Where tables are unavailable, plotting positions may be established as follows:

a. calculate the non-exceedance probability associated with each accumulation time from the formula:

$$p_{i,N} = (i - 0.375)/(N + 0.25)$$

b. calculate $x_{i,N}$ from $p_{i,N}$ using equation 2.1 or tables of the Normal probability integral.

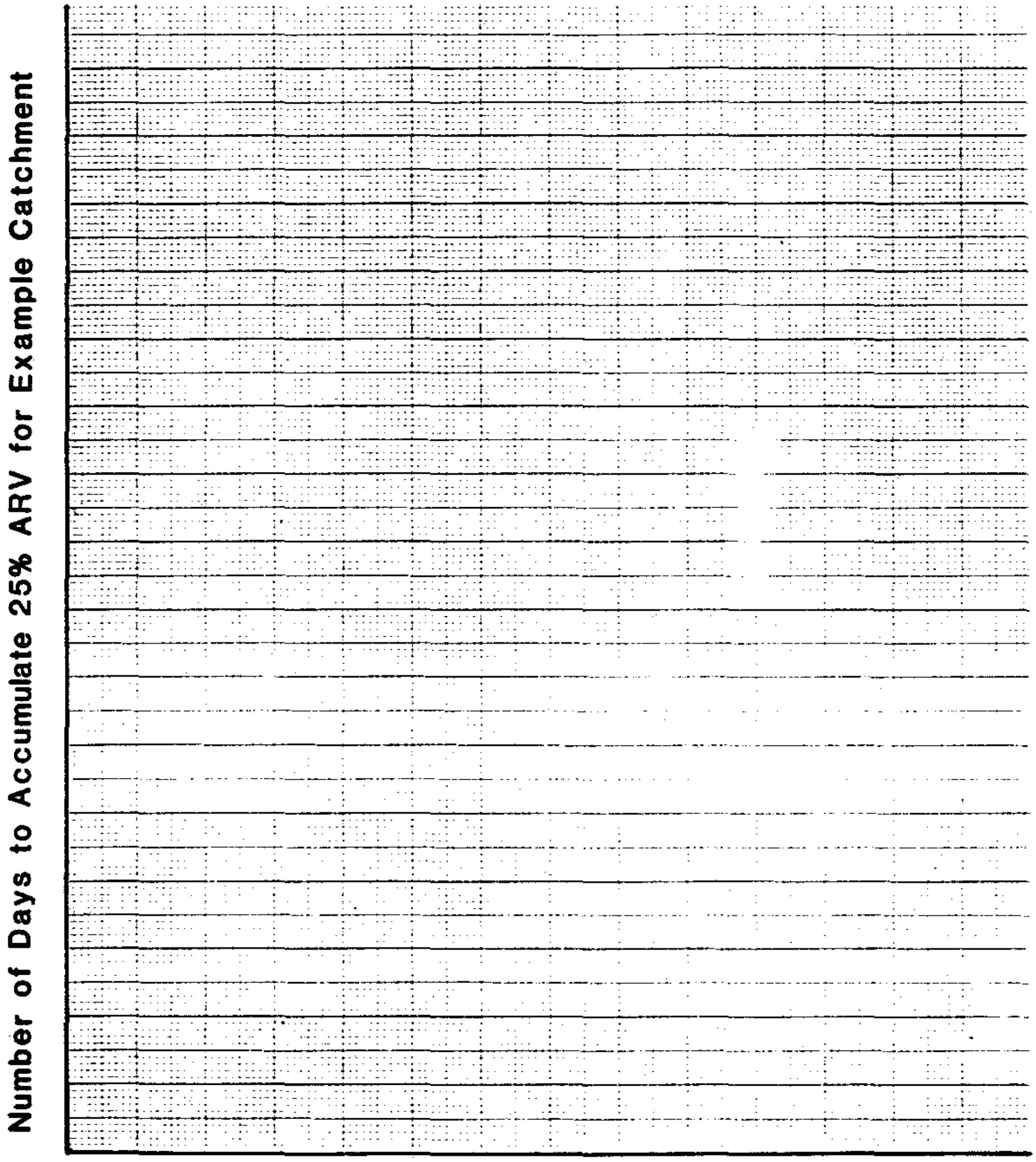

FIGURE 2.2b FREQUENCY DIAGRAM FOR FALLOCH, LANGDON, ROMAN CONSTRUCTED FOR JULY 1ST START DATES

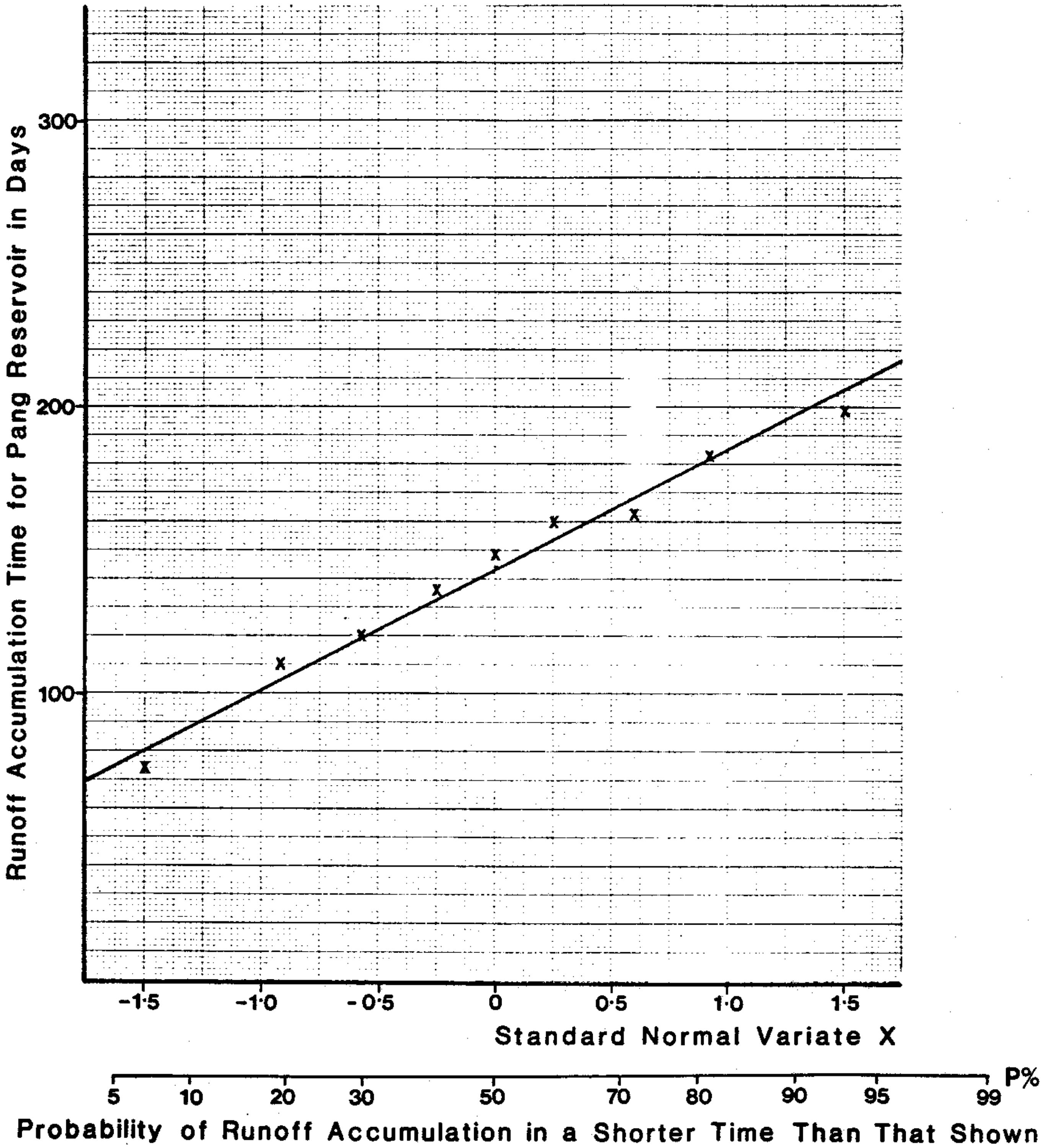

FIGURE 2.2a FREQUENCY DIAGRAM FOR PANG CONSTRUCTED FOR JULY 1ST START DATES

Table 2.3a shows the nine ranked accumulation times for July starts on the river Pang with non-exceedance probability and plotting position. We would not as a rule use such a short record in frequency analysis but do so here in order to provide a convenient example.

TABLE 2.3a Ranked runoff accumulation times for a July start for Pang reservoir

Rank	Year	Accumulation time (days)	$p_{i,N}$	$x_{i,N}$
1	1971	74	0.0675	- 1.49
2	1977	110	0.1757	- 0.93
3	1969	120	0.2838	- 0.57
4	1974	136	0.3919	- 0.27
5	1975	148	0.5000	0.0
6	1972	160	0.6081	+ 0.27
7	1970	162	0.7162	+ 0.57
8	1976	183	0.8243	+ 0.93
9	1973	199	0.9324	+ 1.49

The ranked filling times are plotted against their corresponding $x_{i,N}$ values on Fig 2.2a and an eye guided curve is drawn through the points. As will be explained in Section 3.4 it was generally found that the accumulation time distributions were slightly positively skewed i.e. steeper sloping line to the right of the median than to the left.

Interpretation of the frequency curve

From Fig 2.1b for the Falloch, Langdon, Roman, ascertain the proability of filling occurring by December 1st (i.e. within 152 days). Also establish the average length of time in days for filling to occur.

Average length of time for filling to occur ____________________

Probability of filling occurring by December 1st _______________

Probability of not filling by December 1st _________

2.5 CONSTRUCTION OF RUNOFF ACCUMULATION TIME FREQUENCY DIAGRAM

For speed of application we ask you here to complete the runoff accumulation time frequency diagram for the July start dates - the remainder of the figure has been drawn already. For a more complete example showing all the steps in the procedure see Section 3.

From the best fit curve of Figure 2.2a interpolate the accumulation time for the standard probability values. The accumulation time is translated into a date by counting foward from the beginning of July. Table 3 may assist here.

Reduced variate	*Probability %*	*Accumulation time (days)*	*Accumulation date*
- 1.645	5		
- 1.280	10		
- 0.550	30		
0.0	50		
+ 0.550	70		
+ 1.280	90		
+ 1.645	95		

Plot the seven accumulation dates on either figures 2.3b, c or d against July 1st as abscissa and draw smooth curves between the points to complete the figure.

Interpretation of the frequency curve

From the best fit straight line shown on Fig 2.2a it can be seen that the median or 50% filling time for the Pang reservoir is 144 days (i.e. full by the 21st November), whilst there is a 10% probability of it being filled within 90 days (i.e. by the end of September). The problem originally posed - what is the chance that the reservoir will not fill by December 1st, can also be obtained from Fig 2.2a although it is preferable to await the completion of the entire diagram (Figure 2.3a). Entering Figure 2.2a at an ordinate of 153 days, the best fit straight line indicates a standard Normal variate of 0.225 associated with a non-exceedance probability of 58%. Thus in 58% of years, the reservoir would fill by December 1st, i.e. there is a probability of 42% that it will not fill by December 1st.

2.5 CONSTRUCTION OF RUNOFF ACCUMULATION TIME FREQUENCY DIAGRAM

General

Graphs such as Fig 2.2a showing the frequency relationship for a specific month are generated for each of the twelve months of the year. These are used to construct the complete runoff accumulation time frequency diagram.

The precise procedure to follow is somewhat lengthy although conceptually very simple and is set out in full in Section 3.5 . Note that once the frequency diagrams for each month have been prepared there is no difference between the data based or the catchment characteristic based approaches. For speed of application in this section we assume that the diagram has been completed for every month but July.

Abbreviated procedure

From the best fit curve of figure 2.2a the accumulation time corresponding to any required probability can be estimated and then by counting forward, translated into a calendar date after the start of July 1st (using the Table 3.5 ready reckoner if necessary).

Probability P%	Reduced variate	Start Date	Accumulation time (days)	Accumulation date
5	- 1.645	Jul 1st	76	Sept 14
10	- 1.280	Jul 1st	91	Sept 29
30	- 0.550	Jul 1st	121	Oct 29
50	0.0	Jul 1st	144	Nov 21
70	+ 0.550	Jul 1st	167	Dec 4
90	+ 1.280	Jul 1st	197	Jan 13 (following year)
95	+ 1.645	Jul 1st	212	Jan 28 (following year)

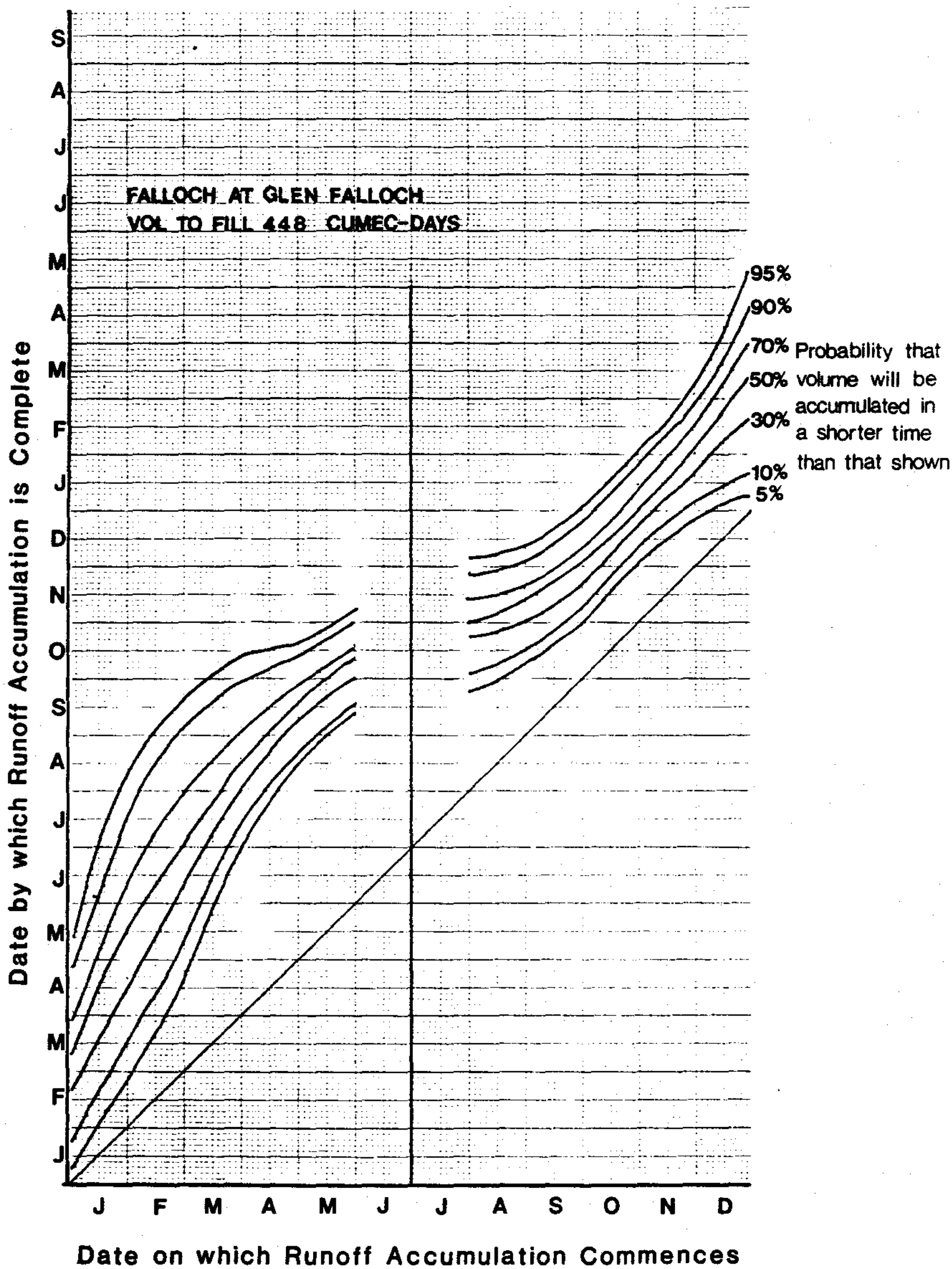

FIGURE 2.3b RUNOFF ACCUMULATION TIME FREQUENCY DIAGRAM FOR FALLOCH

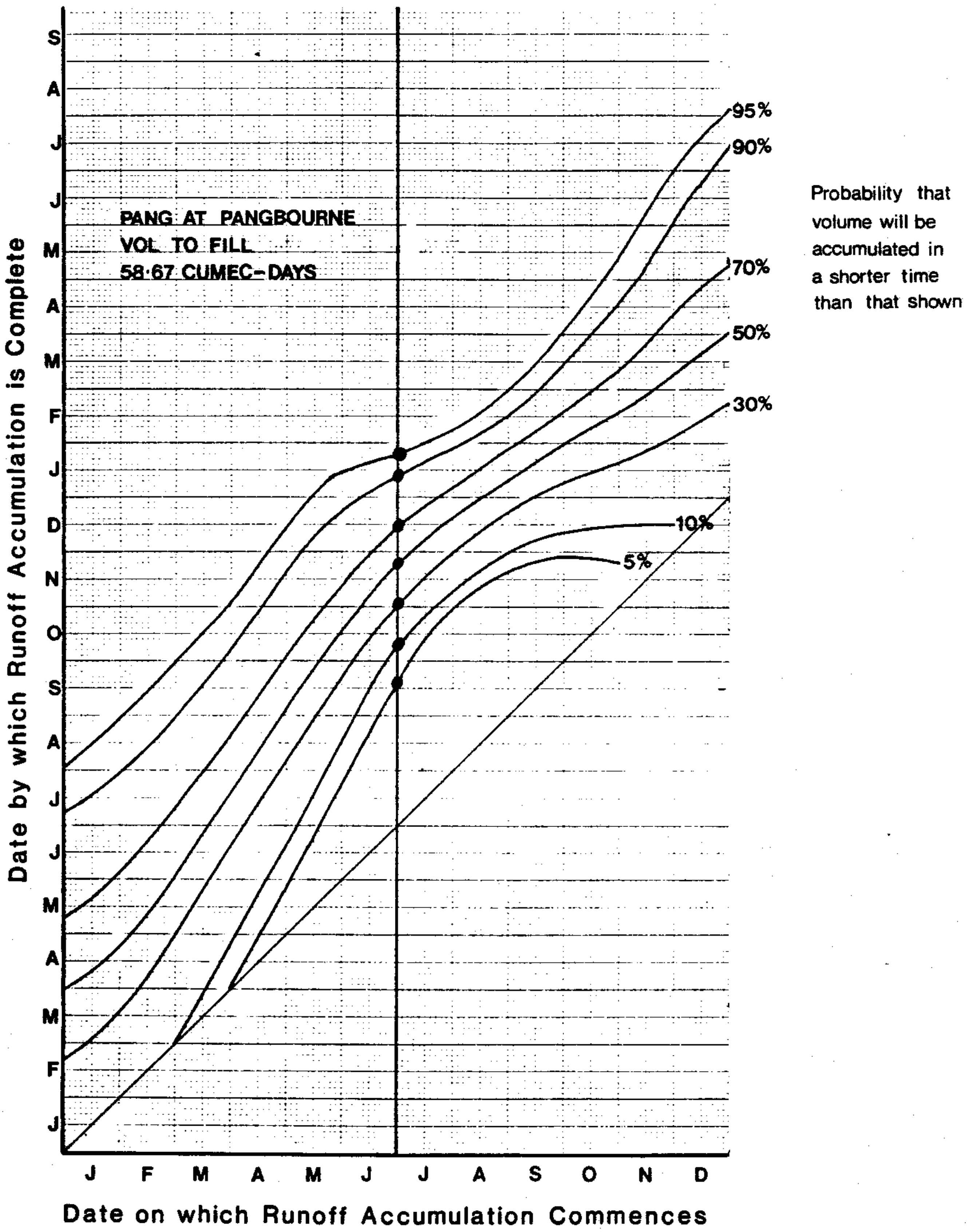

FIGURE 2.3a RUNOFF ACCUMULATION TIME FREQUENCY DIAGRAM FOR PANG RESERVOIR

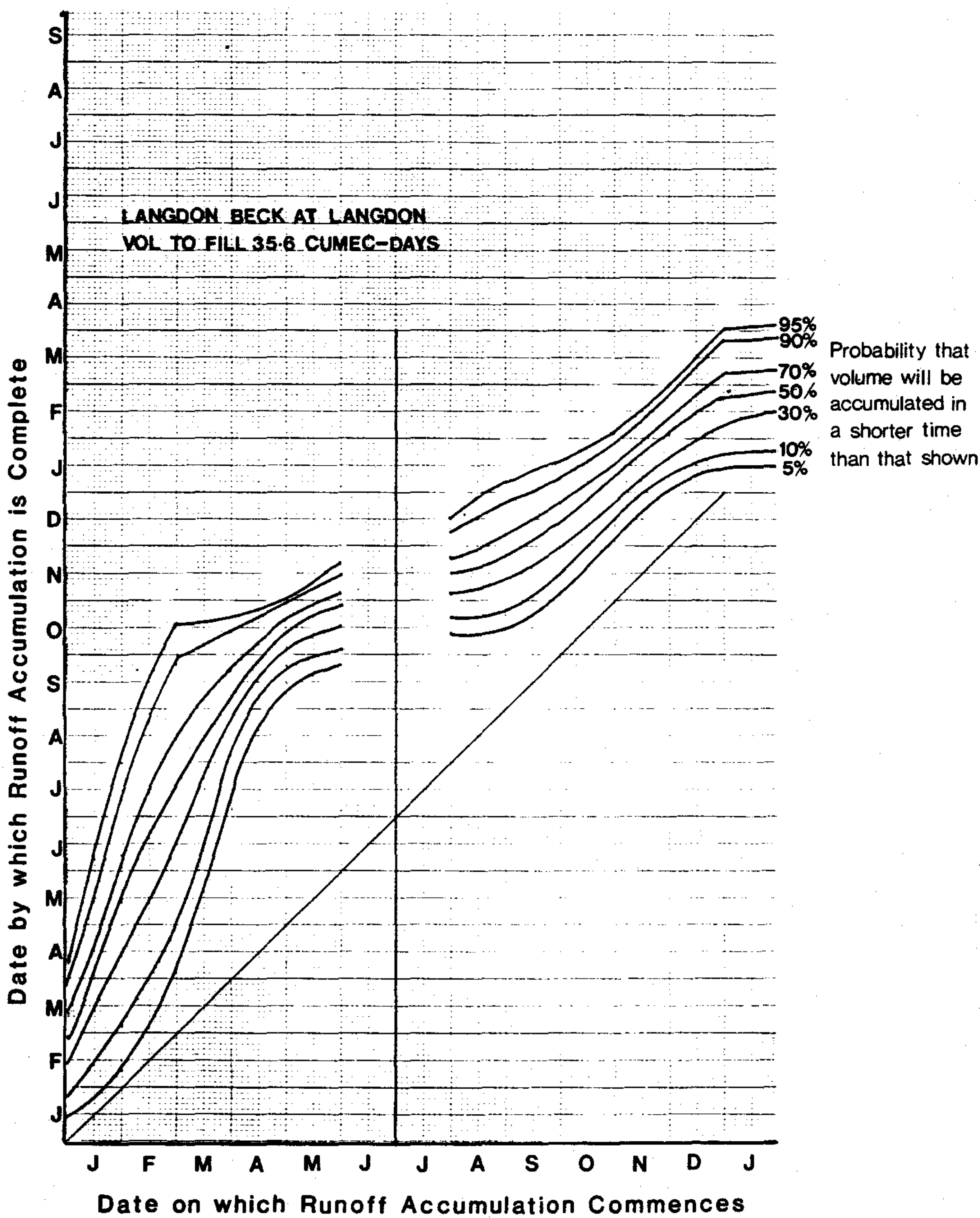

FIGURE 2.3c RUNOFF ACCUMULATION TIME FREQUENCY DIAGRAM FOR LANGDON

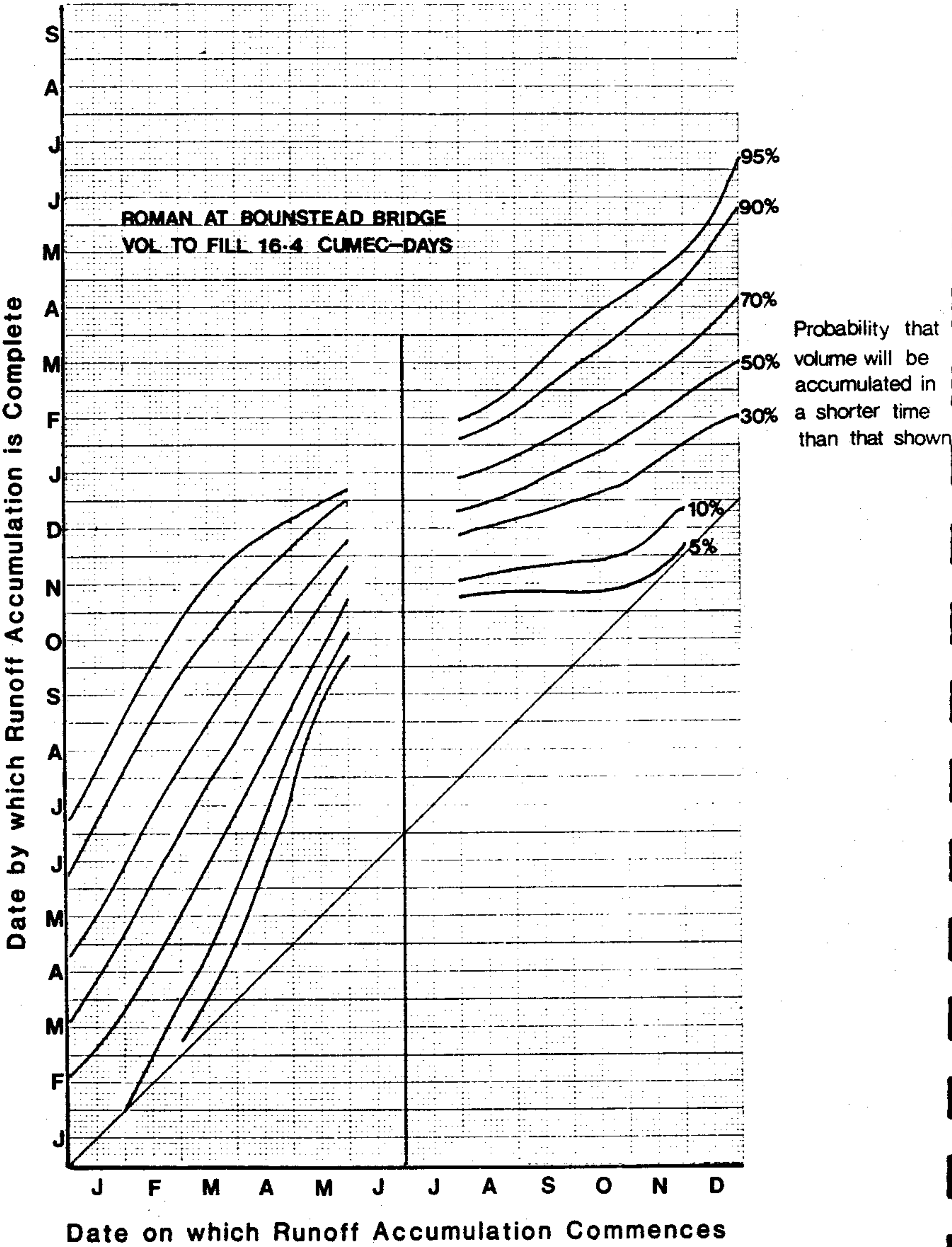

FIGURE 2.3d RUNOFF ACCUMULATION TIME FREQUENCY DIAGRAM FOR ROMAN

The problem

You are asked for the probability of the reservoir not filling by December 1st following a July start. The probability of filling as interpolated on Figure 2.3 b, c or d is _ _ _ % so the probability of not filling is _ _ _ %.

These seven accumulation dates from the above list are displayed on figure 2.3a as a series of dots using July 1st as abscissa and have been connected to the appropriate frequency curves.

Interpretation of diagram

To illustrate the use of the diagram, consider the 95% line on figure 2.3a. Specifically, there is a 95% probability that a volume of the magnitude shown which starts to accumulate on Jan 1st will complete by the start of August the same year. Note that the diagram allows for volumes to complete filling the following year. A diagram constructed for a reservoir volume equivalent to 200% or 300% ARV would need an ordinate which spans several complete years.

Runoff accumulation diagrams even when constructed from long records may well display sharp irregularities. It is permissible to smooth the curves although few hard and fast rules can be given beyond the expectation that the spacing and trend of curves ought to be maintained across the diagram. Two points need to be borne in mind when smoothing the curves. No part of any of the curves can ever drop below the 45^{o} line, as to do so would suggest that a volume had been accumulated before it had started to fill! Secondly all the lines must always continue to rise throughout the diagram. If they did not, it would lead to the paradox that accumulations could be complete from a late starting date sooner than from an early starting date.

The first kind of problem referred to tends to occur for winter starts with small runoff volumes e.g. 50% ARV and less and low probabilities. This problem clearly derives from flood hydrographs which may on occasion account for a substantial proportion of the annual runoff. If such events are of interest then it is recommended that the problem be attacked from the point of view of flood analysis. Chapter 5 of the Flood Studies Report, Volume 1 contains advice on the synthesis of flood volumes over specified durations from 1 to 10 days of any return period. Techniques are given for both the gauged and the ungauged case.

The problem

The original problem, what is the probability of the Pang reservoir not filling by December 1st - can be answered directly from Figure 2.3a. Interpolating in the diagram one reads 60% for the probability of runoff accumulation; hence the probability of not filling is 40%.

3. THE UNGAUGED CATCHMENT CASE

3.1 INTRODUCTION AND OUTLINE OF PROCEDURE

The steps for deriving the runoff accumulation time frequency diagram are described opposite. The instructions given are for the case where no data at all are available. But it may be possible to incorporate small periods of data into the procedure e.g. in determining the value of Q95(10), to be used in section 3.2. More explicit instructions on the approach to be adopted, given any particular data period, are contained within section 1.4.

3. THE UNGAUGED CATCHMENT CASE

3.1 INTRODUCTION AND OUTLINE OF PROCEDURE

This section describes the main procedure for constructing the runoff accumulation frequency diagram where no flow data are available, Section 1.4 gives advice on the appropriate procedure to be followed corresponding to various different periods of data being available. A brief outline of the underlying research is given in each sub-section. In general it was found that catchment permeability and rainfall were the only two useful predictive variables. Methods outlined in this section allow the derivation of curves for runoff volumes from 20% to 300% ARV, in steps of 20% ARV. Only within such a step has interpolation been found to be sufficiently accurate.

The first step is shown in section 3.2 and uses catchment climate and hydrogeology to determine the range and pattern of median accumulation time. Section 3.3 fixes this pattern in time by identifying the month when the accumulation time attains its maximum value. The following step (section 3.4) establishes the accumulation time frequency relationship for each start month using a set of dimensionless frequency curves. The choice of particular curve is determined by runoff volume and start month. The final stage is to construct the runoff accumulation time frequency diagram by combining the results from all start months (section 3.5).

3.2 SEASONAL VARIATION IN AVERAGE ACCUMULATION TIME

Selection of catchment category

The first task is to assign the catchment to one of five categories which describe the seasonal variation of runoff accumulation times. This depends very simply on Q95(10) and SAAR.

For the three example catchments, the value of SAAR can be obtained by reference to Section 2.4 of Report No 3, and Q95(10) can be estimated by methods outlined in Section 3.2 of Report 2.1. The estimation of Q95(10) will involve an assessment of the Base Flow Index for the catchment which should be made in accordance with section 3.2 of Report 3. Enter Figure 3.1 to determine the catchment category.

SAAR = _ _ _ _ _ _ _ _ _ mm   Q95(10) = _ _ _ _ _ _ _ _ _ _ % ADF

∴ *From Fig 3.1 catchment category required = ____(F) ___ (L) ____ (R)*

3.2 SEASONAL VARIATION IN AVERAGE ACCUMULATION TIME

Development of the method

The catchment must be first categorised into one of the five categories which analysis of all catchments demonstrated were sufficient to represent the different seasonal patterns of accumulation time that were encountered. These five types were identified by considering graphs of average runoff accumulation time versus start date. The resultant seasonal curves from many catchments were compared by first aligning them so that the months of maximum and minimum accumulation times were matched and then by simple graphical overlaying. Regression analysis of the features of the individual catchment curves for different volumes on catchment characteristics had shown that the detailed features followed from the amplitude (maximum - minimum accumulation time). This chief feature, the amplitude, was itself determined by two characteristics; Q95(10) representing catchment geology and SAAR representing climate.

The outcome is Figure 3.1 which is a graphical solution of the amplitude regression equation, and Table 3.1 which tabulates the pooled seasonal curves of runoff accumulation time averaged over the catchments falling in each of the five categories. The Figure 3.1 categories serve to categorise the seasonal curve for any runoff volume. The accumulation time tabulations depend on the runoff volume being considered.

Selection of catchment category

The first step is to apply Figure 3.1 to categorise the Pang. Enter Figure 3.1 with:

Q95(10)	Report 2.1	Section 3.2	39.35% ADF
SAAR	Report 3	Section 2.4	722 mm

Seasonal accumulation curve

Using the Figure 3.1 categories for the Falloch, Langdon, Roman identify the 12 monthly average accumulation times which correspond to the %ARV volumes either side of 25% ARV. This volume has been established in Section 2.1.

For the _ catchment

Category _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ required (from Figure 3.1)

Runoff volume	*Average accumulation times*											
_ _ _ *% ARV*	--	--	--	--	--	--	--	--	--	--	--	--
_ _ _ *% ARV*	--	--	--	--	--	--	--	--	--	--	--	--

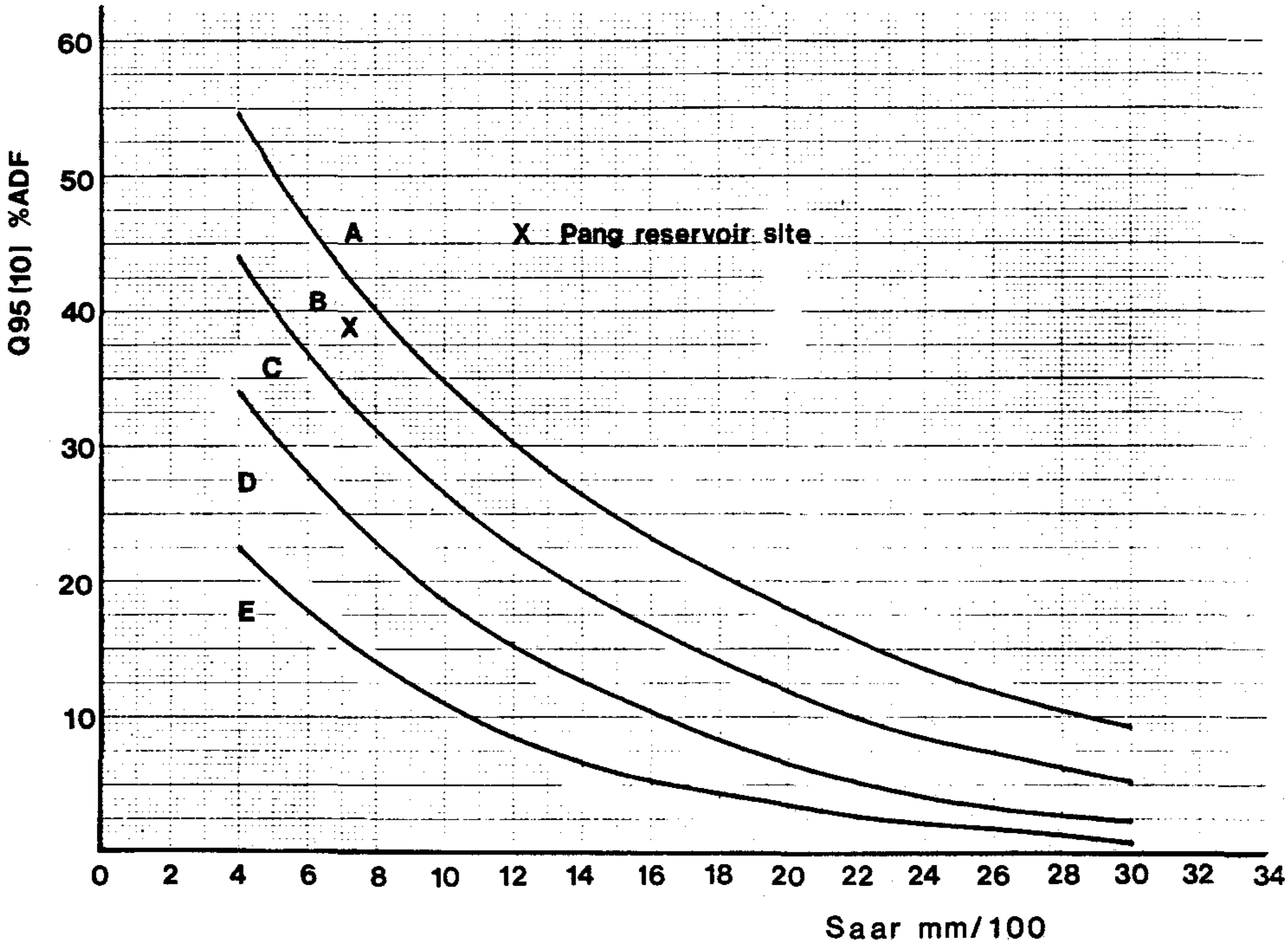

FIGURE 3.1 CATCHMENT CATEGORIES

Figure 3.1 shows that the Pang catchment falls within category B

Seasonal accumulation curve

We are interested in the time required to accumulate 25% ARV on the river Pang. This is not one of the volumes which is contained within Table 3.1. In such cases it is necessary to interpolate using a method which is detailed at the end of section 3.3. From Table 3.1 we extract the category B data for the volume entries above and below the desired runoff volume

Runoff volume	Average accumulation times										
20% ARV	52	52	59	82	111	127	126	118	100	83	68	58
40% ARV	110	107	121	154	190	207	203	190	174	156	132	120

TABLE 3.1 Average runoff accumulation times for all catchment categories and % ARV's

Catchment Category													
20%ARV	A	62	67	82	95	109	112	101	87	77	66	60	58
	B	52	52	59	82	111	127	126	118	100	83	68	58
	C	51	48	58	85	119	134	133	120	102	84	69	59
	D	48	49	65	96	128	150	149	132	112	90	71	55
	E	53	49	62	96	139	167	163	147	123	100	79	62
40%ARV	A	119	121	137	158	174	186	184	178	166	151	138	125
	B	110	107	121	154	190	207	203	190	174	156	132	120
	C	108	100	109	146	192	211	210	198	181	160	140	121
	D	108	99	113	149	202	229	225	210	192	171	148	125
	E	113	101	101	140	202	244	234	226	204	180	156	133
60%ARV	A	191	167	208	228	246	255	253	247	238	224	210	199
	B	180	177	193	223	255	268	266	255	240	225	207	191
	C	178	172	185	214	254	271	271	259	245	228	209	192
	D	185	176	186	204	250	287	283	272	258	242	224	202
	E	178	166	173	211	268	298	297	282	261	240	217	196
80%ARV	A	280	287	295	306	314	315	310	305	299	293	284	283
	B	265	266	280	296	315	324	321	316	309	299	287	274
	C	265	265	281	300	312	323	321	315	307	292	279	270
	D	271	274	287	306	328	341	341	333	325	310	294	279
	E	263	273	293	324	348	350	343	329	313	298	280	265
100%ARV	A	369	371	376	380	388	389	380	371	368	361	361	364
	B	364	366	372	381	390	391	380	372	365	358	356	358
	C	352	359	365	374	380	393	391	383	374	366	356	350
	D	346	362	380	394	408	416	414	407	395	378	359	348
	E	359	375	392	407	420	421	411	395	375	360	355	349

TABLE 3.1 CONTINUED

Catchment Category													
120%ARV	A	430	435	444	453	462	469	469	459	447	440	432	429
	B	422	422	431	447	465	482	477	471	460	445	433	425
	C	417	421	435	453	470	483	479	467	453	435	421	417
	D	429	439	462	478	493	494	482	470	452	433	421	419
	E	421	433	460	487	502	503	489	473	450	433	419	410
140%ARV	A	494	500	515	527	536	544	543	537	428	513	505	495
	B	482	481	495	517	542	556	556	547	536	520	504	491
	C	478	480	489	519	544	561	556	544	531	516	501	485
	D	489	490	507	528	553	565	565	556	545	529	511	498
	E	478	485	498	528	554	574	573	562	544	521	502	489
160%ARV	A	569	576	587	602	609	615	614	607	597	585	578	569
	B	552	558	572	595	613	628	624	612	603	590	575	650
	C	549	548	562	586	611	626	625	616	603	587	571	557
	D	547	565	584	606	630	640	638	628	614	594	574	556
	E	547	566	595	550	643	644	632	616	594	572	562	549
180%ARV	A	649	652	660	671	678	683	682	676	668	659	654	652
	B	633	635	651	664	681	694	691	684	626	664	651	640
	C	624	633	649	668	682	691	686	677	666	651	638	631
	D	628	641	666	683	710	711	701	689	670	650	632	621
	E	616	621	638	669	701	715	714	704	688	666	644	629
200%ARV	A	733	738	745	752	756	758	749	739	728	723	722	727
	B	715	719	730	739	753	766	762	757	746	735	723	716
	C	710	722	731	751	761	763	753	740	725	712	704	705
	D	705	722	742	761	778	780	764	751	736	719	708	700
	E	688	693	712	737	764	784	783	772	757	735	716	703

TABLE 3.1 CONTINUED

Catchment Category													
220%ARV	A	797	807	814	825	834	835	824	814	806	800	794	794
	B	785	786	794	807	823	843	842	836	828	814	801	791
	C	776	771	794	813	827	836	835	828	813	800	786	777
	D	775	778	792	814	833	845	845	837	825	810	793	780
	E	763	768	790	818	837	850	850	841	826	804	785	772
240%ARV	A	863	869	876	890	898	904	902	896	889	880	872	865
	B	853	858	869	887	901	921	918	907	898	884	873	858
	C	839	846	861	880	902	916	913	903	890	872	860	848
	D	840	854	872	890	912	923	921	912	896	876	856	843
	E	832	839	861	886	916	929	927	914	897	872	853	840
260%ARV	A	935	940	956	962	969	975	974	969	958	948	941	936
	B	933	944	960	977	987	990	978	967	956	942	930	926
	C	912	920	928	955	977	990	986	973	963	945	930	919
	D	909	196	929	954	981	996	995	986	974	957	938	922
	E	903	911	934	963	986	1002	1002	988	968	946	931	910
280%ARV	A	1011	1023	1032	1039	1046	1047	1040	1029	1023	1013	1011	1010
	B	1001	1003	1009	1023	1043	1059	1055	1050	1043	1035	1021	1008
	C	973	1008	1023	1045	1047	1061	1050	1036	1022	1004	989	987
	D	990	990	1006	1022	1052	1072	1068	1063	1050	1035	1015	998
	E	978	976	989	1018	1053	1078	1076	1069	1053	1033	1011	992
300%ARV	A	1079	1085	1097	1105	1112	1120	1119	1106	1097	1089	1082	1077
	B	1072	1079	1092	1103	1117	1132	1131	1106	1106	1095	1082	1075
	C	1064	1057	1080	1099	1116	1130	1129	1118	1108	1092	1078	1068
	D	1052	1051	1078	1095	1115	1131	1128	1121	1108	1092	1075	1059
	E	1052	1052	1063	1090	1122	1146	1145	1133	1120	1100	1076	1059

3.3 DETERMINATION OF MONTH OF MAXIMUM RUNOFF ACCUMULATION TIME

Calculation procedure

Enter Table 3.2 with tabulated runoff volumes above and below the required value

		a_0	a_1	a_2
Reservoir volume	___ % ARV			
Tabulated value below:	___ % ARV	___	___	___
Tabulated value above:	___ % ARV	___	___	___

Substitute the coefficients into equation 3.1 to evaluate P for the example catchment and then round to nearest integer month. Note that P = 6 is equivalent to 1st June.

(1) ___ *% ARV*

P = ___ + (___ X ____) + (____ X ____)

= *(month ≡)*

(2) ___ *%*

P = ___ + (____ X ____) + (____ X ____)

= *(month ≡)*

3.3 DETERMINATION OF MONTH OF MAXIMUM RUNOFF ACCUMULATION TIME

Development of method

The seasonal curves of Table 3.2 do not determine the position within the year of the maximum (or other) points. Statistical analysis confirmed the intuitive expectations of Section 1.4 but also revealed a quite complex pattern of behaviour. In general the greater the base flow support in the catchment the later is the month of longest runoff accumulation time. Conversely the wetter the climate of the catchment the earlier the month. However both effects are relatively small, the climate influence especially. The basic influence is the runoff volume itself. This varies from February to April - the tendency is for the later months to apply to runoff volumes corresponding to whole numbers of years i.e. 100%, 200% and 300% ARV (or just below).

Calculation procedure

The month of longest runoff accumulation time is given by the equation:

$$P = a_o + a_1.Q95(10) + a_2.SAAR \qquad (3.1)$$

where P = 1 means Jan 1st etc up to P = 12 (Dec 1st). It is sufficient to round the value of P to the nearest month. The values of a_o, a_1 and a_2 are given in Table 3.2.

TABLE 3.2 Coefficients for equation 3.1

Reservoir volume % ARV	a_o	a_1	a_2
20	4.24	0.0711	- 0.000228
40	3.11	0.0655	- 0.000578
60	2.60	0.0599	- 0.000507
80	3.75	0.0263	- 0.001141
100	4.37	0.0276	- 0.000355
120	2.92	0.0611	- 0.000430
140	2.75	0.0712	- 0.000079
160	4.04	0.0483	- 0.000952
180	3.85	0.0441	- 0.000754
200	3.77	0.0290	- 0.000016
220	3.47	0.0591	- 0.000371
240	3.50	0.0575	- 0.000478
260	3.67	0.0494	- 0.000473
280	4.52	0.0254	- 0.000961
300	2.55	0.0795	- 0.000207

For the Pang reservoir it is necessary to extract the coefficients for the tabulated volumes immediately above and below 25% ARV, the desired volume.

Reservoir volume 25%ARV	a_o	a_1	a_2
Tabulated value below = 20% ARV	4.24	0.0711	- 0.000228
Tabulated value above = 40% ARV	3.11	0.0655	- 0.000578

We are now able to align the seasonal curves so that the month of maximum accumulation time is that given by equation 3.1.

Runoff volume	*Month*											
	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
___ *% ARV*	_	_	_	_	_	_	_	_	_	_	_	_
___ *% ARV*	_	_	_	_	_	_	_	_	_	_	_	_

These values are plotted at the position corresponding to the first day of each month on Figure 3.2b

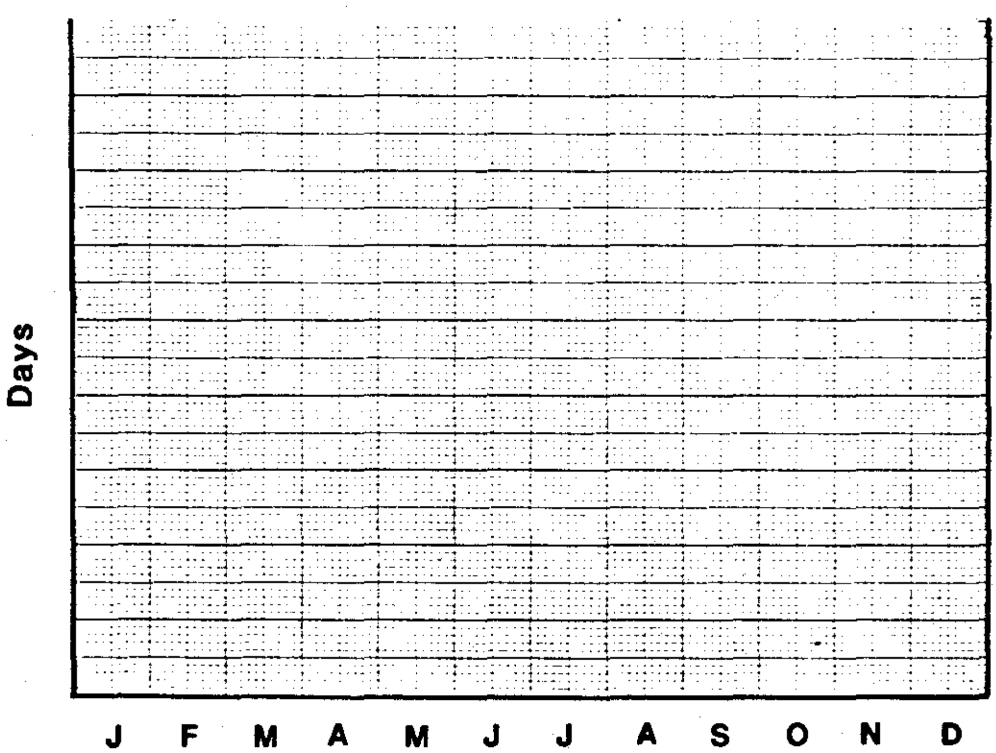

FIGURE 3.2b CONSTRUCTION OF SEASONAL RUNOFF ACCUMULATION CURVE FOR RIVERS FALLOCH, LANGDON, ROMAN

For 20% ARV from table 3.2, month of maximum runoff accumulation time is given by:

$$P = 4.24 + 0.0711 \times 39.35 - 0.000228 \times 722$$

$$= 6.87 (\simeq 7 \equiv \text{July})$$

similarly for 40% ARV

$$P = 3.11 + 0.0655 \times 39.35 - 0.000578 \times 722$$

$$= 5.27 (\simeq 5 \equiv \text{May})$$

The monthly accumulation times given at the end of section 3.2 for 20% and 40% of the ARV (for the Pang catchment) can now be plotted on fig 3.2a, using the knowledge of where the peak average accumulation time is to be positioned to locate the 12 monthly average accumulation times with their correct calendar months.

Runoff volume	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
20% ARV	58	52	52	59	82	111	127	126	118	100	83	68
40% ARV	107	121	154	190	207	203	190	174	156	132	120	110

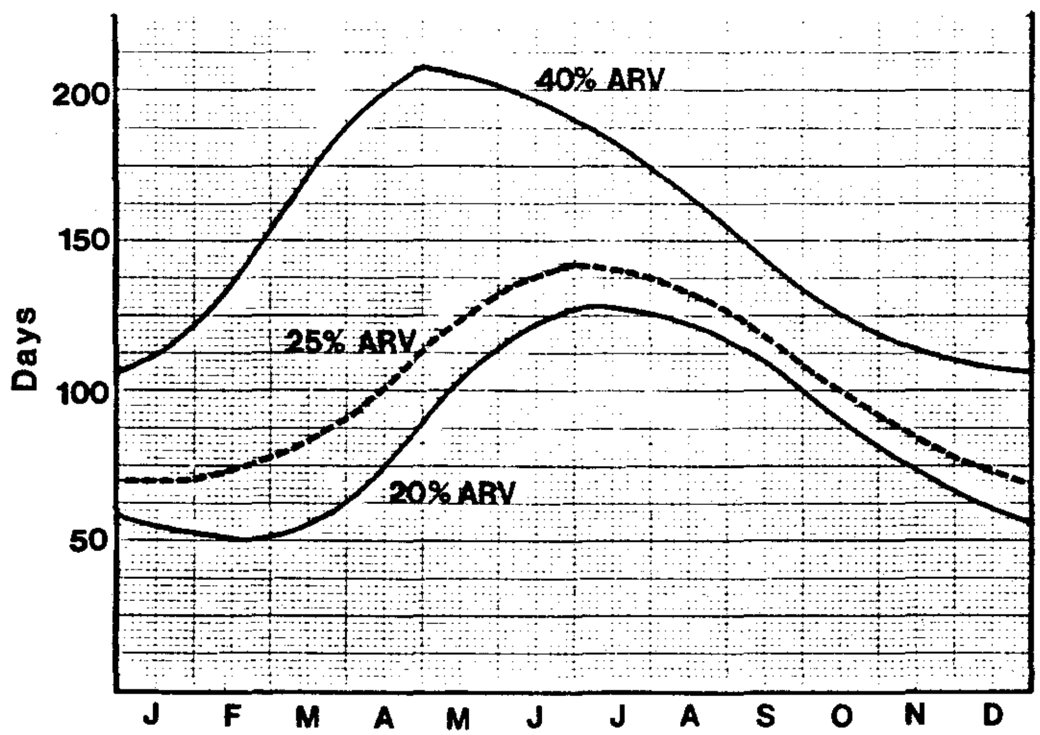

FIGURE 3.2a CONSTRUCTION OF SEASONAL RUNOFF ACCUMULATION CURVE FOR RIVER PANG

Interpolation to required volume.

Interpolate linearly between the tabulated accumulation times to the desired runoff volume. Tabulate the results and draw the seasonal curve on Figure 3.2b.

	Month											
Runoff volume	*J*	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
- - - - - - % *ARV*												

Interpolation to required volume

The runoff volume that is actually required for the Pang corresponds to 25% ARV and this is the stage at which interpolation is most conveniently effected. Linear interpolation is adequate and the derived accumulation times are tabulated below and shown on Figure 3.2a.

Runoff volume	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
25% ARV	70	70	77	90	112	132	142	137	125	107	92	77

3.4 RUNOFF ACCUMULATION TIME FREQUENCY RELATIONSHIP

Identification of frequency curve

For the example river the runoff volume is equivalent to _ _ _ % ARV. Table 3.3 is entered for a July start month and the interpolated frequency curve is _ _ _ . Complete the following table and plot on Figure 3.4b.

Frequency	*Multiple of mean*	*Accumulation time*
50	*1.0*	_ _ _ *(Section 3.3)*
20	_ _	_ _ _
80	_ _	_ _ _

3.4 RUNOFF ACCUMULATION TIME FREQUENCY RELATIONSHIP

Development of Method

For practical problems the average accumulation time is of only limited value. The events of prime interest are those occasions when the runoff is available either much earlier or later than average. For such information it is necessary to derive the frequency distribution of accumulation times. The gauging stations with longer records (greater than 20 years) were studied for this purpose. It appeared that the frequency distributions were approximately normally distributed with some tendency towards positive skewness. The data showed a trend towards reduced variability as the runoff volume increased. However there is also a marked seasonal effect; the variability of winter starts is greater than for summer starts at least for smaller runoff volumes. These trends and features are reflected in the selected prediction procedure which is based upon a standard set of dimensionless frequency curves (Figure 3.3).

Identification of frequency curve

The frequency curves shown in Figure 3.3 express the frequency of occasions when filling time is less than some multiple of the mean runoff accumulation time as obtained in section 3.3.

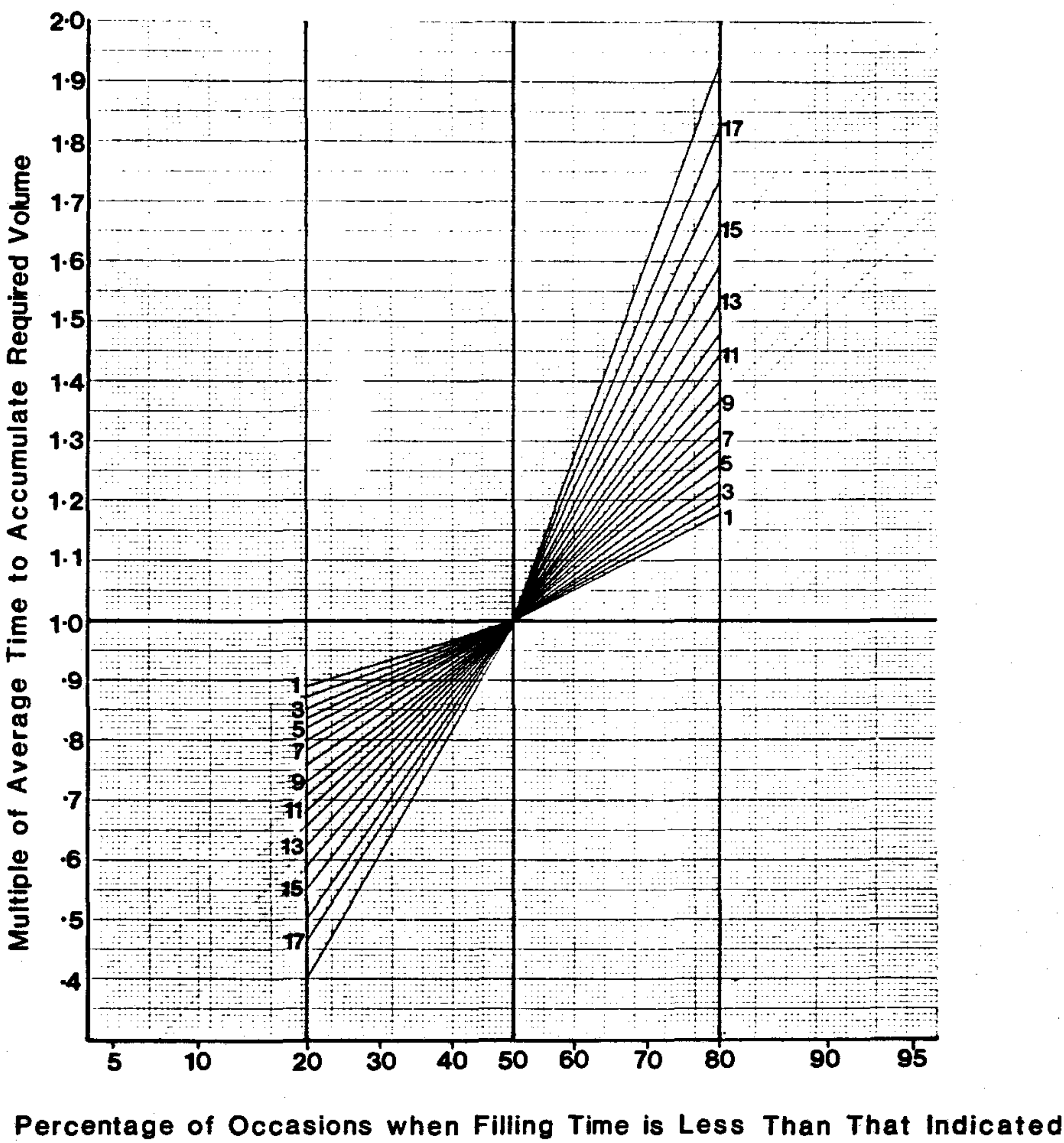

FIGURE 3.3 DIMENSIONLESS FREQUENCY CURVES FOR RUNOFF ACCUMULATION TIME

The frequency curve which applies in a particular instance depends only on the start month and on the runoff volume. This dependence is given on Table 3.3.

TABLE 3.3 Frequency curve numbers for different runoff volumes and start months

Runoff Volume % ARV	Month J	F	M	A	M	J	J	A	S	O	N	D
20	13	14	14	12	9	8	9	10	11	11	12	12
40	13	13	7	5	4	8	10	12	12	12	12	14
60	11	6	3	10	10	10	11	12	12	12	14	16
80	6	4	4	13	13	13	15	15	15	14	12	10
100	4	5	8	14	14	14	13	12	11	9	7	6
120	6	7	16	14	11	10	9	8	7	7	6	6
140	8	8	12	10	9	8	8	8	7	7	7	7
160	7	10	8	8	8	8	8	8	7	7	7	7
180	8	9	9	9	8	8	8	8	8	7	7	6
200	9	9	9	8	8	8	8	8	7	6	7	8
220	9	9	8	8	7	7	7	6	6	7	9	9
240	9	7	7	6	7	7	8	8	10	9	9	9
260	8	7	7	8	9	9	10	10	10	10	8	8
280	5	6	6	10	10	9	9	9	8	8	7	6
300	5	9	9	9	9	8	8	7	7	6	5	5

From Table 3.3 it is seen that the frequency curve number for a combination of July start with 25% ARV runoff volume can be interpolated as 9. The factors from Figure 3.3 are then used to scale the average accumulation time previously obtained in Section 3.3. For a July start the average was found to be 142 days.

Frequency	Multiple of mean	Accumulation time
50	1.0	142
20	0.73	104
80	1.37	195

These three points are transferred to Figure 3.4a and connected by straight lines to interpolate or extend to other frequencies such as those to be used in Section 3.5.

Frequency	10	20	30	50	70	80	90
Accumulation time	83	103	116	142	176	194	223

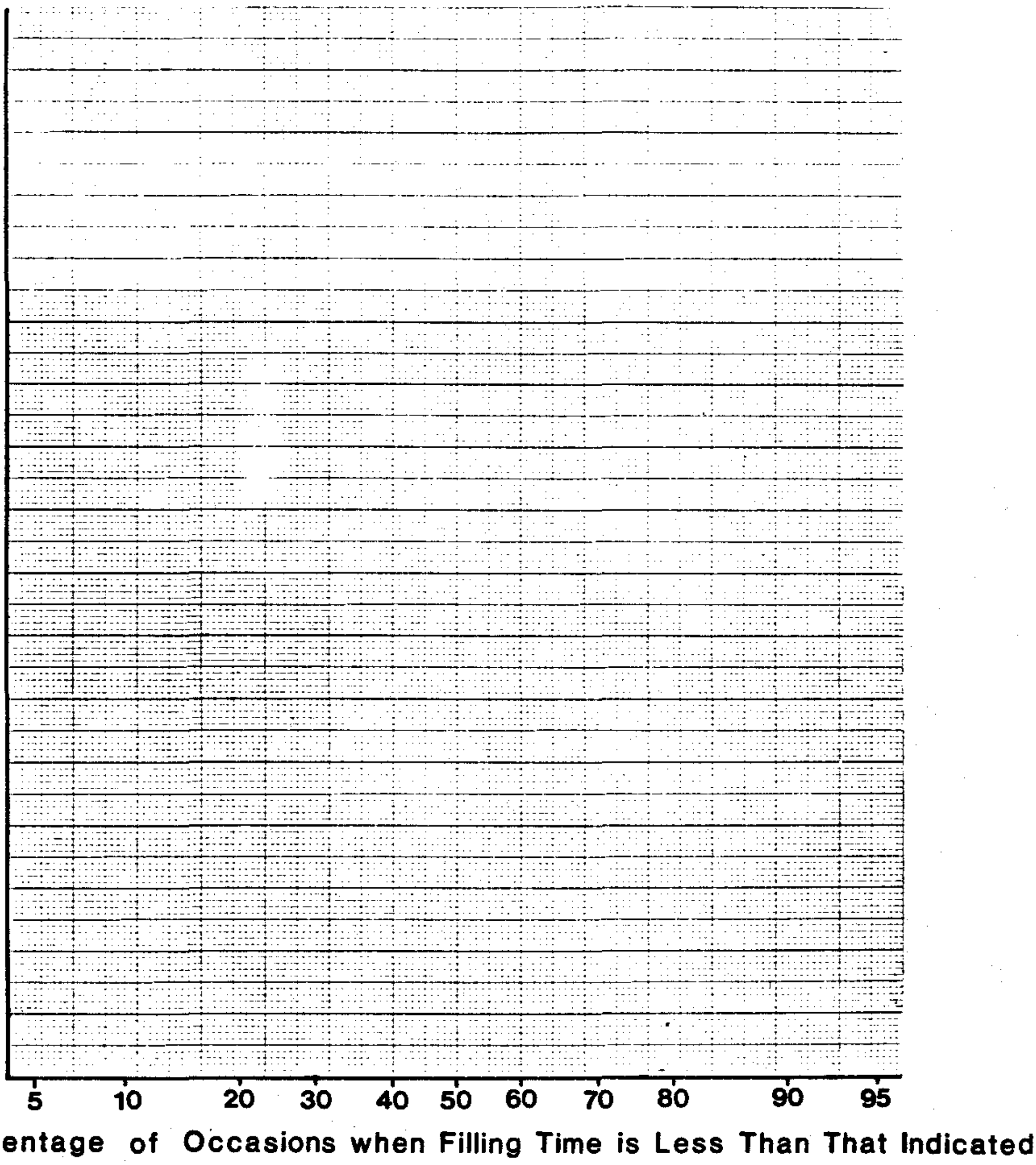

FIGURE 3.4b DURATION FREQUENCY RELATIONSHIP FOR RIVER: __________

Connect the outer points to the average point by straight lines and read off durations corresponding to the following frequencies

Frequency	5	10	20	30	50	70	80	90	95
Accumulation time									

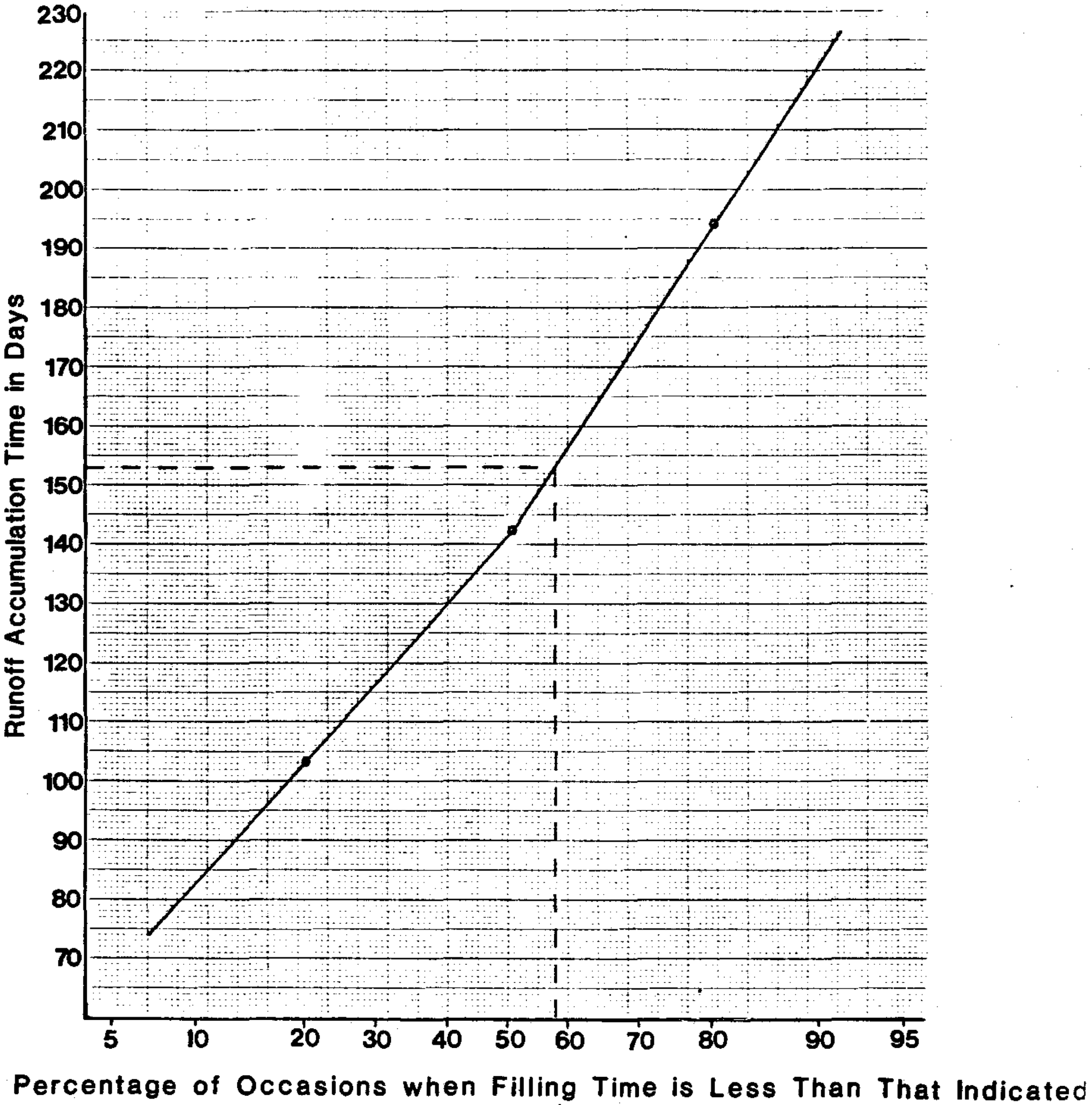

FIGURE 3.4a DURATION FREQUENCY RELATIONSHIP FOR RIVER PANG

Percentage of occasions when filling time is less than that indicated.

Figure 3.4a shows that in 58% of years the reservoir will fill in 153 days, i.e. before December 1st (see original problem as set in Section 1.5). This means that in 42% of years the reservoir will not fill and the existing water supply facilities need to be maintained. It may be advisable to delay this calculation though until the next section where advantage can be taken of other curves to smooth the relationship.

3.5 CONSTRUCTION OF THE ACCUMULATION TIME FREQUENCY DIAGRAM

To complete the entire figure it is necessary to carry out the same analysis as that contained in Section 3.4 for each month in turn. The resultant values are shown in Table 3.4. Complete the table and plot the points on Figure 3.5b, c or d.

Start Month	Frequency				
	10	*30*	*50*	*70*	*90*
January	*21*	*51*	*69*	*87*	*114*
February	*45*	*75*	*105*	*129*	*165*
March	*69*	*99*	*120*	*150*	*183*
April	*102*	*120*	*135*	*153*	*177*
May	*111*	*126*	*138*	*147*	*162*
June	*108*	*120*	*132*	*138*	*150*
July					
August	*63*	*81*	*90*	*102*	*114*
September	*45*	*60*	*72*	*81*	*93*
October	*39*	*51*	*63*	*69*	*84*
November	*42*	*51*	*60*	*72*	*84*
December	*36*	*51*	*63*	*78*	*87*

TABLE 3.4b Accumulation times for Falloch reservoir inflow

Table 3.5 is a 'ready reckoner' to facilitate the calculation of the filling date from the given start date. Use Table 3.5 to complete Table 3.6b and transfer the points to Figure 3.5b.

3.5 CONSTRUCTION OF THE ACCUMULATION TIME FREQUENCY DIAGRAM

The accumulation time frequency diagram is a way of presenting the frequency information of Figure 3.4a so that the filling date may be read directly and avoids the tedious conversion of day numbers to date. Analyses similar to that carried out in Sections 3.1 to 3.4 have been completed for the other 11 months. Table 3.4a shows the results

Start Month	Frequency 10	30	50	70	90
January	30	48	72	93	126
February	24	48	72	96	129
March	33	60	81	105	138
April	51	75	93	117	150
May	69	96	114	138	171
June	81	108	132	159	201
July	81	111	138	171	216
August	78	108	135	171	216
September	69	99	126	162	204
October	57	87	111	144	183
November	45	75	96	123	162
December	33	60	78	102	132

TABLE 3.4a Accumulation times for Pang reservoir inflow

The next step is to convert the intervals of Table 3.4a into an actual filling date by counting forward from the beginning of the month in the left hand column. The ready reckoner of Table 3.5 makes this process much simpler.

Start Month	Frequency				
	10	30	50	70	90
January	22 Jan	21 Feb	11 Mar	29 Mar	25 Apr
February	18 Mar	17 Apr	17 May	10 Jun	16 Jul
March	9 May	8 Jun	29 Jun	29 Jul	31 Aug
April	12 Jul	30 Jul	14 Aug	1 Sep	25 Sep
May	20 Aug	4 Sep	16 Sep	25 Sep	10 Oct
June	17 Sep	29 Sep	11 Oct	17 Oct	29 Oct
July					
August	3 Oct	21 Oct	30 Oct	11 Nov	23 Nov
September	16 Oct	31 Oct	12 Nov	21 Nov	3 Dec
October	9 Nov	21 Nov	3 Dec	9 Dec	24 Dec
November	13 Dec	22 Dec	30 Dec	12 Jan	24 Jan
December	6 Jan	21 Jan	2 Feb	17 Feb	26 Feb

TABLE 3.6b Filling date for Falloch reservoir

The average filling time for July starts was found in Section 3.3 to be 142 days. Scanning down the July column of Table 3.5 for the largest number less than 142 we find 123 for November (of the same year). Filling will therefore occur on average on 19th (142-123) November. Similar calculations for the other entries of Table 3.4a allows Table 3.6a to be completed.

Start Month	Frequency 10	30	50	70	90
January	31 Jan	18 Feb	14 Mar	4 Apr	7 May
February	25 Feb	21 Mar	14 Apr	8 May	10 Jun
March	3 Apr	30 Apr	21 May	14 Jun	17 Jul
April	22 May	15 Jun	3 Jul	27 Jul	29 Aug
May	9 Jul	5 Aug	23 Aug	16 Sep	19 Oct
June	21 Aug	17 Sep	11 Oct	7 Nov	19 Dec
July	20 Sep	20 Oct	16 Nov	19 Dec	2 Feb
August	18 Oct	17 Nov	14 Dec	19 Jan	5 Mar
September	9 Nov	9 Dec	5 Jan	10 Feb	24 Mar
October	27 Nov	27 Dec	20 Jan	22 Feb	2 Apr
November	16 Dec	15 Jan	5 Feb	4 Mar	12 Apr
December	3 Jan	30 Jan	17 Feb	13 Mar	12 Apr

TABLE 3.6a Filling date for Pang reservoir

The filling dates are transferred to Figure 3.5a and smooth curves are passed through the points.

Start Month	Frequency				
	10	30	50	70	90
January	24	42	54	72	87
February	36	75	105	126	162
March	60	105	138	165	210
April	126	144	156	171	192
May	141	153	162	168	177
June	123	135	147	153	165
July					
August	81	93	105	114	126
September	54	72	84	96	114
October	45	60	72	84	99
November	45	54	69	75	87
December	39	48	63	72	84

TABLE 3.4c Accumulation times for Langdon reservoir inflow

Start Month	Frequency				
	10	30	50	70	90
January	-	48	78	114	156
February	-	54	96	132	183
March	30	75	120	156	204
April	60	102	138	171	213
May	105	129	159	183	213
June	138	156	174	189	210
July					
August	105	132	144	162	183
September	84	111	123	144	168
October	57	90	108	129	162
November	33	69	96	120	153
December	24	60	87	111	150

TABLE 3.4d Accumulation times for Roman reservoir inflow

End date		Start date at beginning of months shown in Year 1											
Year	Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1	Feb	31											
1	Mar	59	28										
1	Apr	90	59	31									
1	May	120	89	61	30								
1	Jun	151	120	92	61	31							
1	Jul	181	150	122	91	61	30						
1	Aug	212	181	153	122	92	61	31					
1	Sep	243	212	184	153	123	92	62	31				
1	Oct	273	242	214	183	153	122	92	61	30			
1	Nov	304	273	245	214	184	153	123	92	61	31		
1	Dec	334	303	275	244	214	183	153	122	91	61	30	
2	Jan	365	334	306	275	245	214	184	153	122	92	61	31
2	Feb	396	365	337	306	276	245	215	184	153	123	92	62
2	Mar	424	393	365	334	304	273	243	212	181	151	120	90
2	Apr	455	424	396	365	335	304	274	243	212	182	151	121
2	May	485	454	426	395	365	334	304	273	242	212	181	151
2	Jun	516	485	457	426	396	365	335	304	273	243	212	182
2	Jul	546	515	487	456	426	395	365	334	303	273	242	212
2	Aug	577	566	518	487	457	426	396	365	334	304	273	243
2	Sep	608	597	549	518	488	457	427	396	365	335	304	274
2	Oct	638	607	579	548	518	487	457	426	395	365	334	304
2	Nov	669	638	610	579	549	518	488	457	426	396	365	335
2	Dec	699	668	640	609	579	548	518	487	456	426	395	365
3	Jan	730	699	671	640	610	579	549	518	487	457	426	396
3	Feb	761	730	702	671	641	610	580	549	518	488	457	427
3	Mar	789	758	730	699	669	638	608	577	546	516	485	455
3	Apr	820	789	761	730	700	669	639	608	577	547	516	486
3	May	850	829	791	760	730	700	669	638	607	577	546	516
3	Jun	881	850	822	791	761	730	700	669	638	608	577	547
3	Jul	911	880	852	821	791	761	730	699	668	638	607	577
3	Aug	942	911	883	852	822	791	761	730	699	669	638	608
3	Sep	973	942	914	883	853	822	792	761	730	700	669	639
3	Oct	1003	972	944	913	883	853	822	791	760	730	699	669
3	Nov	1034	1003	975	944	914	883	853	822	791	761	730	700
3	Dec	1064	1033	1005	974	944	914	883	852	821	791	760	730

TABLE 3.5 Ready reckoner for date calculation

Start Month	Frequency				
	10	30	50	70	90
January	25 Jan	12 Feb	24 Feb	14 Mar	29 Mar
February	9 Feb	17 Apr	17 May	7 Jun	13 Jul
March	30 Apr	14 Jun	17 Jul	13 Aug	27 Sep
April	5 Aug	23 Aug	4 Sep	19 Sep	10 Oct
May	19 Sep	1 Oct	10 Oct	16 Oct	25 Oct
June	2 Oct	14 Oct	26 Oct	1 Nov	13 Nov
July					
August	21 Oct	2 Nov	14 Nov	23 Nov	5 Dec
September	25 Oct	12 Nov	24 Nov	6 Dec	24 Dec
October	15 Nov	30 Nov	12 Dec	24 Dec	8 Jan
November	16 Dec	25 Dec	9 Jan	15 Jan	27 Jan
December	9 Jan	18 Jan	2 Feb	11 Feb	23 Feb

TABLE 3.6c Filling date for Langdon reservoir

Start Month	Frequency				
	10	30	50	70	90
January	-	18 Feb	20 Mar	25 Apr	6 Jun
February	-	27 Mar	8 May	13 Jun	3 Aug
March	31 Mar	15 May	29 Jun	4 Aug	21 Sep
April	31 May	12 Jul	17 Aug	19 Sep	31 Oct
May	14 Aug	7 Sep	7 Oct	31 Oct	30 Nov
June	17 Oct	4 Nov	22 Nov	7 Dec	28 Dec
July					
August	14 Nov	11 Dec	23 Dec	10 Jan	31 Jan
September	24 Nov	21 Dec	2 Jan	23 Jan	16 Feb
October	27 Nov	30 Dec	17 Jan	7 Feb	12 Mar
November	4 Dec	9 Jan	5 Feb	1 Mar	3 Apr
December	25 Dec	30 Jan	26 Feb	22 Mar	30 Apr

Table 3.6d Filling date for Roman reservoir

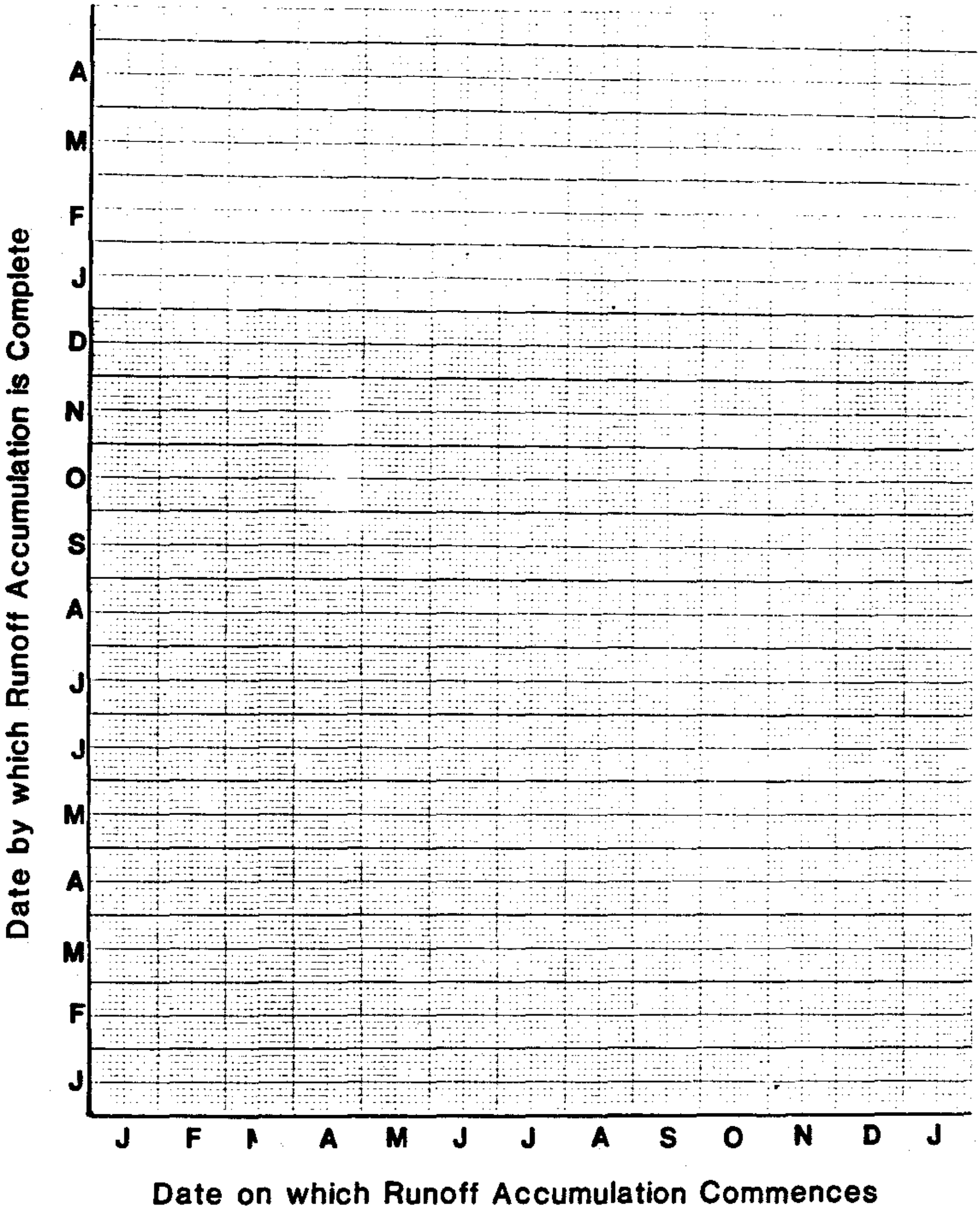

FIGURE 3.5b RUNOFF ACCUMULATION TIME FREQUENCY DIAGRAM FOR FALLOCH, LANGDON, ROMAN

Smooth curves are passed through the points of Figure 3.5b remembering that slope reversals are not feasible and the spacing between curves should be regular and free of sharp discontinuities.

Solution to the problem

The frequency of July 1st starts accumulating the requisite volume by December 1st is found by interpolation in Figure 3.5b to be _ _ _%. Thus the frequency of non accumulation - i.e. the risk of having to maintain the alternative supplies is _ _ _ %.

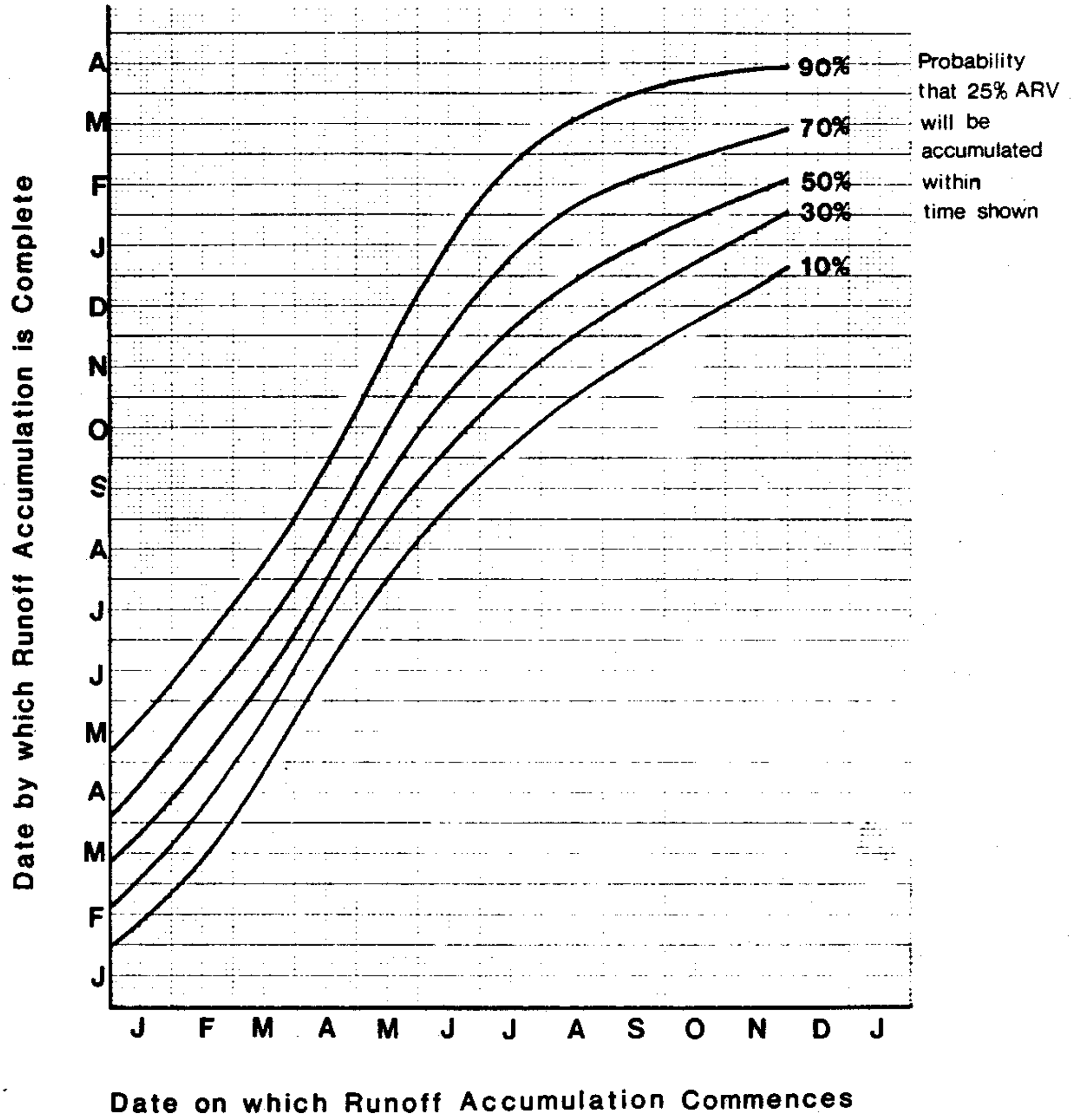

FIGURE 3.5a RUNOFF ACCUMULATION TIME FREQUENCY DIAGRAM FOR PANG RESERVOIR

Solution to the problem

The frequency of July 1st starts accumulating the requisite volume by December 1st is found by interpolation in Figure 3.5a to be about 60%. Thus the frequency of non-accumulation - i.e. the risk of having to maintain the alternative supplies is 40%.