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LOW FLOW ESTIMATION IN ARTIFICIALLY INFLUENCED CATCHMENTS

TRAINING COURSE

Report 1

Estimation of Natural Low Flow Statistics

Preface

There are a variety of low flow measures which describe and quantify different properties of flow regimes and these have different applications in the water industry. This Manual describes procedures for estimating key low flow statistics at ungauged sites within natural catchments based on catchment characteristics. Where catchments contain significant human activities which influence the flow characteristics, reference should be made to Report No 2 for details of defining the cumulative impact of artificial influence above a site and Report No 3 for techniques to adjust low flow statistics to take into account the impact of artificial influences. Report No 4 describes the Micro LOW FLOWS V2.0 software package which incorporates the estimation procedures described in Reports 1 to 3.

Contents

1. Introduction

The estimation of low flow statistics is a major component in the determination of minimum acceptable flows, the issue of abstraction licences and discharge consents and the setting of compensation releases from reservoirs. Four methods of low flow estimation are commonly applied by the UK water industry.

1. Calculation of low flow statistics from continuous gauged flow data series.

2. Direct measurement of low flows at "ungauged" sites by an occasional programme of "spot" current meter measurements.

3. Estimation of time series of river flows using catchment-specific hydrological models.

4. Estimation of low flow statistics by multivariate models which relate low flows to catchment characteristics.

Where continuous flow data are available at the design site of interest Method 1 is the most accurate and preferred technique. However, design information is generally required at ungauged locations and Method 2, or more commonly, flow estimation procedures (Methods 3 or 4) must be used.

The project Low Flow Estimation in Artificially Influenced Catchments (NRA R&D Report 274, Bullock et al., 1994) addressed the problem of assessing the impact of artificial influences on low flows and developed practical design techniques for low flow estimation in artificially-influenced catchments which have been incorporated into the Micro LOW FLOWS V2.1 software package. In particular, methods have been developed to incorporate the impact of:

(i) surface water influences including abstractions and discharges;

(ii) the bulk impact of groundwater abstractions;

(iii) impounding reservoirs.

1.1 THE IMPACT OF ARTIFICIAL INFLUENCES ON LOW FLOWS

In natural rivers, the magnitude of low river flows are determined by climatic and runoff generation processes, amongst which effective rainfall, groundwater recharge and aquifer properties exert a dominant function (Gustard et al., 1992). However, as a result of the development of rivers and catchments for water resource purposes, few rivers now possess natural river flow regimes.

The early development of river regulation began in the late 18th Century initially for navigation requirements and later to meet the growing demands of population centres. In upland areas small rivers were impounded to create reservoirs to store winter high flows to supplement summer low flows. The rate of large dam-building accelerated after 1950.

The demands of the electricity industry, requiring water for cooling, and agriculture for irrigation have continued to grow. Since 1965 the emphasis in water management has been on direct river management, with reservoirs, abstractions, water treatment and inter-basin transfers providing for the integrated management of water resources.

As a consequence of this level of water development, many rivers in England and Wales exhibit artificially influenced river flow regimes and few rivers display natural flow characteristics. As a broad indication of the extent of artificial influences upon low flows, fewer than 20% of the gauged low flow regimes, represent 'natural' conditions. In addition, many artificial influences may operate seasonally, for example abstractions for spray irrigation.

The impact of man's development of water is most severe during periods of low flows when absolute volumes of water transfers represent a significantly higher proportion of the natural flow regime. As a consequence, it is necessary to consider estimation of low flow statistics on a monthly basis.

1.2 SUMMARY OF OVERALL METHOD

The overall methodology for estimating low flow statistics at ungauged sites in artificially influenced catchments, taking into account the effects of abstractions from surface and groundwater sources, discharges to surface water and compensation for estimating flows from impounding reservoirs can be summarised as follows:

1. Estimation of key natural low flow statistics at the ungauged site; specifically mean flow, monthly mean flow, monthly flow duration curves and mean monthly minima;

2. Identification of all artificial influences upstream of the ungauged site;

3. Quantification for all individual artificial influences upstream of actual values of monthly abstraction rates, discharge returns and reservoir compensation flows;

4. Simulation using the Theis analytical solution of the reduction in streamflow associated with abstractions from groundwater sources according to source and aquifer properties;

5. Construction of a monthly artificial influence profile at the ungauged site which represents the net impact of all upstream artificial influences;

6. Combination of the estimated natural monthly low flow statistics with the monthly artificial influence profile to estimate artificially influenced monthly low flow statistics;

7. Aggregation of monthly artificially influenced low flow statistics to produce annual artificially influenced low flow statistics for design purposes, notably mean flow, flow duration curves and low flow frequency statistics;

8. Estimation of natural and artificially influenced low flow statistics at numerous locations along a river to construct residual flow diagrams.

The estimation procedure makes use of natural low flow statistics and artificial influence data estimated on a monthly basis. This allows the seasonal variations in flows and operation of individual artificial influences to be taken into account. In particular, the lower summer flows are more sensitive to variations in the scale of the artificial influence.

1.3 LOW FLOW ESTIMATION MANUALS

This report represents the first in a series of estimation manuals which provide procedures for estimating artifially influences flow statistics in ungauged catchments. Report No. 2 describes techniques for defining the cumulative impact of artificial influences above a site. Report No. 3 describes how the low flow statistics can be adjusted. The implementation within the software is discussed in Report No.4.

This manual describes the estimation of natural monthly low flow statistics at ungauged sites, specifically mean flow and monthly mean flow, monthly flow duration curves and mean monthly minima. Section 2 describes the methods for estimating catchment characteristics and Section 3 the methods for estimating annual low flow statistics. Section 4 describes the methodology for estimation of mean flow for monthly time periods. Section 5 describes the methodology for estimation of monthly flow duration curves. Section 6 describes the methodology for estimation of mean monthly minima and Section 7 discusses the Micro LOW FLOWS implementation of the estimation of monthly statistics.

To help explain the estimation techniques, Appendix A provides a worked example for the Pang catchment for which all calculations have been completed. Information for the Roman catchment is provided for the reader to work through the procedures during the syndicate exercises.

2. Estimation of Catchment Characteristics and Annual Flow Statistics

Hydrological design methods for estimating annual low flow statistics, particularly the mean annual 7-day minimum, MAM(7), and the 95 percentile exceedance flow, Q95(1), at ungauged sites using catchment characteristics have been developed by the Institute of Hydrology (IH) and published in the Low Flow Studies Report (Institute of Hydrology, 1980) and updated in Report 108, Low Flow Estimation in the United Kingdom (Gustard et al., 1992). The Low Flow Studies Report concluded that when low flows are expressed as a percentage of the long-term mean flow (standardised), the dependence on the climatic variability across the country and the effect of catchment area are removed. As a result, the estimation of low flows at an ungauged site is largely dependent on the geological characteristics of the catchment. Therefore, the estimation procedures are based on statistical models describing the relationship between low flow statistics and hydrological response variables derived from catchment geology and soils.

The estimation of the hydrological characteristics at a site involves the following steps:

1. Identification of the catchment boundary above the site and estimation of the catchment area;

2. Estimation of the catchment average rainfall and potential evaporation from gridded climate maps;

3. Estimation of the mean flow from the rainfall, potential evaporation and catchment area;

4. Calculation of the representative low flow statistic, expressed as a percentage of the mean flow, from gridded maps derived using the relationship between flows and soil characteristics;

5. Estimation of the flow regime within the catchment as represented by the flow duration curve and flow frequency curve.

Each of these steps is discussed in detail in Introduction to Low Flow Hydrology, Reports 1-3 and Report 108 and summarised in the following sections.

2.1 CATCHMENT AREA

The catchment area is defined as the total area contributing to the flow at a particular point within the river network. The catchment boundary can be identified and digitised from topographic maps using the best available scale, normally 1:25 000 or 1:50 000. The boundary definition should be guided by the river network, contours and spot heights. In some catchments, predominantly chalk and limestone catchments, the extent of the aquifer may be significantly different from the topographic boundary. Therefore the groundwater divide should be used in these cases. The catchment area can then be calculated using a planimeter or overlaying the boundary onto graph paper and counting the squares.

2.2 CATCHMENT AVERAGE RAINFALL AND POTENTIAL EVAPORATION

The mean annual average rainfall is calculated using maps of standard period (1941-70) average annual rainfall (SAAR) available from the Meteorological Office at a scale of 1:625 000. The catchment boundary is overlaid onto the map and the catchment average rainfall is calculated using a weighted area technique or by taking the average of 20 equally spaced points.

The mean annual average potential evaporation is calculated in an identical way using maps of annual average Potential Evaporation (PE) available from the Meteorological Office at a scale of 1:2000 000.

The rainfall and evaporation maps are also available as gridded databases at a resolution of $1km^2$. The boundary can be overlaid onto the grids and the catchment average is then the average of the cell values within the catchment boundary.

2.3 MEAN FLOW

Long-term mean flow is used to scale the flow duration curve so that the range of flows can be expressed in cubic metres per second (m^3s^{-1}). The mean flow can be estimated from the average annual runoff depth (AARD) in mm over the whole catchment (AREA in km^2) using the equation:

$$MF = AARD \times AREA \times 3.17 \times 10^{-5} \quad (1)$$

In the UK, the average annual runoff depth is derived using a water balance given by

$$AARD = SAAR - (r \times PE) \quad (2)$$

where $r = (0.00061 \times SAAR) + 0.475$ for $SAAR < 850mm$
$r = 1$ for $SAAR \geq 850mm$ (3)

For catchments with rainfall in excess of 850mm, the actual evaporation is equal to the potential evaporation as a result of relatively short periods when evaporation is limited by soil moisture deficit. Where evaporation is limited by rainfall (of less than 850mm), an adjustment factor (r) is applied to the potential evaporation.

2.4 LOW FLOW STATISTICS

The key low flow statistics which are used to characterise the low flow regime are the long term Q95, the flow exceeded or equalled for 95% of the time, and the MAM(7), the mean annual 7-day minimum flow. These natural statistics are normally expressed as a percentage of the long-term mean flow and referred to as standardised flow statistics. They are estimated using statistical multivariate regression models which have been derived by relating the low flow statistics to the hydrological characteristics of soils within gauged catchments. The hydrological characteristics of soils are represented by the Hydrology of Soil Types (HOST) classification (Boorman & Hollis, 1990) and the derived Low Flow HOST Groups (Gustard *et al.*, 1992).

The HOST classification scheme is based on the assignment of underlying soil and drift geology into 29 classes and differentiation of the overlying soil types according to physical properties, specifically: depth to impermeable layer; depth to a gleyed layer; integrated air capacity; and the presence, or absence, of peat. Two further classes are urban (in England and Wales only) and lake. Comparison of Q95 values derived for each of the HOST classes identified that these HOST classes could be aggregated into 12 Low Flow HOST Groups for each of which estimates of Q95 have been defined.

For any ungauged catchment the procedure for calculating the natural long term Q95 can be summarised as:

1. Define the catchment boundary (as described in Section 2.1);

2. Rescale the catchment boundary and overlay the catchment boundary onto a 1:250000 scale soil association map (published by the Soil Survey & Land Research Centre (1983) for England and Wales; Macaulay Land Use Research Institute (1990) for Scotland);

3. The fractional extent of each soil association can be calculated using a planimeter or counting squares. Ensure that the sum of the areas of the soil associations is equal to the catchment area;

4. The appropriate HOST class and Low Flow HOST Groups can be identified from Appendix 4 of Report 108 and the corresponding value of Q95 can be found;

5. The weighted Q95 for each soil association is calculated;

6. The catchment average Q95 is then the sum of the weighted Q95 values.

This method is presented in more detail in Introduction to Low Flow Hydrology, Report 3. The natural long term Q95 is required for the estimation of the natural annual flow duration curve and also for the estimation of the monthly mean flow.

The MAM(7) is estimated in exactly the same way and is used subsequently to estimate natural frequency curves and also for the estimation of mean monthly minima.

2.5 ANNUAL FLOW DURATION CURVE

The flow duration curve is used to illustrate the cumulative distribution of flows over the whole range of flows. Using the flow duration curve it is possible to identify the percentage of time that any given flow is exceeded. (Refer to Introduction to Low Flow Hydrology, Report 1 and Gustard et al., 1992 for more detailed information).

The gradient of a flow duration curve is principally controlled by the catchment low flow response, as represented by the magnitude of the standardised Q95. The procedure for deriving the long term flow duration curve at an ungauged site utilises the family of derived type curves (Figure 2.1) and can be divided into two components:

1. Estimate the natural Q95 (as a %MF);

2. Use the Q95 to identify the appropriate type curve(s) using Table 2.1 and interpolate between curves if necessary

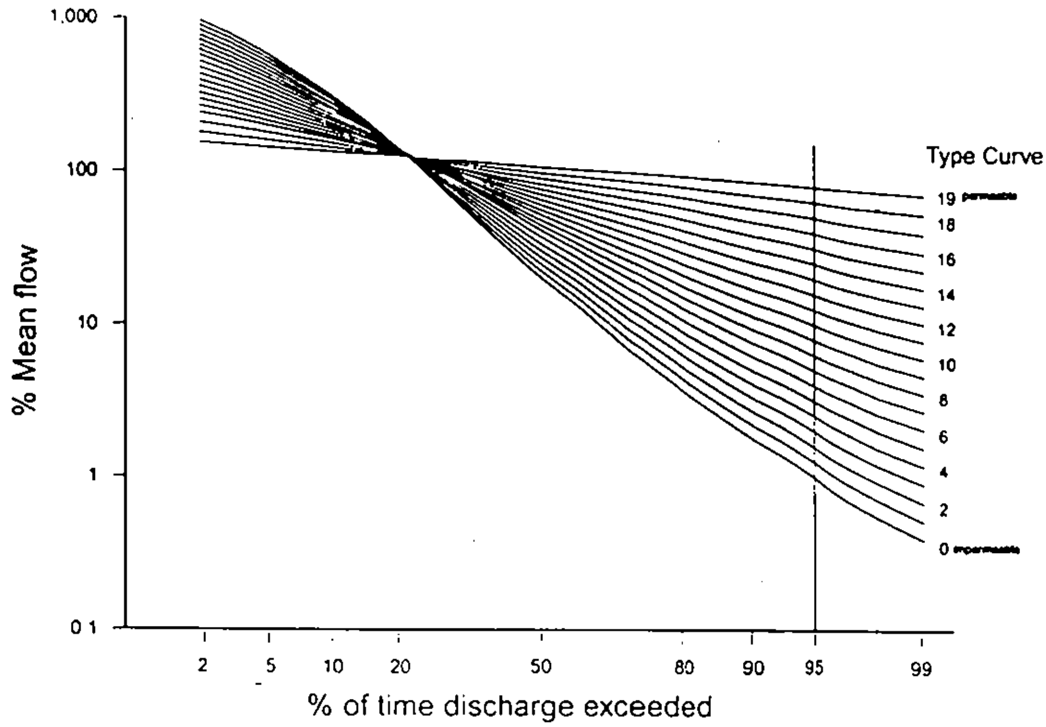

Figure 2.1 *Annual flow duration type curves*

Table 2.1 *Flow duration type curves (as percentage of mean flow)*

Type curve		0	1	2	3	4	5	6	7	8	9
Percentile	2	975.70	904.17	838.77	776.04	719.91	667.48	618.22	572.53	520.00	472.29
	5	577.26	534.08	511.37	480.48	452.42	425.82	400.44	376.64	350.65	326.46
	50	20.49	22.69	25.10	27.86	30.82	34.11	37.81	41.82	45.10	48.64
	80	3.70	4.42	5.27	6.33	7.54	9.00	10.77	12.86	15.20	17.98
	90	1.73	2.13	2.62	3.25	3.99	4.92	6.07	7.47	9.16	11.22
	95	1.00	1.26	1.58	2.00	2.51	3.16	3.98	5.01	6.30	7.94
	99	0.38	0.51	0.67	0.88	1.16	1.53	2.02	2.65	3.46	4.52

Type curve		10	11	12	13	14	15	16	17	18	19
Percentile	2	428.96	389.60	353.86	321.39	291.65	264.89	240.09	206.89	178.28	153.69
	5	303.93	282.96	263.44	245.26	228.19	212.45	197.49	176.99	158.62	142.20
	50	52.46	56.57	61.01	65.79	71.00	76.57	82.60	89.91	97.86	106.49
	80	21.25	25.13	29.71	35.12	41.58	49.16	58.08	67.82	79.21	92.46
	90	13.75	16.86	20.66	25.32	31.09	38.10	46.67	56.95	69.50	84.77
	95	10.00	12.57	15.83	19.93	25.13	31.64	39.81	50.13	63.12	79.43
	99	5.89	7.69	10.03	13.08	17.11	22.32	29.13	39.00	52.22	69.85

2.6 LOW FLOW FREQUENCY CURVE

The low flow frequency curve illustrates the probability that a year will contain an annual minima less than a given discharge. The probability is commonly expressed in terms of the average interval (in years) between the occurrence of an event with a specified severity, referred to as the return period. The curve may be drawn from a daily or monthly flow data or from the minima from consecutive D-day periods (Refer to Introduction to Low Flow Hydrology, Report 2 or Gustard et al for more information).

The flow frequency curve 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 and used for cost benefit analysis.

In common with the flow duration curve estimation, in the absence of gauged flow data, the natural low flow frequency curve can be derived from a family of flow frequency type curves (Figure 2.2) based on the estimated natural MAM(7) and the duration of interest using the following steps:

1. Estimate the natural MAM(7) from soil characteristics, expressed as a percentage of the natural long term mean flow (Refer to Section 2.4);

2. Use the MAM(7) to estimate the mean annual minimum for the duration of interest (MAM(D)) (optional).

   The relationship between the MAM(D), expressed as a fraction of MAM(7), and duration D is linear (Gustard et al., 1992), and the gradient of the line (GRADMAM) is dependent upon the natural MAM(7) and the catchment average rainfall:

   $$\text{GRADMAM} = \text{SAAR}^{0.629} \times \text{MAM}(7)^{-1.02} \times 2.12 \times 10^{-3}$$

   Therefore MAM(D) can be derived using:

   $$\text{MAM(D)} = \{1 + (D - 7) \times \text{GARDMAM}\} \times \text{MAM}(7)$$

3. Use MAM(7) and D to identify the appropriate type curve from Table 2.2 and estimate the annual minima for the return periods, using the factors given in Table 2.3 applied to the MAM(D).

Table 2.2 *Type curves for required duration and MAM(7)*

MAM(7) as % MF	Duration days 1	7	60	180
5	2	2	1	1
10	5	5	4	5
15	6	6	5	6
20	7	7	7	7
25	7	7	7	7
30	7	7	7	7
35	7	7	7	8
40	7	7	7	8
45	8	8	8	9
50	7	8	9	10
55	11	11	12	12

Table 2.3 *Flow frequency type curves*

Plotting position W	TYPE CURVE 1	2	3	4	5	6	7	8	9	10	11	12
0.5	0.85	0.86	0.87	0.89	0.90	0.91	0.92	0.93	0.94	0.96	0.96	0.96
1.0	0.66	0.69	0.70	0.72	0.75	0.76	0.79	0.80	0.82	0.84	0.86	0.87
1.5	0.50	0.53	0.55	0.58	0.61	0.62	0.66	0.68	0.71	0.73	0.76	0.79
2.0	0.34	0.38	0.40	0.44	0.48	0.50	0.54	0.57	0.61	0.64	0.68	0.71
2.5	0.20	0.24	0.27	0.32	0.36	0.39	0.44	0.48	0.52	0.56	0.60	0.65
3.0	0.07	0.12	0.16	0.21	0.25	0.30	0.35	0.40	0.44	0.49	0.53	0.59

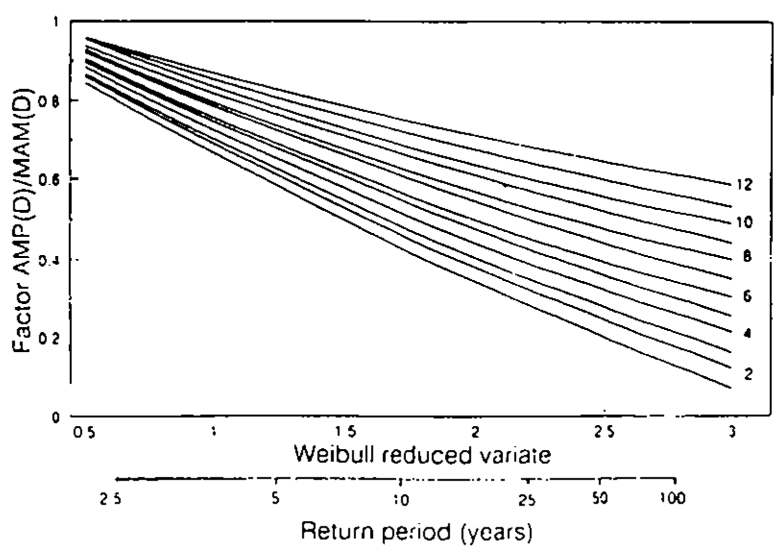

Figure 2.2 *Flow frequency type curves*

3. Estimation of Monthly Statistics

As discussed in Section 1, the adjustment of natural low flow statistics for artificial influences requires the estimation of monthly low flow statistics. This allows both the seasonal variations in flows and influences be taken into account. In order to derive artificially influenced flow statistics, the key monthly statistics which need to be estimated are:

(i) 12 values of monthly mean flow;

(ii) 12 monthly flow duration curves;

(iii) mean monthly 7-day minima for 12 months.

Figure 3.1 provides an overview of the overall estimation procedure. Each of the monthly statistics and methods for estimating them are discussed in the following sections.

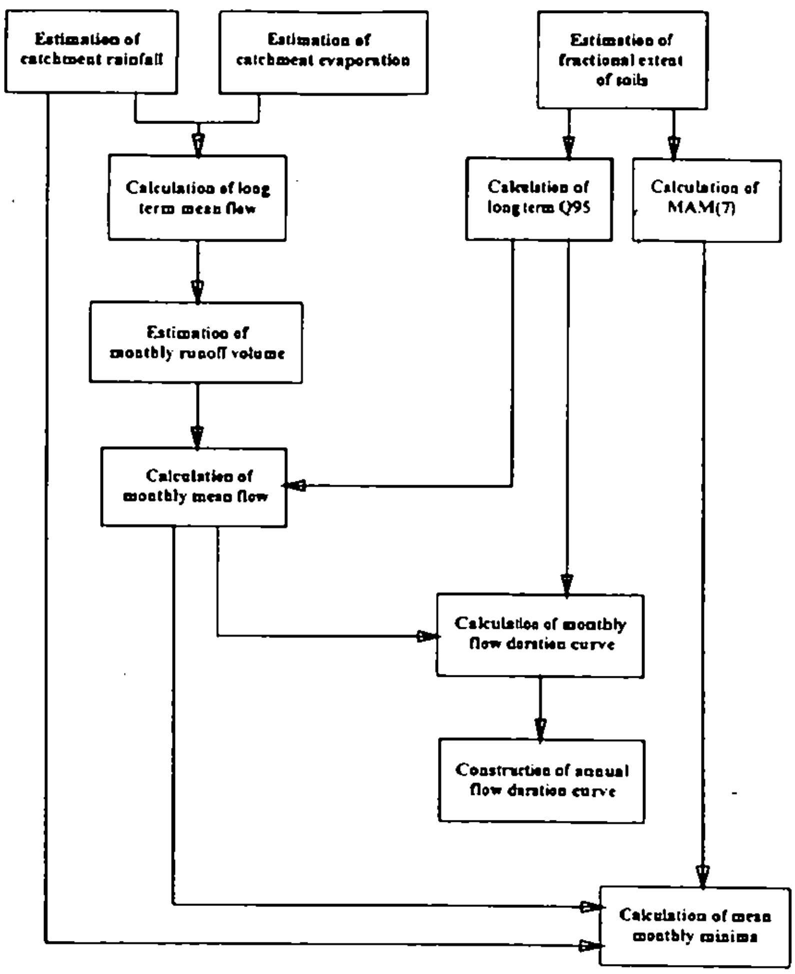

Figure 3.1 *Overall estimation procedure*

4. Estimation of Monthly Mean Flow

The monthly flow duration curve and mean monthly minima are expressed, and estimated, as a percentage of the monthly mean flow. As discussed in Section 1, the magnitude of the variation in UK flow regimes is dominated by catchment hydrogeology. Expressing these flow statistics in dimensionless form removes the overlying effects of the scale of catchment hydrological processes and enables statistical relationships between these low flow statistics and catchment characteristics to be made. Estimates of the monthly mean flows are required so these estimated low flow statistics can be expressed in cumecs.

Three stages are required for the derivation of the monthly mean flows illustrated in Figure 4.1. The first is the estimation of the long term annual mean flow (discussed previously in Section 2). The second is the estimation of the monthly runoff volume in each month standardised by the long term annual runoff volume. The third is the conversion of the monthly runoff volume to monthly mean flow.

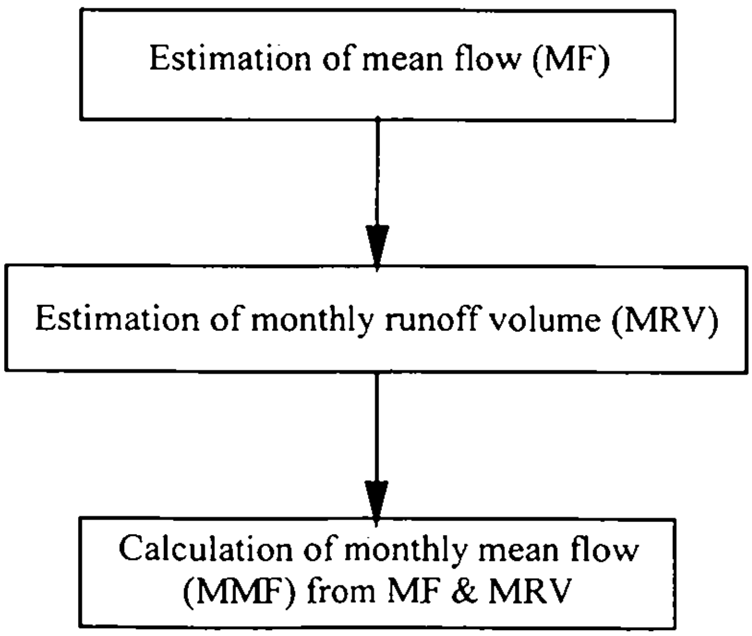

Figure 4.1 *Stages in the estimation of monthly mean flow*

4.1 ESTIMATION OF LONG TERM MEAN FLOW

The natural long term mean flow is derived from catchment characteristics using the water balance equation described in detail in Section 2.

4.2 ESTIMATION OF MONTHLY RUNOFF VOLUME

The variability of Monthly Runoff Volumes (MRV) (expressed as a percentage of long term annual runoff volume, ARV) is related to the magnitude of standardised Q95; i.e. the permeability of the catchment. To estimate the runoff volume in each month:

1. Calculate the natural mean flow and Q95 (as described in Section 2);

2. If the catchment is in Great Britain with a Q95 of less than 30% of mean flow select the appropriate national maps of MRV for each month; these are illustrated in Figures 4.2 and 4.3;

3. For catchments in Great Britain which have Q95 flows greater than 30% of mean flow, the spatial variability of MRV across Great Britain is low. Therefore the average runoff volume can be represented in each month by a single value; these are presented in Table 4.1.

Table 4.1 *Monthly runoff volume for catchments in Great Britain with Q95 >30%MF*

Monthly Runoff Volume (% Annual Runoff Volume)											
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
11.8	14.2	13.0	10.3	8.1	6.4	5.0	4.6	4.5	5.3	7.0	9.8

4. The monthly runoff volumes within catchments in Northern Ireland display small regional variations. The average monthly runoff volumes are given in Table 4.2.

Table 4.2 *Monthly runoff volume for Northern Ireland catchments*

Monthly Runoff Volume (% Annual Runoff Volume)											
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
16.8	12.3	8.7	5.3	3.9	2.7	2.4	3.4	5.9	9.9	12.9	16.0

4.3 ESTIMATION OF MONTHLY MEAN FLOW

Having obtained the monthly runoff volume from the above method, the average monthly mean flow (MMF) is calculated in $m^3 s^{-1}$ within each month.

$$MMF = \frac{MRV \times MF}{(100/12)}$$

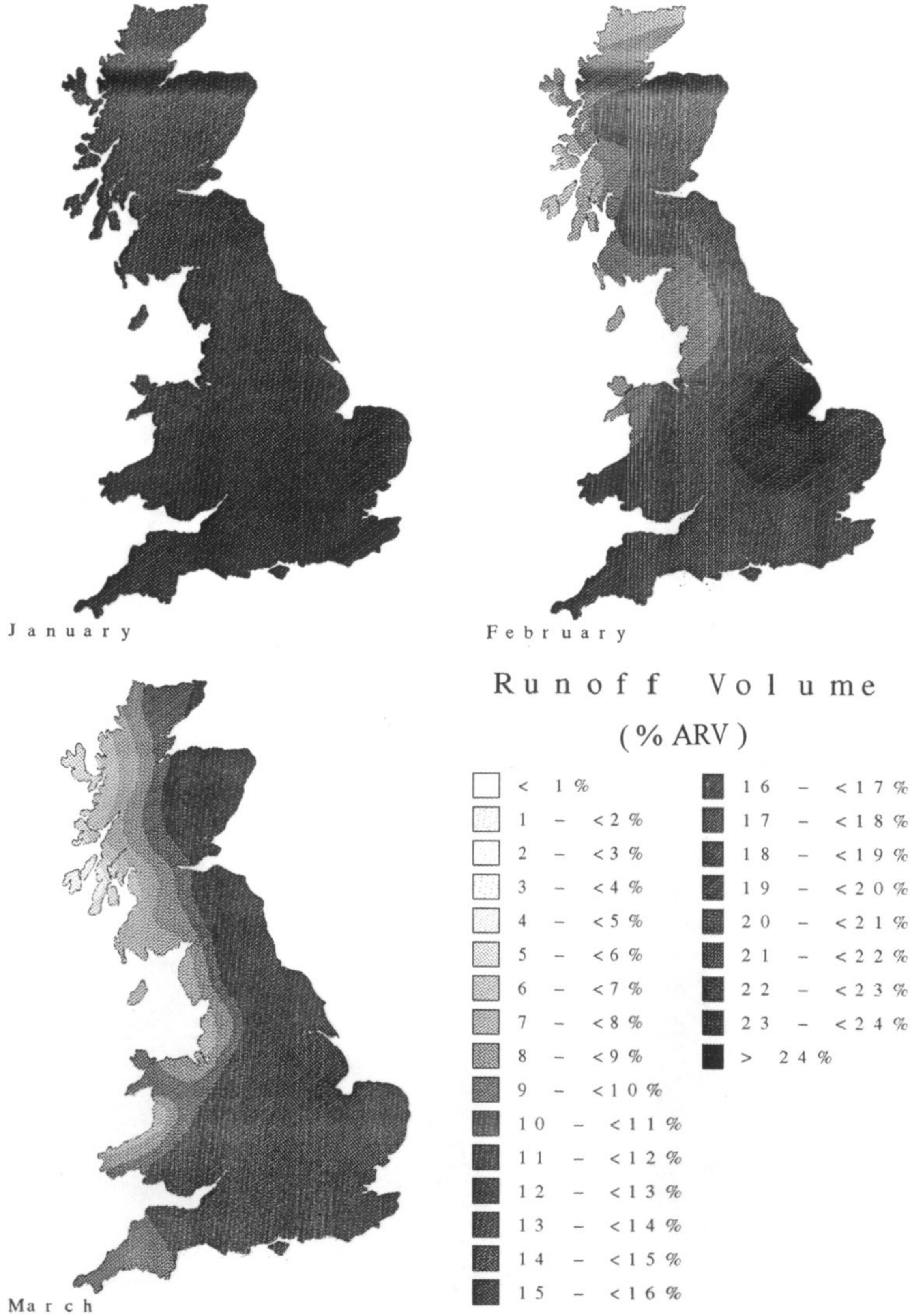

Figure 4.2 *Monthly runoff volumes (as a percentage of annual runoff volume) occurring in catchments with Q95 in the range 0-15% of the mean flow*

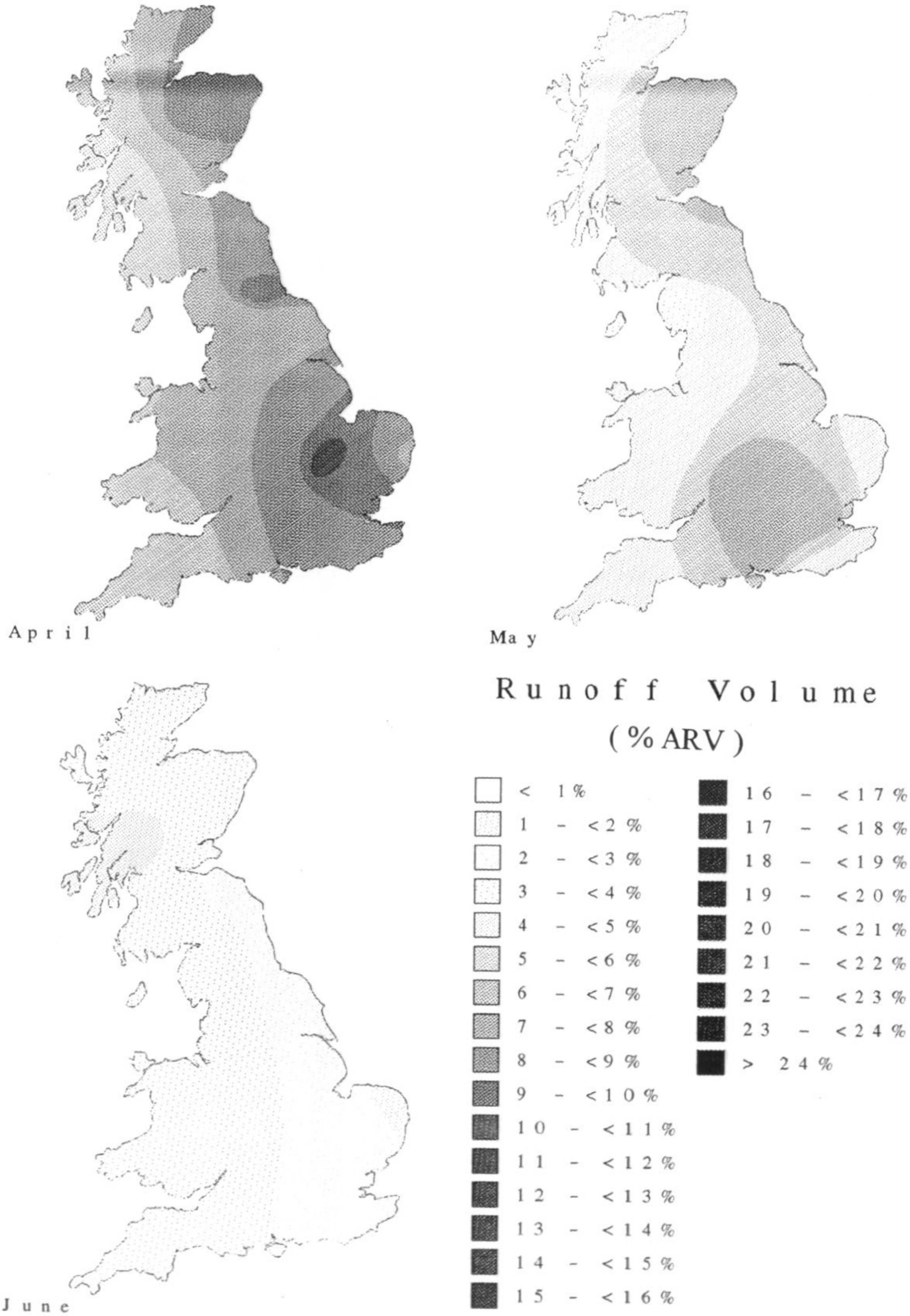

Figure 4.2 Contd. *Monthly runoff volumes (as a percentage of annual runoff volume) occurring in catchments with Q95 in the range 0–15% of the mean flow*

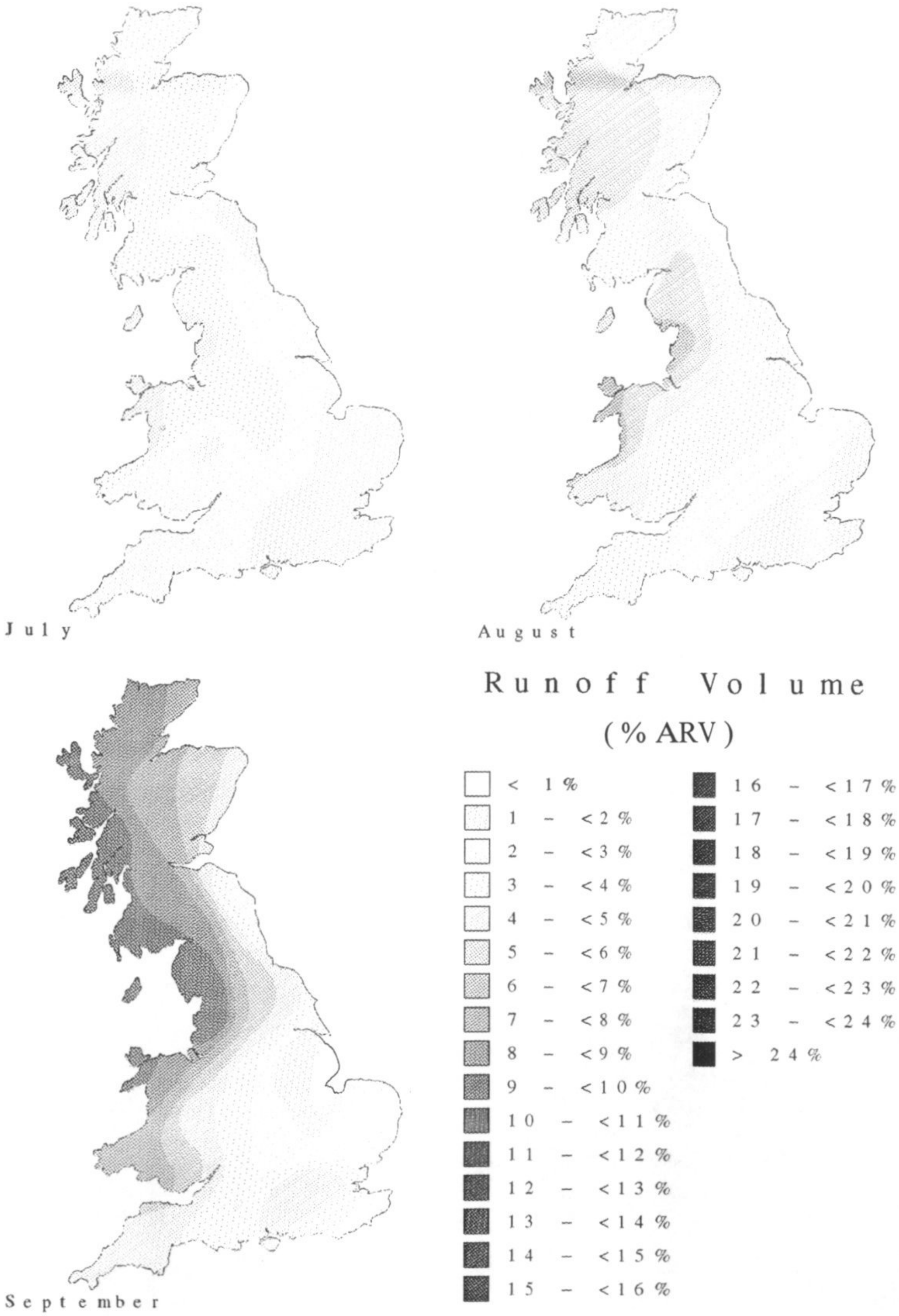

Figure 4.2 Contd. *Monthly runoff volumes (as a percentage of annual runoff volume) occurring in catchments with Q95 in the range 0–15% of the mean flow*

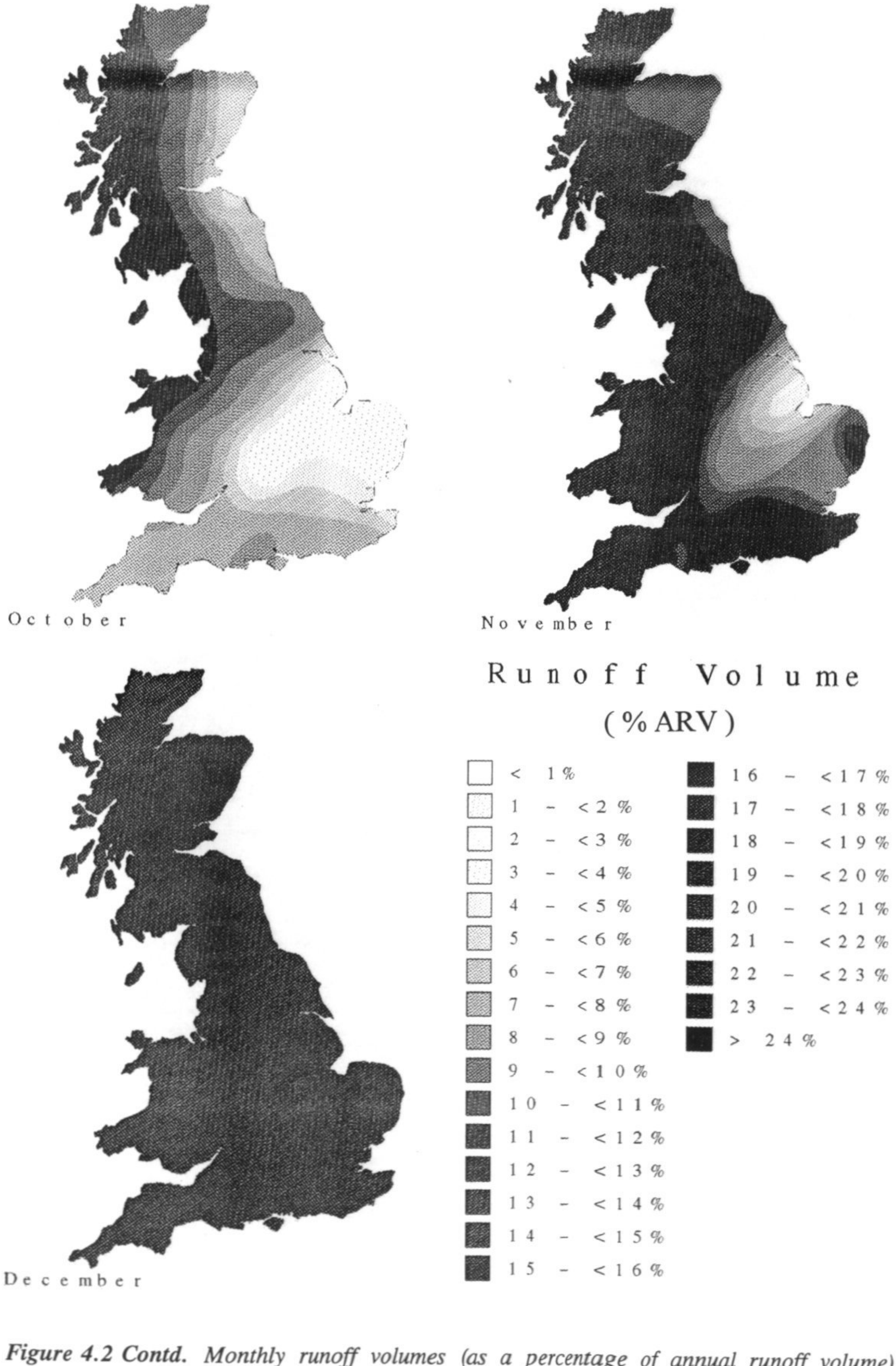

Figure 4.2 Contd. *Monthly runoff volumes (as a percentage of annual runoff volume) occurring in catchments with Q95 in the range 0–15% of the mean flow*

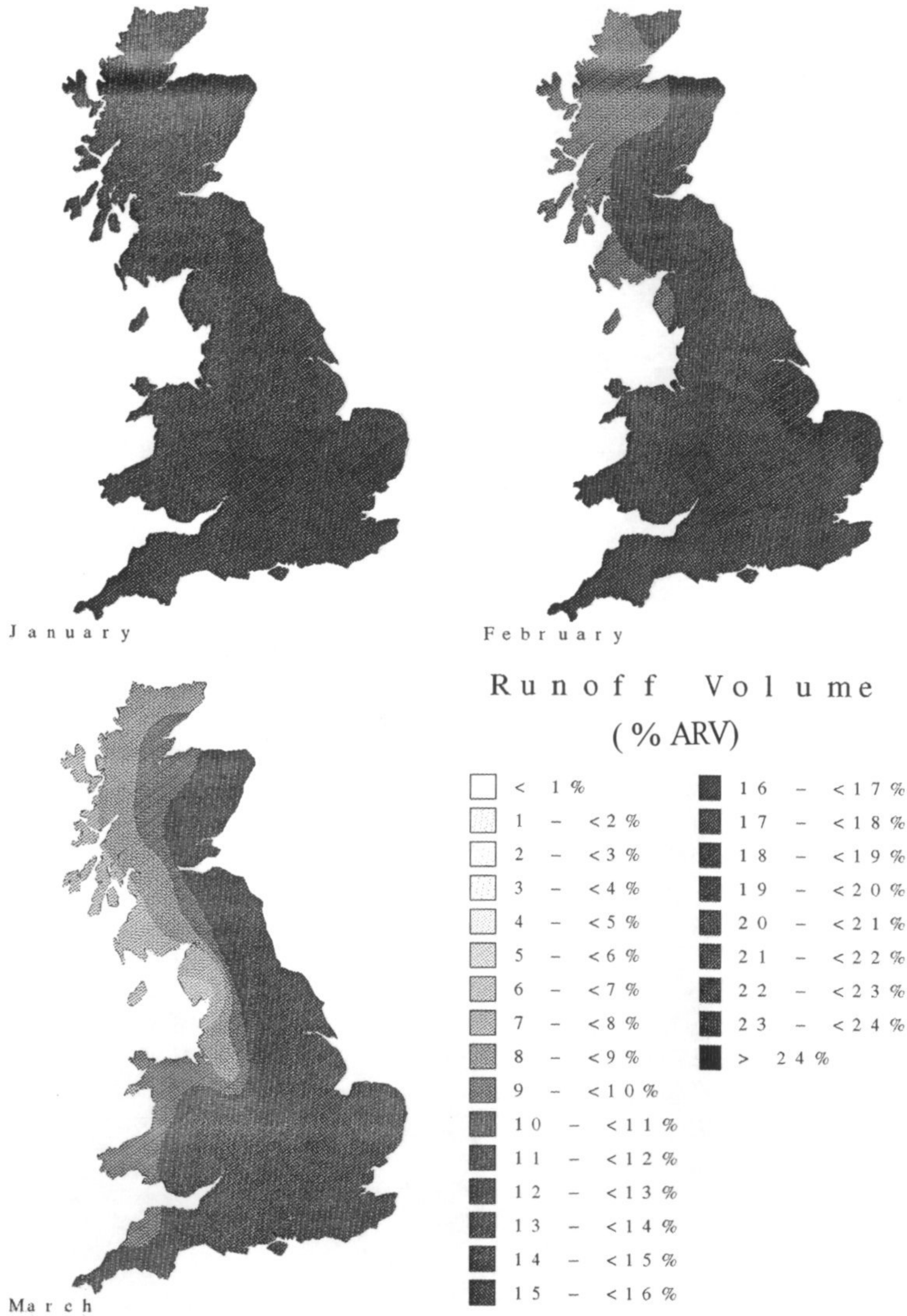

Figure 4.3 *Monthly runoff volumes (as a percentage of annual runoff volume) occurring in catchments with Q95 in the range 15-30% of the mean flow*

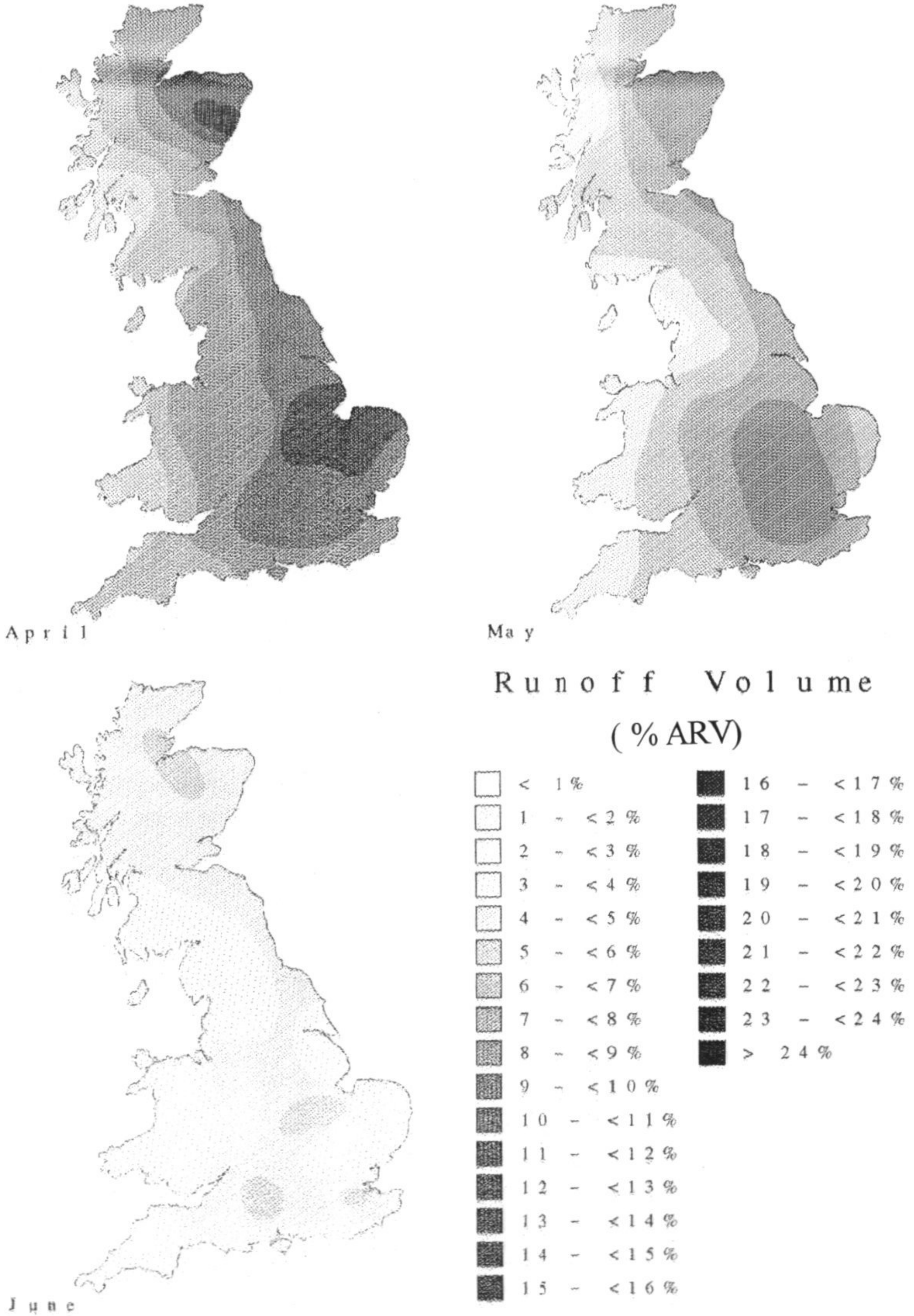

Figure 4.3 Contd. *Monthly runoff volumes (as a percentage of annual runoff volume) occurring in catchments with Q95 in the range 15-30% of the mean flow*

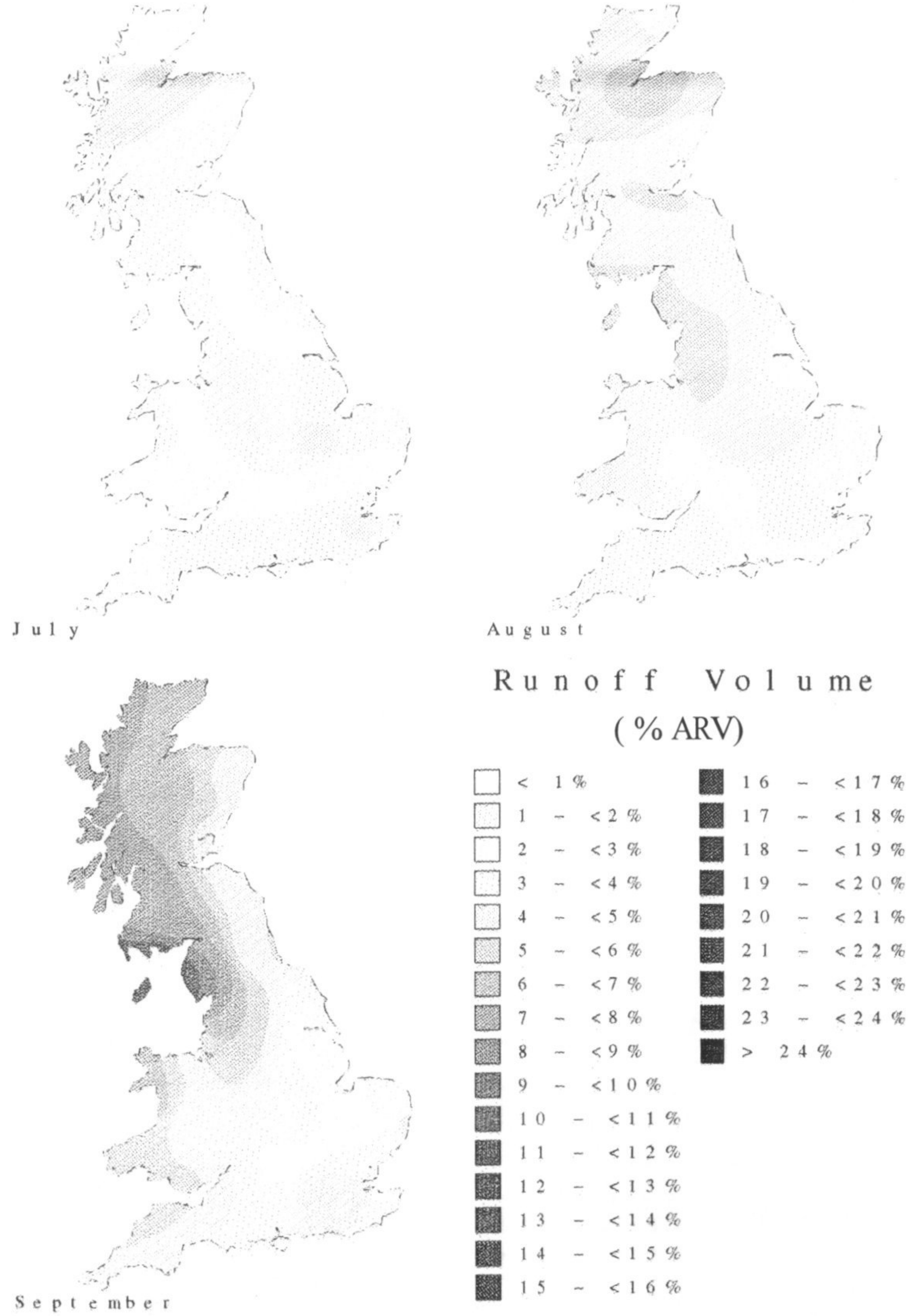

Figure 4.3 Contd. *Monthly runoff volumes (as a percentage of annual runoff volume) occurring in catchments with Q95 in the range 15-30% of the mean flow*

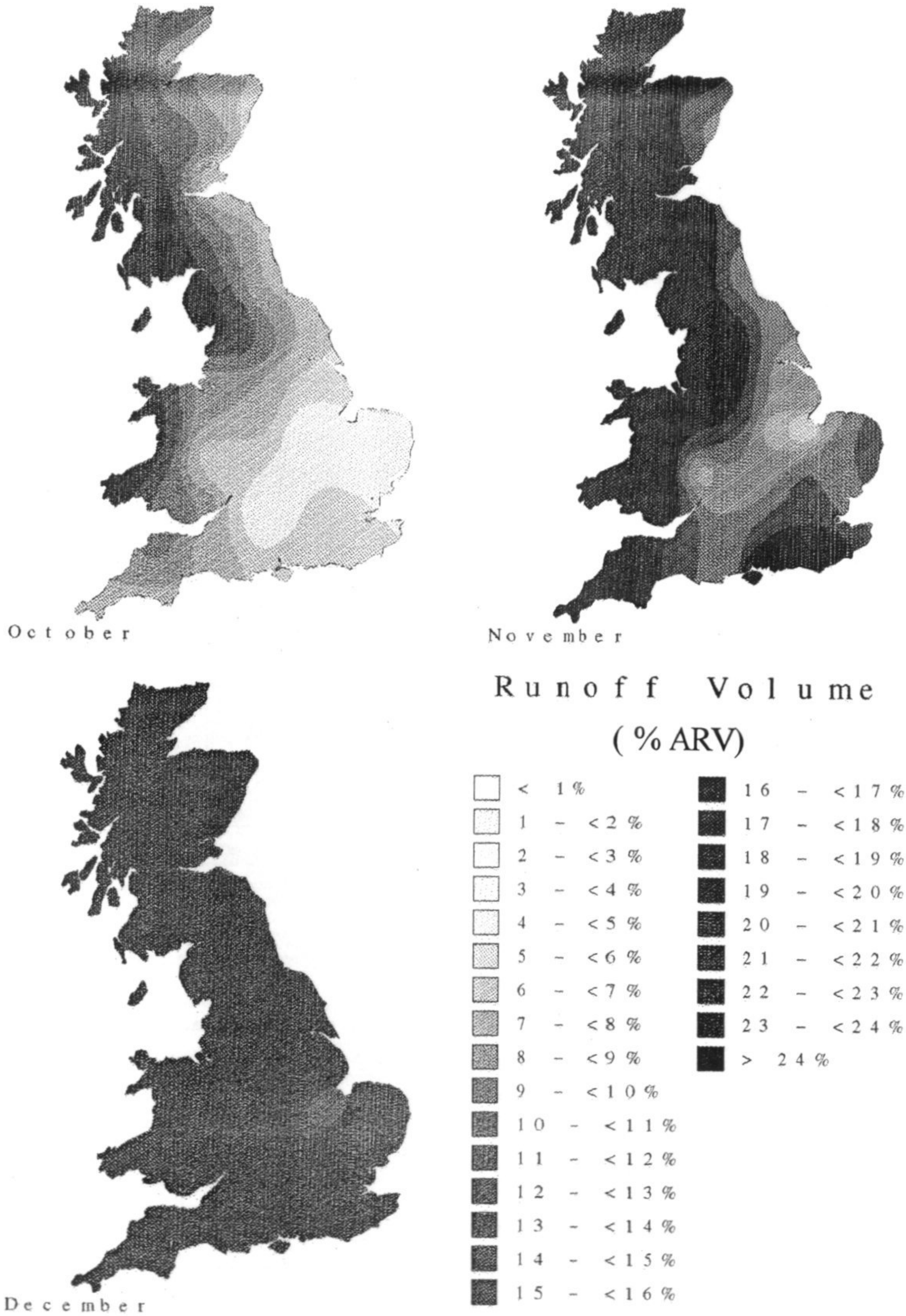

Figure 4.3 Contd. *Monthly runoff volumes (as a percentage of annual runoff volume) occurring in catchments with Q95 in the range 15-30% of the mean flow*

5. Monthly and Reconstructed Annual Flow Duration Curve

The seasonal variations of the flow regime are lost when the flows are represented using the long term annual flow duration curve. Therefore procedures are needed for the estimation of monthly flow duration curves. Analysis of pooled monthly flow duration curves from 687 gauged catchments indicated that the shape of the curves, when expressed as a percentage of the monthly mean flow, were consistent with the family of type curves used for estimating the annual flow duration curve at an ungauged site (Bullock *et al.*, 1994). Therefore the method for estimating monthly flow duration curves makes use of the existing type of curves. The capability to estimate natural monthly flow duration curves allows variations in monthly abstraction, discharge and reservoir impacts to be taken into account on a month by month basis, thus combining the natural seasonal variability of flows with the seasonal distribution of artificial influences.

5.1 MONTHLY FLOW DURATION CURVES

The method for the estimation of the standardised monthly flow duration curves involves two steps: first the calculation of the natural Q95 and second the identification of the appropriate type curves for the individual months. The annual flow duration curve can be reconstructed from the 12 standardised monthly flow duration curves and the monthly mean flow estimates. It is important that the reconstructed annual flow duration curve equals the natural annual flow duration curve estimated by Gustard *et al.* (1992), for purposes of consistency. The estimation procedure is summarised in Figure 5.1.

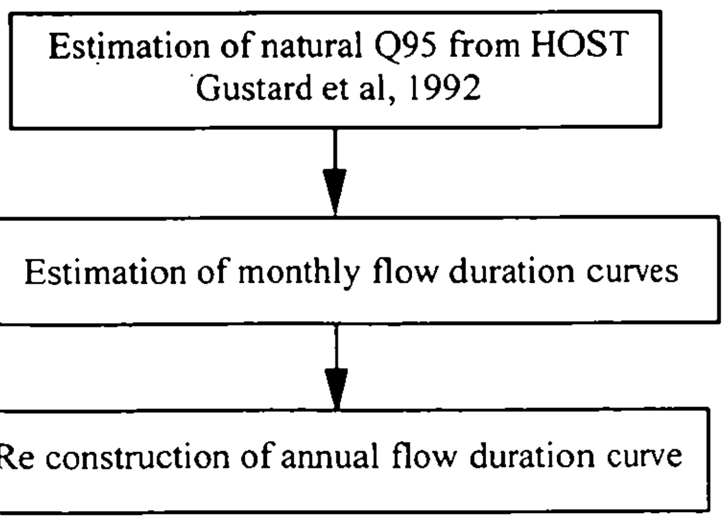

Figure 5.1 Stages in the estimation of monthly flow duration curves

The procedure for estimating the monthly flow duration curves is given below:

1. Calculate the natural annual Q95 using methods described in Section 2 (and discussed in detail in Introduction to Low Flow Hydrology, Report 1);.

2. From Table 5.2 identify the appropriate Q95 group and read the appropriate annual type curve for each month;

3. Select the corresponding type curves from Table 5.3;

4. Plot the selected curves.

Table 5.2 *Matrix of type curves for monthly pooled flow duration curves*

Q95 Group	Annual type curves											
% MF	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-2.5	10	11	11	10	8	8	8	6	6	5	7	9
2.5-7.5	12	12	12	12	10	10	11	9	9	9	10	11
7.5-12.5	13	13	13	14	13	13	13	12	12	11	12	12
12.5-17.5	14	14	14	15	15	15	15	14	13	12	13	13
17.5-22.5	14	15	15	15	16	16	16	15	15	13	14	14
22.5-27.5	15	15	15	16	16	16	16	16	16	14	15	14
27.5-32.5	15	16	16	16	16	17	17	16	17	16	15	15
32.5-37.5	16	16	16	17	17	17	17	17	17	16	16	15
37.5-42.5	16	16	17	17	17	18	18	17	18	17	17	16
42.5-47.5	17	17	17	17	17	18	18	18	18	17	17	17
47.5-52.5	18	17	18	17	18	18	18	18	18	18	18	18
52.5-57.5	18	18	18	18	18	18	18	18	18	18	18	18
57.5-62.5	18	18	18	18	18	18	18	19	18	18	18	18
62.5-67.5	18	18	18	18	18	18	18	19	19	19	19	18
72.5-77.5	18	19	19	19	19	19	19	19	19	19	19	18

Table 5.3 Flow duration type curves (as percentage of mean flow)

Type curve		0	1	2	3	4	5	6	7	8	9
Percentile	2	975.70	904.17	838.77	776.04	719.91	667.48	618.22	572.53	520.00	472.29
	5	577.26	534.08	511.37	480.48	452.42	425.82	400.44	376.64	350.65	326.46
	50	20.49	22.69	25.10	27.86	30.82	34.11	37.81	41.82	45.10	48.64
	80	3.70	4.42	5.27	6.33	7.54	9.00	10.77	12.86	15.20	17.98
	90	1.73	2.13	2.62	3.25	3.99	4.92	6.07	7.47	9.16	11.22
	95	1.00	1.26	1.58	2.00	2.51	3.16	3.98	5.01	6.30	7.94
	99	0.38	0.51	0.67	0.88	1.16	1.53	2.02	2.65	3.46	4.52
Type curve		**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Percentile	2	428.96	389.60	353.86	321.39	291.65	264.89	240.09	206.89	178.28	153.69
	5	303.93	282.96	263.44	245.26	228.19	212.45	197.49	176.99	158.62	142.20
	50	52.46	56.57	61.01	65.79	71.00	76.57	82.60	89.91	97.86	106.49
	80	21.25	25.13	29.71	35.12	41.58	49.16	58.08	67.82	79.21	92.46
	90	13.75	16.86	20.66	25.32	31.09	38.10	46.67	56.95	69.50	84.77
	95	10.00	12.57	15.83	19.93	25.13	31.64	39.81	50.13	63.12	79.43
	99	5.89	7.69	10.03	13.08	17.11	22.32	29.13	39.00	52.22	69.85

5.2 RECONSTRUCTION OF ANNUAL FLOW DURATION CURVE

A month is not an hydrologically significant period of time, but a year is significant. The annual flow duration curve is a more robust estimate of the flow regime than the monthly curves. It is important that the sum of the twelve individual monthly flow duration curves equals the natural annual flow duration curve when there are no artificial influences for reasons of consistency with Gustard *et al.* (1992) (Refer to Bullock *et al.*, 1994 for further details). Therefore the following method is used to reconstruct the natural annual flow duration curve from the 12 monthly flow duration curves and fit the resultant curve to the directly estimated annual flow duration curve:

1. The type curves are expressed as a percentage of the monthly mean flow, therefore the first step is to convert the monthly flows to $m^3 s^{-1}$ for each of the plotting positions.

2. The resultant monthly curves (in $m^3 s^{-1}$) are disaggregated into 30 "daily flows" at equally distributed percentiles, as shown in Figure 5.2. The flows are identified for equal percentile values to ensure that these reflect the true distribution of flows within the month. The "daily flows" for each percentile are assigned a flag to identify the month from which the flows are derived.

3. A composite flow duration curve (CURVEM) is derived by ranking the 360 "daily flow" values (derived from the 30 flows from each of the 12 months) from highest (rank 1) to lowest (rank 360) and then calculating a probability of exceedance (P_n) for each of the 360 flows by the equation:

$$P_n = X_n \frac{100}{360}$$

where X_n = rank

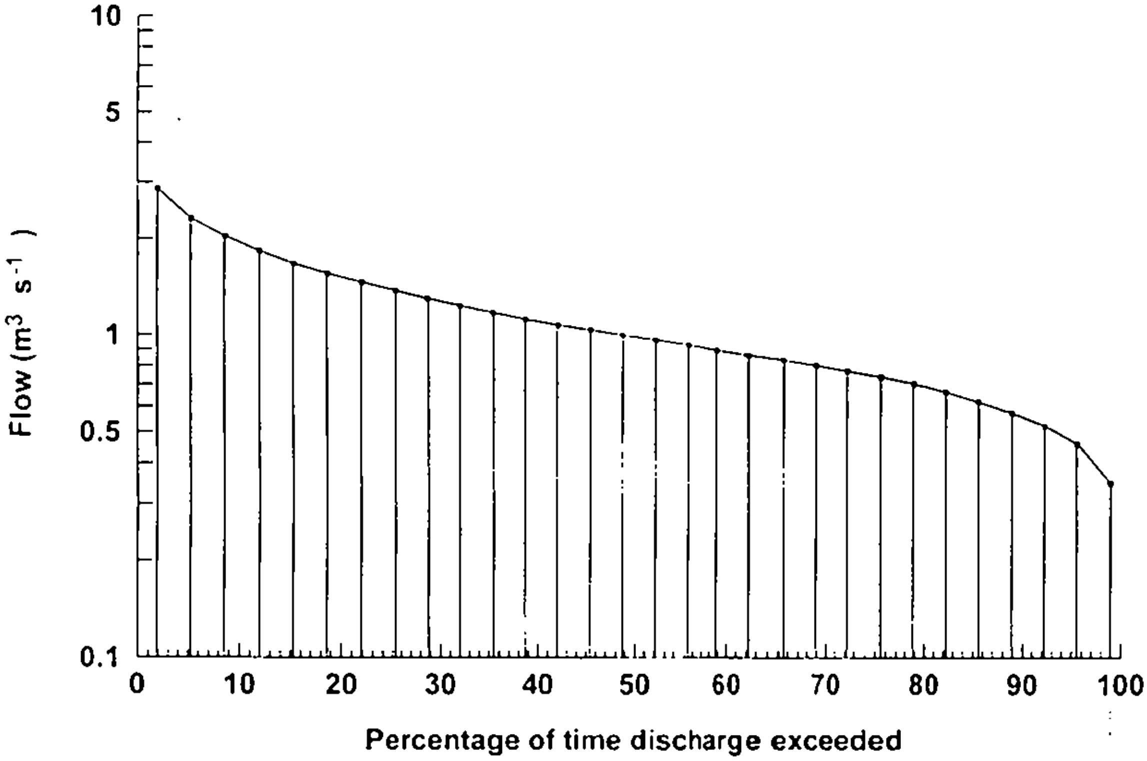

Figure 5.2 *Identification of "daily flows"*

4. Daily flow values are identified from the natural annual flow duration curve (derived in Section 2) (CURVEA) for each of the 360 percentiles, P_n.

5. At this stage, each of the 360 percentiles (P_n) is associated with a flow value from the natural annual curve (CURVEA) and a flow value from the composite curve (CURVEM) (with the flag identifying the month of origin).

6. Compare the two sets of flows for each percentile. The flow value from CURVEM is set to equal the flow value of CURVEA if the two are different.

   i.e. for P_n: $flow_n$ (composite) = $flow_n$ (annual).

7. The 30 flows within each month are then extracted by means of the flag, which provide the natural monthly flow duration curve for adjustments for artificial influences.

6. Mean Monthly Minima

The low flow frequency curve is used for assessing the severity of extreme events of D-day duration and may be derived for ungauged catchments based on the value of the MAM(7). However, the temporal occurrence of the minimum flow varies from year to year and between catchments. Therefore, in order to be able to adjust the flow frequency curve, time series of artificial influence data and a method for estimating the timing of minimum flows in any given year would be required. The latter is not feasible using statistical relationships between long term average flow statistics and catchment characteristics. Therefore, unlike the flow duration curve, procedures have not been developed to derive monthly low flow frequency curves from which to construct an annual flow frequency curve. Rather, estimation focuses on mean annual minimum (MAM(7)) and twelve mean monthly minima (of seven day duration) as illustrated in Figure 6.1.

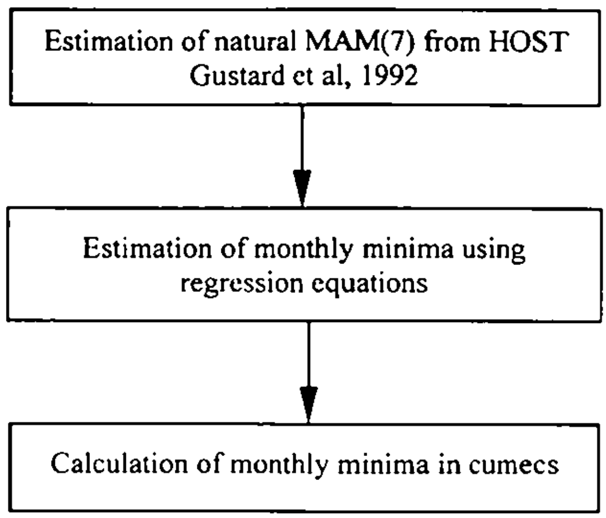

Figure 6.1 *Stages in the estimation of monthly minima*

6.1 ESTIMATION OF MEAN MONTHLY MINIMA

The estimation of the mean monthly minimum is based on a statistical relationship between observed mean monthly minima and MAM(7) and catchment rainfall. The mean monthly minimum and monthly mean flow were identified for each month from flow records from 687 gauging stations. The monthly minima were then expressed as a percentage of the monthly mean flow. Multivariate regression analysis was used to identify a model for predicting the mean monthly minima in each month using the long term MAM(7) and the standard period catchment rainfall. The procedure for estimating the monthly minimum expressed as a percentage of the monthly mean flow is as follows:

1. Estimate the natural long term MAM(7) from soil data (as summarised in Section 2 and described in detail in Introduction to Low Flow Hydrology, Report 3);

2. Estimate the catchment average annual rainfall (refer to Section 2 and Introduction to Low Flow Hydrology, Report 3);

3. Use the values of the parameter estimates shown in Table 6.1, in the following general relationship, to calculate the mean monthly minima, expressed as a percentage of the monthly mean flow:

$$MMM(7)_{MON} = a \times MAM(7)^{b} \times SAAR^{c}$$

Table 6.1 Parameter estimates for mean monthly minimum equations

	Error parameters		Parameter estimates		
MMM(7)	R^2	fse	a const	b MAM(7)	c SAAR
JAN	57	1.20	15.52	0.314	0.038
FEB	65	1.18	39.32	0.303	-0.084
MAR	67	1.18	36.25	0.323	-0.079
APR	73	1.18	31.35	0.359	-0.066
MAY	71	1.16	17.99	0.337	0.035
JUN	78	1.17	39.04	0.398	-0.107
JUL	72	1.22	101.80	0.380	-0.238
AUG	75	1.20	50.04	0.414	-0.157
SEP	77	1.21	55.76	0.446	-0.197
OCT	69	1.21	19.99	0.385	-0.029
NOV	59	1.21	8.82	0.349	0.105
DEC	61	1.20	11.77	0.344	0.059

4. Scale the monthly minima by the natural monthly mean flow to give mean monthly minima in m^3s^{-1}

7. Micro LOW FLOWS Implementation

The principal developments for the estimation of natural low flow estimates within Micro LOW FLOWS V2.1 can be summarised as follows:

1. Estimation of natural long term mean flow, annual flow duration curve, mean annual minimum and low flow frequency curves remains as within Version 1.31, with the ability to display and plot the stretch estimates and the flow duration and flow frequency curves.

2. Modifications to facilitate estimation of natural monthly mean flows, monthly flow duration curves and mean monthly minima, with the ability to display twelve monthly estimates for a stretch.

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APPENDIX A

LOW FLOW ESTIMATION IN ARTIFICIALLY INFLUENCED CATCHMENTS

TRAINING COURSE

Syndicate Exercise

Estimation of Natural Low Flow Statistics

Estimation of Natural Low Flow Statistics

1. INTRODUCTION

This syndicate exercise describes methods for the estimation of the natural annual and monthly low flow statistics. A worked example is provided for the Pang catchment. Information is provided for the Roman to allow the reader to work through the calculations.

The structure of this exercise is as follows:

Section 2:	Catchment characteristics (no work required)
Section 3:	Estimation of natural mean flow (no work required)
Section 4:	Estimation of natural Q95 (refer to Introduction to Low Flow Hydrology, Report 3)
Section 5:	Estimation of natural MAM(7) (refer to Introduction to Low Flow Hydrology, Report 3)
Section 6:	Estimation of the twelve natural monthly mean flows
Section 7:	Estimation of monthly flow duration curves
Section 8:	Estimation of mean monthly minima

2. CATCHMENT CHARACTERISTICS

Figure 1 shows the location of the two example catchments.

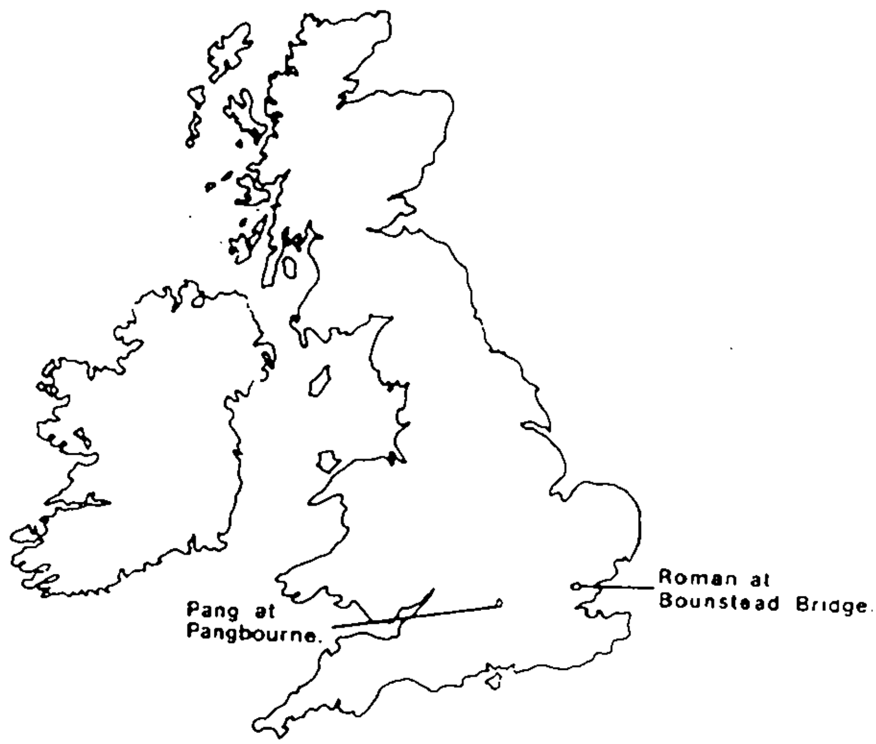

Figure 1 *Location of catchments*

The River Pang is a tributray of the River Thames. The catchment is predominantly chalk but contains impermeable regions comprising Reading Beds and London Clays. The flow regime is affected by groundwater pumping within the catchment. The flows are recorded at the gauging station at Pangbourne (IH No. 39027) with a catchment area of $166km^2$.

The Roman catchment is a tributary of the River Colne in Essex. The catchment geology is predominantly impermeable, consisting of London Clays overlain by Boulder Clay and glacial deposits in the upper reaches. The flows are recorded at Bounstead Bridge (IH NO. 37021) with a catchment area of $52.6km^2$.

Figures 2a and b illustrate the geology of the Pang and Roman catchments, and Figures 3a and 3b illustrate standard period average annual rainfall.

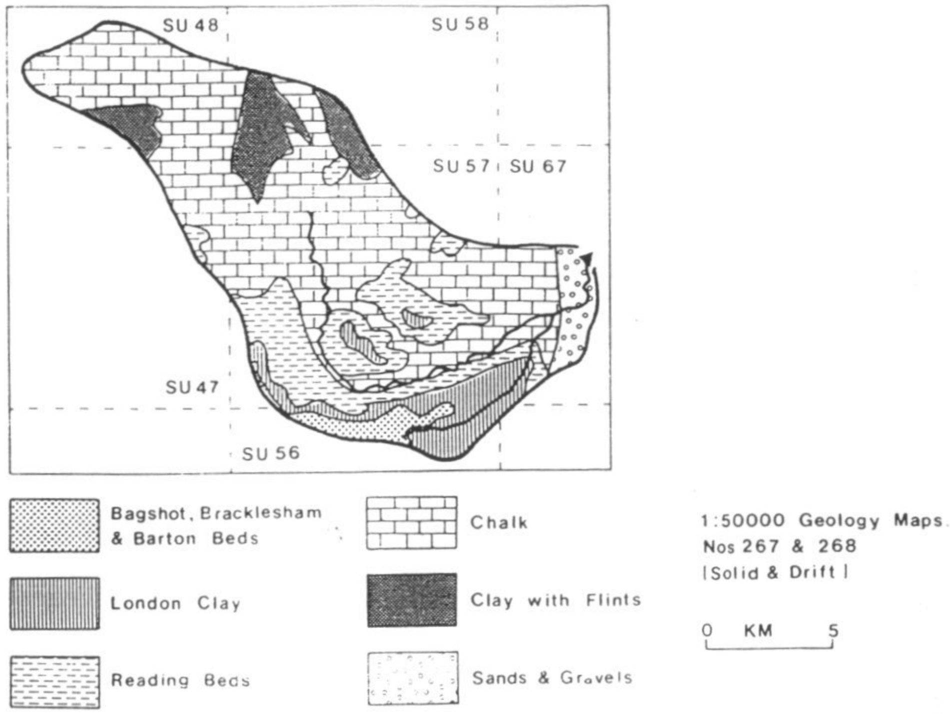

Figure 2.a *Geology of the Pang Catchment*

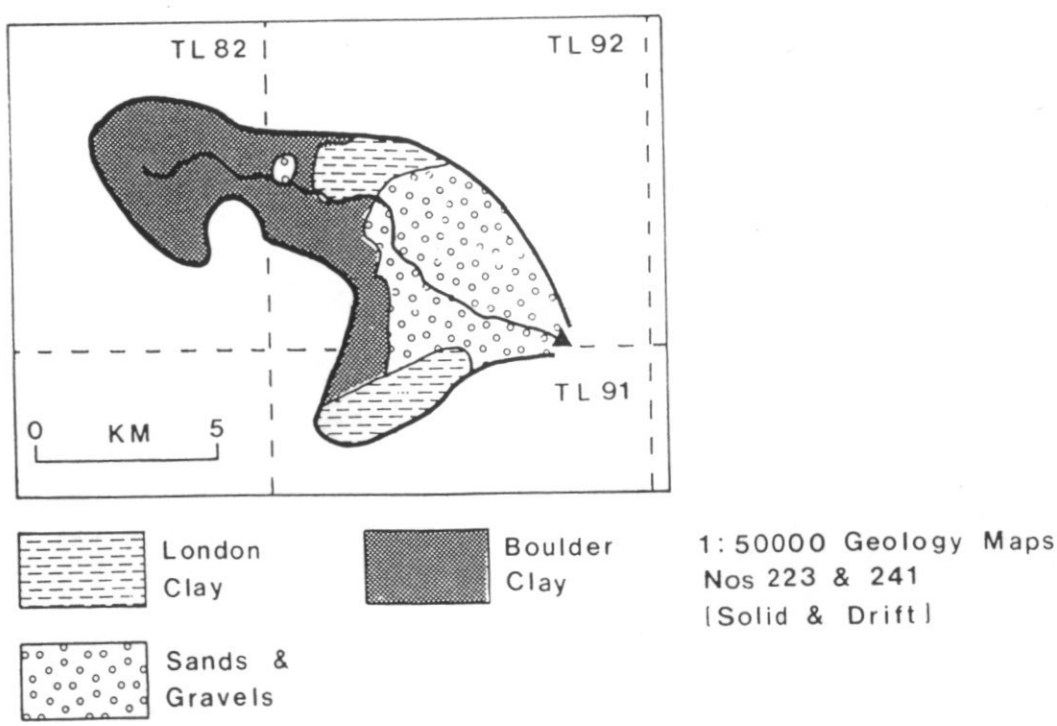

Figure 2b *Geology of the Roman Catchment*

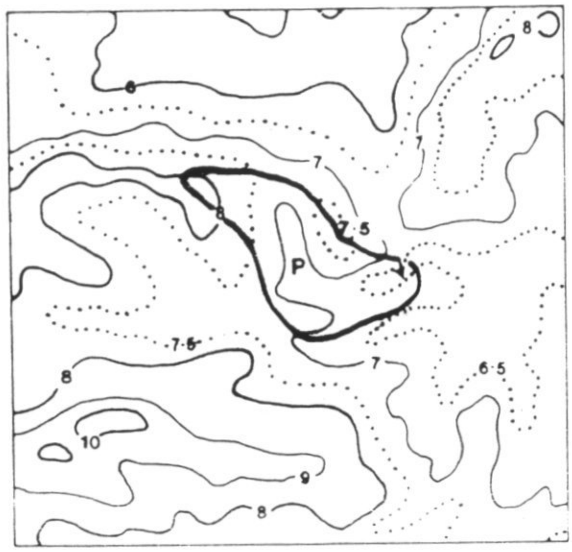

Figure 3a *Standard period Average Annual Rainfall (SAAR) for the Pang (mm x 10^2)*

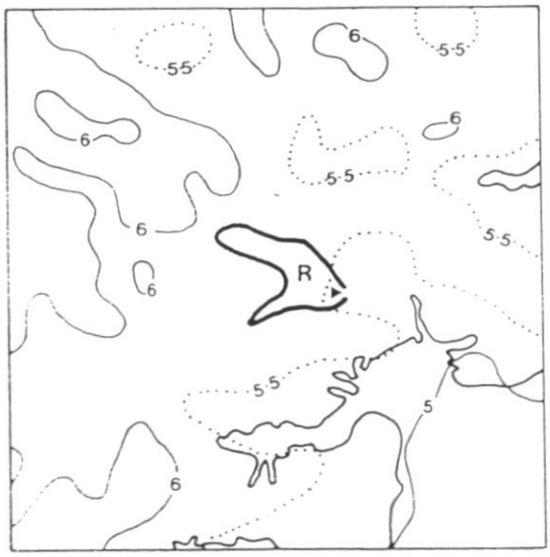

Figure 3b *Standard period Average Annual Rainfall (SAAR) for the Roman (mm x 10^2)*

Catchment characteristics for the two catchments, which have been derived within Micro LOW FLOWS, are presented in Table 1. (Note that throughout these course notes the catchment characteristics from Micro LOW FLOWS may vary from those which have been calculated previously using manual derivation techniques in Introduction to Low Flow Hydrology Report 3).

Table 1 *Catchment Characteristics*

Gauging Station	Name	NGR	Catchment Area	SAAR	PE
39027	Pang at Pangbourne	SU634766	166km^2	704mm	543mm
37021	Roman at Bounstead Bridge	TL985205	52.6km^2	570mm	541mm

3. ESTIMATION OF THE NATURAL MEAN FLOW (MF)

The natural long term mean flow is calculated using the water balance method based on the catchment characteristics, where mean flow (in m^3s^{-1}) can be estimated by the procedure described below:

Calculate average annual runoff depth (AARD) in mm for average annual rainfall (SAAR) and LOSSES, where

$$AARD = SAAR - LOSSES$$

Losses are estimated from

$$LOSSES = r.PE$$

Where $r = (0.00061\ SAAR) + 0.475$ for $SAAR < 850mm$
$r = 1.0$ for $SAAR \geq 850mm$

Convert AARD in mm to mean flow in m^3s^{-1} by the conversion

$$MF = AARD \times AREA \times (3.17 \times 10^{-5})$$

where AREA = catchment area in km^2

The procedures are presented in Introduction to Low Flow Hydrology Report No 3. Using catchment characteristics derived from Micro LOW FLOWS, the estimated mean flow in m^3s^{-1} are as follows:

Location	Mean Flow
River Pang	$1.08m^3s^{-1}$
River Roman	$0.14m^3s^{-1}$

4. ESTIMATION OF NATURAL Q95 AND MAM(7)

The soil associations for the Pang and Roman catchments are illustrated in Figures 4a and b and the fractional extent of each association are given in Tables 2a and 2b.

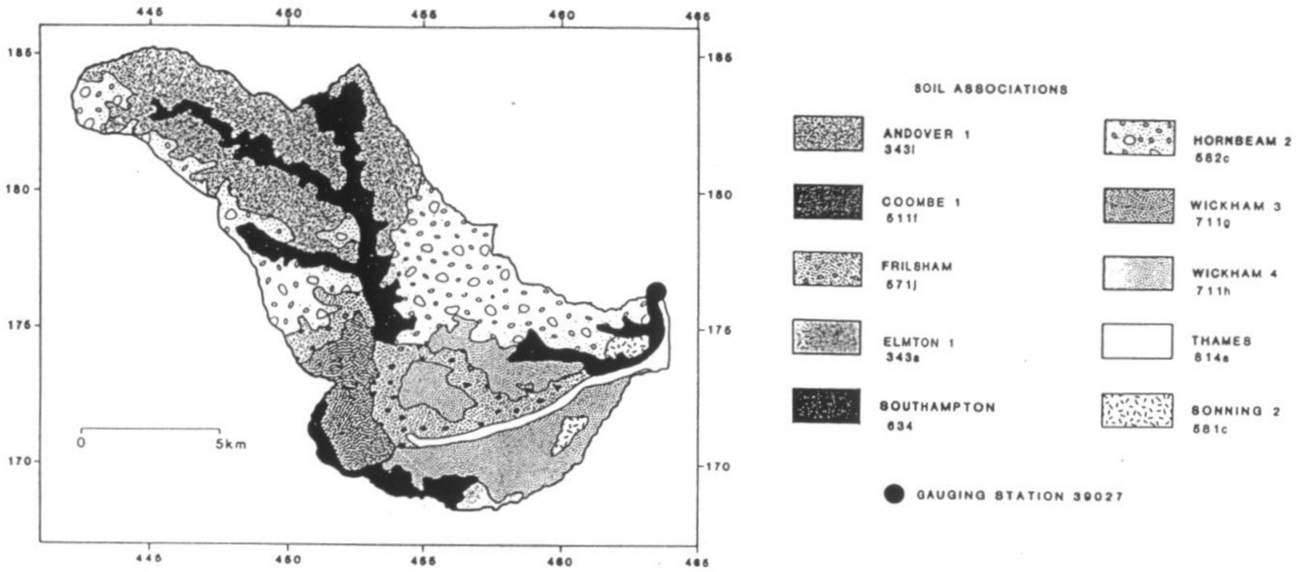

Figure 4a *Soil Associations in the Pang Catchment*

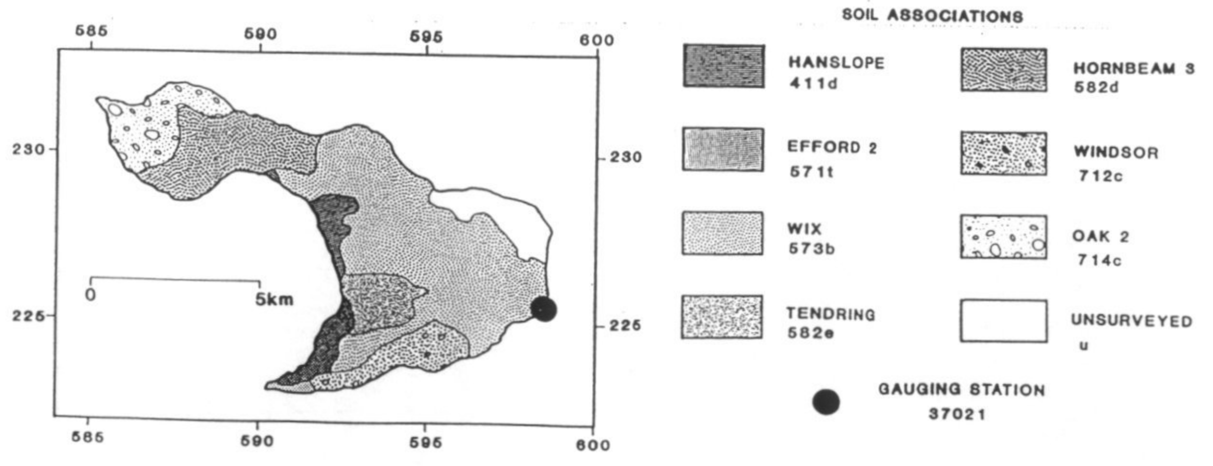

Figure 4b *Soil Associations in the Roman Catchment*

Table 2a *Calculation of Q95 for the Pang*

(a) Soil Association		(b) AREA (as fraction of total area)	(c) Association Q95	(d) Weighted Q95 (col b x col c)
343a	Elmton 1	0.005	31.9	0.2
343h	Andover 1	0.27	41.6	11.2
511f	Coombe 1	0.09	42.6	3.8
571j	Frilsham	0.09	40.8	3.7
581c	Sonning 2	0.01	17.2	0.1
582c	Hornbeam 2	0.22	22.0	4.8
634	Southampton	0.005	23.1	0.1
711g	Wickham 3	0.05	3.0	0.2
711h	Wickham 4	0.15	1.1	0.2
814a	Thames	0.11	6.5	0.7
SUM		1.0		25.0

The catchment estimate of Q95 (as a % of Mean Flow) is the sum of column d.

Catchment Q95 (as a % of Mean Flow) = 25.0
Mean Flow (cumecs) = 1.08
Q95 (cumecs) = 0.27

Table 2b *Calculation of Q95 for the Roman*

(a) Soil Association		*(b) AREA (as fraction of total area)*	*(c) Association Q95*	*(d) Weighted Q95 (col b x col c)*
411d	*Hanslope*	*0.053*	*10.7*	
571t	*Efford 2*	*0.009*	*13.7*	
573b	*Wix*	*0.478*	*10.2*	
582e	*Tendring*	*0.083*	*13.4*	
582d	*Hornbeam 3*	*0.160*	*10.7*	
712c	*Windsor*	*0.073*	*1.1*	
714c	*Oak 2*	*0.070*	*10.7*	
u	*Urban*	*0.065*	*29.4*	
SUM				

The catchment estimate of Q95 (as a % of Mean Flow) is the sum of column d.

Catchment Q95 (as a % of Mean Flow) =
Mean Flow (cumecs) =
Q95 (cumecs) =

Table 3a *Calculation of MAM(7) for the Pang*

(a) Soil Association		(b) AREA (as fraction of total area)	(c) Association MAM(7)	(d) Weighted MAM(7) (col b x col c)
343a	Elmton 1	0.005	40.3	0.2
343h	Andover 1	0.27	51.1	13.8
511f	Coombe 1	0.09	51.4	4.63
571j	Frilsham	0.09	50.8	4.57
581c	Sonning 2	0.01	18.8	0.19
582c	Hornbeam 2	0.22	26.8	5.90
634	Southampton	0.005	25.5	0.13
711g	Wiedham 3	0.05	1.6	0.08
711h	Wickham 4	0.15	0.1	0.02
814a	Thames	0.11	1.4	0.15
SUM		1.0		28.4

The catchment estimate of MAM(7) (as a % of Mean Flow) is the sum of column d.

Catchment MAM(7) (as a % of Mean Flow)	=	28.4
Mean Flow (cumecs)	=	1.08
MAM(7) (cumecs)	=	0.30

Table 3b *Calculation of MAM(7) for the Roman*

(a) Soil Association		*(b) AREA (as fraction of total area)*	*(c) Association MAM(7)*	*(d) Weighted MAM(7) (col b x col c)*
411d	*Hanslope*	*0.053*	*12.4*	
571t	*Efford 2*	*0.009*	*14.4*	
573b	*Wix*	*0.478*	*7.4*	
582e	*Tendring*	*0.083*	*12.3*	
582d	*Hornbeam 3*	*0.160*	*12.4*	
712c	*Windsor*	*0.073*	*0.1*	
714c	*Oak 2*	*0.079*	*12.4*	
u	*Urban*	*0.065*	*33.8*	
SUM				

The catchment estimate of MAM(7) (as a % of Mean Flow) is the sum of column d.

Catchment MAM(7) (as a % of Mean Flow)	=	
Mean Flow (cumecs)	=	
MAM(7) (cumecs)	=	

The natural low flow statistics estimated for the Pang and the Roman using catchment characteristics derived from Mirco LOW FLOWS are given in Table 4.

Table 4 *Low Flow Statistics*

Gauging Station	Name	MF	Q95		MAM(7)	
			%MF	m^3s^{-1}	%MF	m^3s^{-1}
39027	Pang at Pangbourne	1.08	25.0	0.27	28.4	0.30
37021	Roman at Bounstead Bridge	0.14	10.7	0.02	10.2	0.02

5. ESTIMATION OF THE TWELVE NATURAL MONTHLY MEAN FLOWS

This is achieved in three stages:

1. Estimate natural Q95 from soil associations (refer to Section 4).

   For the River Pang:

   Q95 = 25.0% of MF
= 0.27 $m^3 s^{-1}$

   For the River Roman:

   Q95 = ... % of MF
= .... $m^3 s^{-1}$

2. Estimate monthly runoff volumes MRV (as a % of annual runoff volume) for each of the 12 months. Use the appropriate grid maps if Q95 is less than 30% of MF (two different sets of grids are available for Q95 in the range 0-15% of MF and 15-30% of MF). If Q95 is >30%, use the following table.

Table 5a *Monthly runoff volume for catchments in Great Britain with Q95(1) >30%*

Monthly Runoff Volume (% Annual Runoff Volume)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
11.8	14.2	13.0	10.3	8.1	6.4	5.0	4.6	4.5	5.3	7.0	9.8

If the catchment is in Northern Ireland, use the following table.

Table 5b *Monthly runoff volume for Northern Ireland catchments*

Monthly Runoff Volume (% Annual Runoff Volume)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
16.8	12.3	8.7	5.3	3.9	2.7	2.4	3.4	5.9	9.9	12.9	16.0

For the practical purposes of this exercise, grid maps are not provided. Calculated MRV values for the Pang are presented in Table 6a, and a partially complete set for the Roman in Table 6b. Complete the Table for the River Roman by inserting the following three MRV values in the correct months:

8.48, 12.39, 1.87

Table 6a *Monthly runoff volume for the Pang*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MRV	13.7	14.7	12.9	9.3	7.6	5.4	3.9	3.7	4.1	5.2	8.2	11.3

Table 6b *Monthly runoff volume for the Roman*

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
MRV	*18.72*	*17.65*	*15.29*		*5.84*	*2.50*	*1.62*		*2.83*	*3.99*	*8.80*	

3. Estimate monthly mean flow. Having obtained the monthly runoff volume, the monthly mean flow (MMF) is calculated in m^3 s^{-1} by the following equation.

$$MMF = \frac{MRV \times MF}{(100/12)}$$

$$MMF = \frac{MRV \times MF}{8.333}$$

Monthly mean flows have been calculated for the River Pang and given in Table 7a complete the missing values for the Roman in Table 7b.

Table 7a *Monthly Mean Flows for the Pang*

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MRV	13.7	14.7	12.9	9.3	7.6	5.4	3.9	3.7	4.1	5.2	8.2	11.3
MF	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
MMF	1.77	1.89	1.66	1.19	0.98	0.70	0.51	0.48	0.53	0.68	1.06	1.46

Table 7b *Monthly Mean Flows for the Roman*

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
MRV	*18.72*	*17.65*	*15.29*		*5.84*	*2.50*	*1.62*		*2.83*	*3.99*	*8.80*	
MF	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*	*0.14*
MMF	*0.32*	*0.30*	*0.26*		*0.10*	*0.04*	*0.03*		*0.05*	*0.07*	*0.15*	

6. ESTIMATION OF MONTHLY FLOW DURATION CURVE

1. Select appropriate type curves

   Identify the appropriate type curve number for individual months, based on estimated Q95 using Table 8 and Figure 5. Type curves for the Pang are shown in Table 9a. Complete Table 9b.

Table 8 Type curves for monthly flow duration curves

Q95 Group	Annual type curves											
% MF	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-2.5	10	11	11	10	8	8	8	6	6	5	7	9
2.5-7.5	12	12	12	12	10	10	11	9	9	9	10	11
7.5-12.5	13	13	13	14	13	13	13	12	12	11	12	12
12.5-17.5	14	14	14	15	15	15	15	14	13	12	13	13
17.5-22.5	14	15	15	15	16	16	16	15	15	13	14	14
22.5-27.5	15	15	15	16	16	16	16	16	16	14	15	14
27.5-32.5	15	16	16	16	16	17	17	16	17	16	15	15
32.5-37.5	16	16	16	17	17	17	17	17	17	16	16	15
37.5-42.5	16	16	17	17	17	18	18	17	18	17	17	16
42.5-47.5	17	17	17	17	17	18	18	18	18	17	17	17
47.5-52.5	18	17	18	17	18	18	18	18	18	18	18	18
52.5-57.5	18	18	18	18	18	18	18	18	18	18	18	18
57.5-62.5	18	18	18	18	18	18	18	19	18	18	18	18
62.5-67.5	18	18	18	18	18	18	18	19	19	19	19	18
72.5-77.5	18	19	19	19	19	19	19	19	19	19	19	18

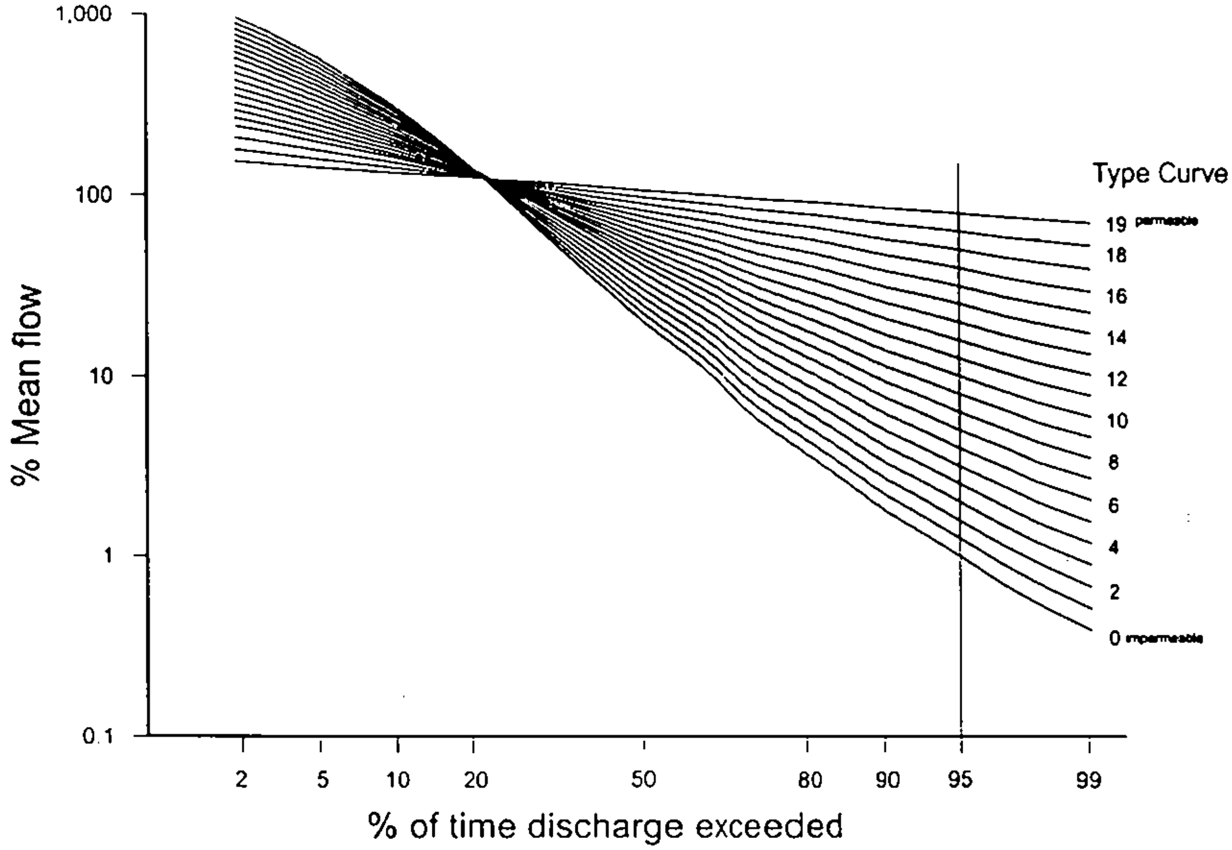

Figure 5 *Annual flow duration type curves*

For the River Pang:

Table 9a *Monthly Type Curves*

Q95	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
25.1%	15	15	15	16	16	16	16	16	16	14	15	14

For the River Roman:

Table 9b *Monthly Type Curves*

Q95	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*

2. Calculate monthly flow duration curve

Using Table 10, estimate the monthly flows, in m^3s^{-1}, for April and August for the key percentiles shown, based on the appropriate Type Curve number. This is illustrated for the River Pang in Table 11a. Complete Table 11b for the River Roman.

Table 10 *Flow duration type curves (as percentage of mean flow)*

Type curve		0	1	2	3	4	5	6	7	8	9
Percentile	2	975.70	904.17	838.77	776.04	719.91	667.48	618.22	572.53	520.00	472.29
	5	577.26	534.08	511.37	480.48	452.42	425.82	400.44	376.64	350.65	326.46
	50	20.49	22.69	25.10	27.86	30.82	34.11	37.81	41.82	45.10	48.64
	80	3.70	4.42	5.27	6.33	7.54	9.00	10.77	12.86	15.20	17.98
	90	1.73	2.13	2.62	3.25	3.99	4.92	6.07	7.47	9.16	11.22
	95	1.00	1.26	1.58	2.00	2.51	3.16	3.98	5.01	6.30	7.94
	99	0.38	0.51	0.67	0.88	1.16	1.53	2.02	2.65	3.46	4.52
Type curve		10	11	12	13	14	15	16	17	18	19
Percentile	2	428.96	389.60	353.86	321.39	291.65	264.89	240.09	206.89	178.28	153.69
	5	303.93	282.96	263.44	245.26	228.19	212.45	197.49	176.99	158.62	142.20
	50	52.46	56.57	61.01	65.79	71.00	76.57	82.60	89.91	97.86	106.49
	80	21.25	25.13	29.71	35.12	41.58	49.16	58.08	67.82	79.21	92.46
	90	13.75	16.86	20.66	25.32	31.09	38.10	46.67	56.95	69.50	84.77
	95	10.00	12.57	15.83	19.93	25.13	31.64	39.81	50.13	63.12	79.43
	99	5.89	7.69	10.03	13.08	17.11	22.32	29.13	39.00	52.22	69.85

Table 11a *Monthly flow duration curve for the River Pang: April and August*

April Type Curve No: 16 April Mean Flow = 1.193 m^3s^{-1}			August Type Curve No: 16 August Mean Flow = 0.480 m^3s^{-1}		
%	%age of monthly mf	flow (m^3s^{-1})	%	%age of monthly mf	flow (m^3s^{-1})
2	240.1	2.864	2	240.1	1.152
5	197.5	2.356	5	197.5	0.948
50	82.6	0.985	50	82.6	0.396
80	58.1	0.693	80	58.1	0.279
90	46.7	0.557	90	46.7	0.224
95	39.8	0.475	95	39.8	0.191
99	29.1	0.347	99	29.1	0.140

Table 11b *Monthly flow duration curve for the River Roman: April and August*

April Type Curve No: .... *April Mean Flow = ...m^3s^{-1}*			*August Type Curve No: ....* *August Mean Flow = ...m^3s^{-1}*		
%	*%age of monthly mf*	*flow (m^3s^{-1})*	*%*	*%age of monthly mf*	*flow (m^3s^{-1})*
2			*2*		
5			*5*		
50			*50*		
80			*80*		
90			*90*		
95			*95*		
99			*99*		

3. Estimate daily flows

Within Micro LOW FLOWS the monthly flow duration curves are divided into 30 flow values derived from the monthly flow duration curves at equally spaced percentiles, as illustrated in Figure 6, so that the curves can be adjusted. Calculated flow for 7 key percentiles have been given, as an illustration of the use of type curves for monthly flow duration curves. For the practical purposes of this exercise, the step of estimating 30 flow values has been undertaken for you and data are presented in Tables 12a - d.

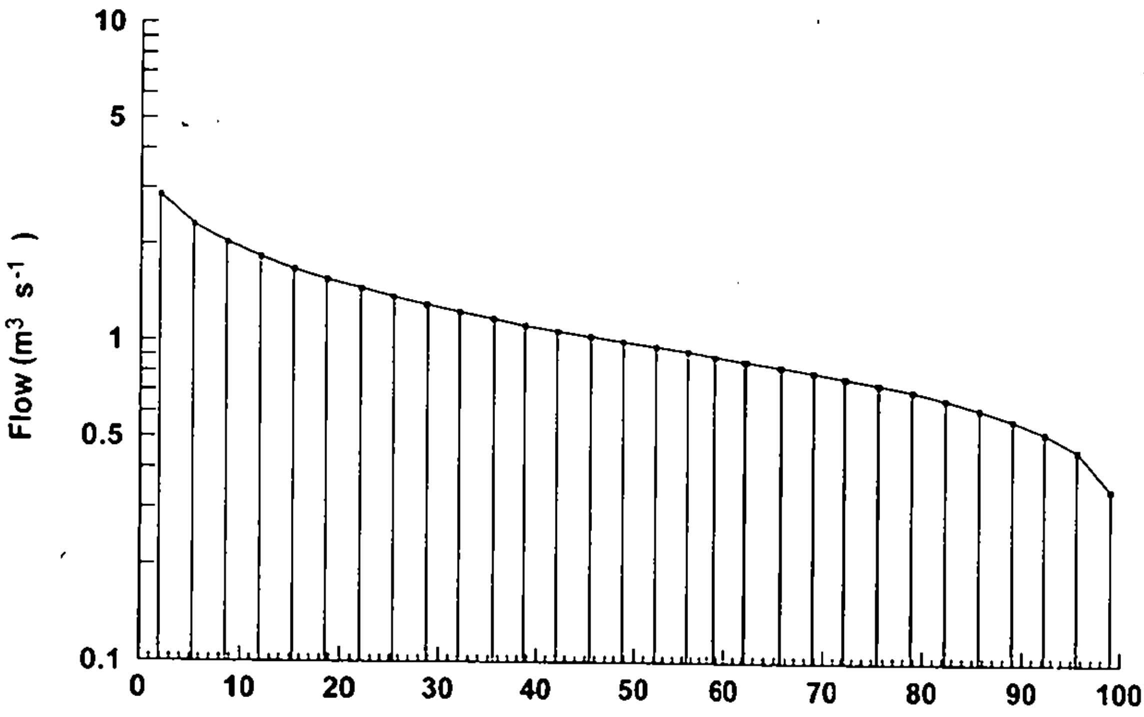

Figure 6 *Identification of daily flows*

Table 12a River Pang: April flow duration curve

%ile	Flow (m^3s^{-1})	%ile	Flow (m^3s^{-1})	%ile	Flow (m^3s^{-1})
2.0	2.864	35.4	1.176	68.9	0.803
5.3	2.314	38.8	1.121	72.2	0.771
8.7	2.032	42.1	1.076	75.6	0.737
12.0	1.829	45.5	1.036	79.0	0.704
15.4	1.670	48.8	0.998	82.3	0.664
18.7	1.556	52.2	0.963	85.6	0.620
22.0	1.459	55.5	0.930	89.0	0.572
25.4	1.376	58.8	0.900	92.3	0.523
28.7	1.302	62.2	0.866	95.6	0.459
32.1	1.236	65.5	0.834	99.0	0.348

Table 12b River Pang: August flow duration curve

%ile	Flow (m^3s^{-1})	%ile	Flow (m^3s^{-1})	%ile	Flow (m^3s^{-1})
2.0	1.153	35.4	0.473	68.9	0.323
5.3	0.932	38.8	0.451	72.2	0.310
8.7	0.818	42.1	0.433	75.6	0.297
12.0	0.736	45.5	0.417	79.0	0.283
15.4	0.672	48.8	0.402	82.3	0.267
18.7	0.626	52.2	0.388	85.6	0.250
22.0	0.587	55.5	0.375	89.0	0.230
25.4	0.554	58.8	0.361	92.3	0.210
28.7	0.524	62.2	0.349	95.6	0.185
32.1	0.498	65.5	0.336	99.0	0.140

Table 12c *River Roman: April flow duration curve*

%ile	Flow	%ile	Flow	%ile	Flow
2.0	0.423	35.4	0.133	68.9	0.075
5.3	0.324	38.8	0.125	72.2	0.071
8.7	0.274	42.1	0.118	75.6	0.066
12.0	0.240	45.5	0.111	79.0	0.618
15.4	0.214	48.8	0.105	82.3	0.057
18.7	0.194	52.2	0.010	85.6	0.052
22.0	0.178	55.5	0.094	89.0	0.047
25.4	0.164	58.8	0.089	92.3	0.041
28.7	0.153	62.2	0.846	95.6	0.035
32.1	0.142	65.5	0.080	99.0	0.025

Table 12d *River Roman: August flow duration curve*

%ile	Flow	%ile	Flow	%ile	Flow
2.0	0.11	35.4	0.027	68.9	0.013
5.3	0.082	38.8	0.025	72.2	0.011
8.7	0.067	42.1	0.023	75.6	0.010
12.0	0.057	45.5	0.022	79.0	0.010
15.4	0.050	48.8	0.020	82.3	0.008
18.7	0.044	52.2	0.018	85.6	0.007
22.0	0.040	55.5	0.017	89.0	0.007
25.4	0.036	58.8	0.016	92.3	0.005
28.7	0.033	62.2	0.015	95.6	0.004
32.1	0.030	65.5	0.013	99.0	0.003

4. Construct a composite annual flow duration curve from the derived monthly flow values.

   Rank the 360 'daily' flow values (derived from the 30 flows from each of the 12 months), from highest (rank 1) to lowest (rank 360). Calculate a probability of exceedance (P_n) for each of the 360 flows using the following equation.

$$P_n = X_n \frac{100}{360}$$

where X_n = rank

Ensure the 360 flow values carry a flag indicating the month from which the flow value derived. Also, derive a set of flows from the estimated annual duration curve for percentiles used in the composite annual flow duration and tabulate the flows. For reasons of simplicity, this exercise has been undertaken for you and data are presented in Tables 13a and b.

Table 13a *Annual flow duration data for River Pang from composite and estimated annual duration curves*

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
1	.28	5.01	3.14	2	28	7.78	2.19	2.11	3
2	.56	4.68	3.14	1	29	8.06	2.16	2.09	1
3	.83	4.40	3.14	3	30	8.33	2.16	2.06	2
4	1.11	4.25	3.14	12	31	8.61	2.15	2.04	12
5	1.39	3.93	3.14	2	32	8.89	2.03	2.01	3
6	1.67	3.67	3.14	1	33	9.17	2.03	1.99	4
7	1.94	3.45	3.14	3	34	9.44	2.03	1.97	2
8	2.22	3.39	3.06	2	35	9.72	2.02	1.95	1
9	2.50	3.25	2.98	12	36	10.00	1.98	1.93	10
10	2.78	3.17	2.91	1	37	10.28	1.95	1.91	12
11	3.06	3.01	2.84	2	38	10.56	1.91	1.88	2
12	3.33	2.98	2.77	3	39	10.83	1.90	1.86	11
13	3.61	2.86	2.70	4	40	11.11	1.90	1.84	3
14	3.89	2.81	2.64	1	41	11.39	1.89	1.82	5
15	4.17	2.81	2.59	11	42	11.67	1.89	1.80	1
16	4.44	2.75	2.54	12	43	11.94	1.83	1.78	4
17	4.72	2.72	2.49	2	44	12.22	1.80	1.76	2
18	5.00	2.64	2.45	3	45	12.50	1.79	1.75	12
19	5.28	2.54	2.41	1	46	12.78	1.78	1.73	1
20	5.56	2.50	2.37	2	47	13.06	1.78	1.71	3
21	5.83	2.41	2.33	12	48	13.33	1.70	1.70	2
22	6.11	2.38	2.29	3	49	13.61	1.69	1.68	11
23	6.39	2.34	2.26	5	50	13.89	1.68	1.66	1
24	6.67	2.33	2.23	1	51	14.17	1.67	1.65	6
25	6.94	2.31	2.20	2	52	14.44	1.67	1.63	3
26	7.22	2.31	2.17	4	53	14.72	1.67	1.62	4
27	7.50	2.21	2.14	11	54	15.00	1.66	1.60	5

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
55	15.28	1.65	1.59	12	88	24.44	1.27	1.24	5
56	15.56	1.62	1.58	2	89	24.72	1.26	1.24	1
57	15.83	1.59	1.56	1	90	25.00	1.25	1.23	12
58	16.11	1.58	1.55	3	91	25.28	1.24	1.22	4
59	16.39	1.56	1.54	4	92	25.56	1.24	1.21	3
60	16.67	1.54	1.52	2	93	25.83	1.23	1.20	2
61	16.94	1.53	1.51	12	94	26.11	1.22	1.20	7
62	17.22	1.52	1.50	11	95	26.39	1.21	1.19	11
63	17.50	1.52	1.49	10	96	26.67	1.20	1.18	1
64	17.78	1.51	1.48	1	97	26.94	1.19	1.18	5
65	18.06	1.50	1.46	5	98	27.22	1.19	1.17	6
66	18.33	1.49	1.45	3	99	27.50	1.18	1.16	3
67	18.61	1.47	1.44	2	100	27.78	1.18	1.15	12
68	18.89	1.46	1.43	4	101	28.06	1.18	1.15	4
69	19.17	1.44	1.42	1	102	28.33	1.17	1.14	2
70	19.44	1.43	1.41	12	103	28.61	1.15	1.13	8
71	19.72	1.42	1.40	3	104	28.89	1.15	1.13	1
72	20.00	1.41	1.39	2	105	29.17	1.14	1.12	11
73	20.28	1.40	1.38	11	106	29.44	1.13	1.11	3
74	20.56	1.38	1.37	4	107	29.72	1.13	1.11	5
75	20.83	1.37	1.36	1	108	30.00	1.12	1.10	10
76	21.11	1.37	1.35	5	109	30.28	1.12	1.09	4
77	21.39	1.35	1.34	3	110	30.56	1.12	1.09	2
78	21.67	1.35	1.33	6	111	30.83	1.12	1.08	12
79	21.94	1.35	1.32	2	112	31.11	1.10	1.07	1
80	22.22	1.34	1.31	12	113	31.39	1.08	1.07	3
81	22.50	1.31	1.30	1	114	31.67	1.08	1.06	4
82	22.78	1.30	1.29	4	115	31.94	1.07	1.06	11
83	23.06	1.30	1.29	11	116	32.22	1.07	1.05	6
84	23.33	1.29	1.28	3	117	32.50	1.07	1.04	5
85	23.61	1.29	1.27	2	118	32.78	1.06	1.04	2
86	23.89	1.28	1.26	10	119	33.06	1.06	1.03	12
87	24.17	1.28	1.25	9	120	33.33	1.04	1.03	1

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
121	33.61	1.04	1.02	4	151	41.94	.88	.87	2
122	33.89	1.03	1.02	9	152	42.22	.88	.87	3
123	34.17	1.03	1.01	3	153	42.50	.88	.86	5
124	34.44	1.01	1.00	5	154	42.78	.87	.86	4
125	34.72	1.01	1.00	11	155	43.06	.86	.86	11
126	35.00	1.01	.99	2	156	43.33	.86	.85	7
127	35.28	1.00	.99	10	157	43.61	.85	.85	6
128	35.56	1.00	.98	12	158	43.89	.85	.84	12
129	35.83	1.00	.98	4	159	44.17	.85	.84	5
130	36.11	.99	.97	1	160	44.44	.83	.84	4
131	36.39	.98	.97	7	161	44.72	.83	.83	10
132	36.67	.98	.96	3	162	45.00	.83	.83	3
133	36.94	.98	.96	6	163	45.28	.83	.82	1
134	37.22	.96	.95	4	164	45.56	.83	.82	11
135	37.50	.96	.95	5	165	45.83	.82	.82	8
136	37.78	.95	.94	11	166	46.11	.82	.81	5
137	38.06	.95	.94	12	167	46.39	.82	.81	2
138	38.33	.95	.93	2	168	46.67	.82	.81	9
139	38.61	.94	.93	1	169	46.94	.80	.80	6
140	38.89	.93	.92	3	170	47.22	.80	.80	12
141	39.17	.93	.92	8	171	47.50	.80	.79	4
142	39.44	.93	.91	4	172	47.78	.79	.79	11
143	39.72	.92	.91	5	173	48.06	.79	.79	5
144	40.00	.91	.90	10	174	48.33	.78	.78	7
145	40.28	.91	.90	6	175	48.61	.78	.78	3
146	40.56	.91	.89	9	176	48.89	.77	.78	4
147	40.83	.91	.89	11	177	49.17	.77	.77	10
148	41.11	.90	.89	4	178	49.44	.76	.77	1
149	41.39	.90	.88	12	179	49.72	.76	.77	5
150	41.67	.88	.88	1	180	50.00	.76	.76	6

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
181	50.28	.76	.76	12	211	58.61	.65	.66	9
182	50.56	.75	.75	11	212	58.89	.63	.66	5
183	50.83	.74	.75	9	213	59.17	.63	.66	6
184	51.11	.74	.75	2	214	59.44	.63	.65	11
185	51.39	.74	.75	4	215	59.72	.63	.65	8
186	51.67	.74	.74	8	216	60.00	.62	.65	1
187	51.94	.73	.74	5	217	60.28	.62	.65	10
188	52.22	.72	.74	6	218	60.56	.62	.64	12
189	52.50	.72	.73	11	219	60.83	.62	.64	4
190	52.78	.72	.73	3	220	61.11	.62	.64	7
191	53.06	.71	.73	10	221	61.39	.61	.63	9
192	53.33	.71	.72	12	222	61.67	.61	.63	6
193	53.61	.71	.72	7	223	61.94	.60	.63	5
194	53.89	.71	.72	5	224	62.22	.60	.62	11
195	54.17	.70	.71	4	225	62.50	.59	.62	3
196	54.44	.69	.71	1	226	62.78	.59	.62	8
197	54.72	.69	.71	9	227	63.06	.58	.62	10
198	55.00	.69	.70	11	228	63.33	.58	.61	7
199	55.28	.69	.70	6	229	63.61	.58	.61	6
200	55.56	.68	.70	5	230	63.89	.58	.61	9
201	55.83	.67	.69	8	231	64.17	.58	.60	2
202	56.11	.67	.69	2	232	64.44	.58	.60	5
203	56.39	.67	.69	10	233	64.72	.57	.60	12
204	56.67	.67	.68	12	234	65.00	.57	.60	4
205	56.94	.66	.68	4	235	65.28	.56	.59	11
206	57.22	.66	.68	7	236	65.56	.56	.59	6
207	57.50	.66	.68	11	237	65.83	.55	.59	8
208	57.78	.66	.67	5	238	66.11	.55	.59	7
209	58.06	.65	.67	6	239	66.39	.55	.58	9
210	58.33	.65	.67	3	240	66.67	.55	.58	10

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
241	66.94	.54	.58	6	271	75.28	.46	.49	7
242	67.22	.54	.57	5	272	75.56	.45	.49	8
243	67.50	.54	.57	1	273	75.83	.45	.49	6
244	67.78	.53	.57	11	274	76.11	.45	.48	9
245	68.06	.52	.57	7	275	76.39	.44	.48	10
246	68.33	.52	.56	6	276	76.67	.44	.48	7
247	68.61	.52	.56	9	277	76.94	.43	.48	8
248	68.89	.52	.56	8	278	77.22	.43	.47	6
249	69.17	.52	.55	4	279	77.50	.43	.47	9
250	69.44	.52	.55	12	280	77.78	.43	.47	5
251	69.72	.52	.55	10	281	78.06	.42	.46	7
252	70.00	.51	.55	5	282	78.33	.42	.46	2
253	70.28	.51	.54	6	283	78.61	.42	.46	10
254	70.56	.51	.54	3	284	78.89	.42	.46	8
255	70.83	.50	.54	9	285	79.17	.42	.45	11
256	71.11	.50	.54	7	286	79.44	.42	.45	12
257	71.39	.50	.53	8	287	79.72	.41	.45	9
258	71.67	.50	.53	11	288	80.00	.41	.44	6
259	71.94	.49	.53	10	289	80.28	.41	.44	7
260	72.22	.49	.52	6	290	80.56	.40	.44	8
261	72.50	.48	.52	9	291	80.83	.40	.44	9
262	72.78	.48	.52	7	292	81.11	.40	.43	10
263	73.06	.47	.52	8	293	81.39	.40	.43	7
264	73.33	.47	.51	12	294	81.67	.39	.43	1
265	73.61	.47	.51	6	295	81.94	.39	.42	8
266	73.89	.47	.51	5	296	82.22	.39	.42	6
267	74.17	.47	.50	10	297	82.50	.39	.42	9
268	74.44	.46	.50	9	298	82.78	.38	.42	7
269	74.72	.46	.50	4	299	83.06	.38	.41	5
270	75.00	.46	.50	11	300	83.33	.38	.41	11

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
301	83.61	.37	.41	10	331	91.94	.29	.31	10
302	83.89	.37	.40	8	332	92.22	.28	.31	5
303	84.17	.37	.40	9	333	92.50	.28	.30	8
304	84.44	.37	.40	3	334	92.78	.28	.30	7
305	84.72	.37	.39	7	335	93.06	.28	.30	9
306	85.00	.36	.39	6	336	93.33	.27	.29	6
307	85.28	.36	.39	8	337	93.61	.27	.29	8
308	85.56	.36	.38	9	338	93.89	.27	.28	10
309	85.83	.35	.38	7	339	94.17	.26	.28	7
310	86.11	.35	.38	10	340	94.44	.26	.28	9
311	86.39	.35	.38	12	341	94.72	.25	.27	8
312	86.67	.35	.37	8	342	95.00	.25	.27	12
313	86.94	.35	.37	4	343	95.28	.24	.26	10
314	87.22	.34	.37	9	344	95.56	.24	.26	7
315	87.50	.34	.36	7	345	95.83	.24	.25	11
316	87.78	.34	.36	8	346	96.11	.23	.25	9
317	88.06	.33	.36	6	347	96.39	.23	.24	8
318	88.33	.33	.35	10	348	96.67	.22	.24	7
319	88.61	.33	.35	9	349	96.94	.22	.23	10
320	88.89	.33	.35	7	350	97.22	.21	.23	8
321	89.17	.32	.34	8	351	97.50	.20	.22	9
322	89.44	.32	.34	11	352	97.78	.20	.22	6
323	89.72	.31	.34	9	353	98.06	.19	.21	7
324	90.00	.31	.33	7	354	98.33	.19	.20	10
325	90.28	.31	.33	10	355	98.61	.18	.19	8
326	90.56	.31	.33	8	356	98.89	.16	.19	10
327	90.83	.31	.32	6	357	99.17	.16	.18	9
328	91.11	.30	.32	7	358	99.44	.15	.18	7
329	91.39	.30	.32	8	359	99.72	.14	.18	8
330	91.67	.30	.31	9	360	100.00	.12	.18	10

Table 13b *Annual flow duration data for River Roman from composite and estimated annual duration curves*

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
1	.28	1.03	.60	1	31	8.61	.33	.33	12
2	.56	.97	.60	2	32	8.89	.32	.32	4
3	.83	.84	.60	3	33	9.17	.32	.32	5
4	1.11	.77	.60	1	34	9.44	.32	.31	3
5	1.39	.75	.60	12	35	9.72	.32	.31	11
6	1.67	.72	.60	2	36	10.00	.31	.30	2
7	1.94	.64	.60	1	37	10.28	.31	.30	1
8	2.22	.63	.57	3	38	10.56	.29	.29	3
9	2.50	.60	.55	2	39	10.83	.29	.29	12
10	2.78	.55	.53	1	40	11.11	.29	.28	2
11	3.06	.54	.52	12	41	11.39	.28	.28	1
12	3.33	.53	.50	11	42	11.67	.27	.28	4
13	3.61	.52	.48	3	43	11.94	.27	.27	3
14	3.89	.52	.47	2	44	12.22	.27	.27	11
15	4.17	.49	.46	1	45	12.50	.27	.26	2
16	4.44	.46	.44	2	46	12.78	.27	.26	10
17	4.72	.45	.43	3	47	13.06	.26	.26	1
18	5.00	.44	.42	12	48	13.33	.26	.25	12
19	5.28	.44	.41	1	49	13.61	.25	.25	3
20	5.56	.42	.40	4	50	13.89	.25	.25	2
21	5.83	.41	.39	2	51	14.17	.25	.24	1
22	6.11	.40	.39	3	52	14.44	.24	.24	4
23	6.39	.39	.38	1	53	14.72	.24	.24	5
24	6.67	.39	.37	11	54	15.00	.24	.24	12
25	6.94	.38	.36	12	55	15.28	.23	.23	11
26	7.22	.37	.36	2	56	15.56	.23	.23	2
27	7.50	.36	.35	1	57	15.83	.23	.23	3
28	7.78	.35	.34	3	58	16.11	.23	.22	1
29	8.06	.34	.34	2	59	16.39	.22	.22	2
30	8.33	.33	.33	1	60	16.67	.22	.22	1

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
61	16.94	.22	.22	3	91	25.28	.16	.16	3
62	17.22	.21	.21	12	92	25.56	.15	.16	12
63	17.50	.21	.21	4	93	25.83	.15	.15	11
64	17.78	.21	.21	11	94	26.11	.15	.15	4
65	18.06	.20	.21	2	95	26.39	.15	.15	5
66	18.33	.20	.20	1	96	26.67	.15	.15	10
67	18.61	.20	.20	3	97	26.94	.15	.15	2
68	18.89	.20	.20	5	98	27.22	.15	.15	1
69	19.17	.20	.20	12	99	27.50	.15	.15	3
70	19.44	.19	.19	4	100	27.78	.14	.14	12
71	19.72	.19	.19	2	101	28.06	.14	.14	4
72	20.00	.19	.19	1	102	28.33	.14	.14	11
73	20.28	.19	.19	3	103	28.61	.14	.14	2
74	20.56	.19	.19	10	104	28.89	.14	.14	6
75	20.83	.19	.18	11	105	29.17	.14	.14	3
76	21.11	.18	.18	12	106	29.44	.14	.14	1
77	21.39	.18	.18	2	107	29.72	.14	.14	5
78	21.67	.18	.18	1	108	30.00	.13	.13	4
79	21.94	.18	.18	4	109	30.28	.13	.13	12
80	22.22	.18	.17	3	110	30.56	.13	.13	11
81	22.50	.17	.17	5	111	30.83	.13	.13	2
82	22.78	.17	.17	9	112	31.11	.13	.13	3
83	23.06	.17	.17	2	113	31.39	.13	.13	10
84	23.33	.17	.17	11	114	31.67	.13	.13	1
85	23.61	.17	.17	1	115	31.94	.12	.13	4
86	23.89	.17	.16	12	116	32.22	.12	.13	9
87	24.17	.17	.16	3	117	32.50	.12	.12	12
88	24.44	.16	.16	4	118	32.78	.12	.12	5
89	24.72	.16	.16	2	119	33.06	.12	.12	3
90	25.00	.16	.16	1	120	33.33	.12	.12	11

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
121	33.61	.12	.12	2	151	41.94	.09	.10	4
122	33.89	.12	.12	4	152	42.22	.09	.09	7
123	34.17	.12	.12	1	153	42.50	.09	.09	5
124	34.44	.11	.12	12	154	42.78	.09	.09	11
125	34.72	.11	.12	8	155	43.06	.09	.09	9
126	35.00	.11	.12	5	156	43.33	.09	.09	3
127	35.28	.11	.12	3	157	43.61	.09	.09	12
128	35.56	.11	.11	4	158	43.89	.09	.09	6
129	35.83	.11	.11	11	159	44.17	.08	.09	4
130	36.11	.11	.11	2	160	44.44	.08	.09	1
131	36.39	.11	.11	10	161	44.72	.08	.09	10
132	36.67	.11	.11	12	162	45.00	.08	.09	8
133	36.94	.11	.11	1	163	45.28	.08	.09	5
134	37.22	.11	.11	4	164	45.56	.08	.09	11
135	37.50	.10	.11	5	165	45.83	.08	.09	4
136	37.78	.10	.11	3	166	46.11	.08	.09	2
137	38.06	.10	.11	6	167	46.39	.08	.08	12
138	38.33	.10	.11	11	168	46.67	.08	.08	3
139	38.61	.10	.10	9	169	46.94	.08	.08	5
140	38.89	.10	.10	4	170	47.22	.08	.08	11
141	39.17	.10	.10	2	171	47.50	.08	.08	4
142	39.44	.10	.10	12	172	47.78	.08	.08	10
143	39.72	.10	.10	5	173	48.06	.08	.08	9
144	40.00	.10	.10	1	174	48.33	.07	.08	1
145	40.28	.09	.10	10	175	48.61	.07	.08	6
146	40.56	.09	.10	3	176	48.89	.07	.08	5
147	40.83	.09	.10	4	177	49.17	.07	.08	12
148	41.11	.09	.10	11	178	49.44	.07	.08	4
149	41.39	.09	.10	12	179	49.72	.07	.08	11
150	41.67	.09	.10	2	180	50.00	.07	.08	2

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
181	50.28	.07	.08	3	211	58.61	.05	.06	5
182	50.56	.07	.08	10	212	58.89	.05	.06	4
183	50.83	.07	.07	5	213	59.17	.05	.06	10
184	51.11	.07	.07	8	214	59.44	.05	.06	11
185	51.39	.07	.07	9	215	59.72	.05	.06	3
186	51.67	.07	.07	4	216	60.00	.05	.06	8
187	51.94	.07	.07	7	217	60.28	.05	.06	9
188	52.22	.07	.07	11	218	60.56	.05	.06	5
189	52.50	.06	.07	12	219	60.83	.05	.06	6
190	52.78	.06	.07	6	220	61.11	.05	.06	7
191	53.06	.06	.07	5	221	61.39	.05	.06	10
192	53.33	.06	.07	4	222	61.67	.05	.06	4
193	53.61	.06	.07	10	223	61.94	.05	.06	11
194	53.89	.06	.07	1	224	62.22	.05	.06	12
195	54.17	.06	.07	11	225	62.50	.05	.05	5
196	54.44	.06	.07	3	226	62.78	.04	.05	9
197	54.72	.06	.07	9	227	63.06	.04	.05	6
198	55.00	.06	.07	5	228	63.33	.04	.05	8
199	55.28	.06	.07	12	229	63.61	.04	.05	10
200	55.56	.06	.07	6	230	63.89	.04	.05	5
201	55.83	.06	.07	2	231	64.17	.04	.05	7
202	56.11	.06	.07	8	232	64.44	.04	.05	1
203	56.39	.06	.06	4	233	64.72	.04	.05	11
204	56.67	.06	.06	10	234	65.00	.04	.05	4
205	56.94	.06	.06	5	235	65.28	.04	.05	9
206	57.22	.06	.06	11	236	65.56	.04	.05	6
207	57.50	.06	.06	7	237	65.83	.04	.05	10
208	57.78	.05	.06	9	238	66.11	.04	.05	2
209	58.06	.05	.06	6	239	66.39	.04	.05	8
210	58.33	.05	.06	12	240	66.67	.04	.05	12

Rank	%ile	Composite FDC	Estim. FDC	Month Flag
241	66.94	.04	.05	5
242	67.22	.04	.05	9
243	67.50	.04	.05	6
244	67.78	.04	.05	7
245	68.06	.04	.05	11
246	68.33	.04	.05	10
247	68.61	.04	.05	5
248	68.89	.04	.05	8
249	69.17	.04	.05	9
250	69.44	.04	.05	6
251	69.72	.04	.04	4
252	70.00	.03	.04	3
253	70.28	.03	.04	7
254	70.56	.03	.04	10
255	70.83	.03	.04	5
256	71.11	.03	.04	6
257	71.39	.03	.04	9
258	71.67	.03	.04	8
259	71.94	.03	.04	11
260	72.22	.03	.04	12
261	72.50	.03	.04	7
262	72.78	.03	.04	10
263	73.06	.03	.04	6
264	73.33	.03	.04	9
265	73.61	.03	.04	8
266	73.89	.03	.04	5
267	74.17	.03	.04	6
268	74.44	.03	.04	10
269	74.72	.03	.04	7
270	75.00	.03	.04	9
271	75.28	.03	.04	11
272	75.56	.03	.04	8
273	75.83	.03	.04	6
274	76.11	.03	.04	7
275	76.39	.03	.04	5
276	76.67	.03	.04	10
277	76.94	.03	.04	9
278	77.22	.03	.04	6
279	77.50	.03	.03	8
280	77.78	.02	.03	4
281	78.06	.02	.03	7
282	78.33	.02	.03	9
283	78.61	.02	.03	10
284	78.89	.02	.03	6
285	79.17	.02	.03	8
286	79.44	.02	.03	5
287	79.72	.02	.03	7
288	80.00	.02	.03	11
289	80.28	.02	.03	9
290	80.56	.02	.03	6
291	80.83	.02	.03	10
292	81.11	.02	.03	8
293	81.39	.02	.03	7
294	81.67	.02	.03	12
295	81.94	.02	.03	9
296	82.22	.02	.03	6
297	82.50	.02	.03	8
298	82.78	.02	.03	7
299	83.06	.02	.03	10
300	83.33	.02	.03	6

Rank	%ile	Composite FDC	Estim. FDC	Month Flag	Rank	%ile	Composite FDC	Estim. FDC	Month Flag
301	83.61	.02	.03	9	331	91.94	.01	.02	9
302	83.89	.02	.03	5	332	92.22	.01	.02	8
303	84.17	.02	.03	8	333	92.50	.01	.02	7
304	84.44	.02	.03	7	334	92.78	.01	.02	6
305	84.72	.02	.03	6	335	93.06	.01	.02	7
306	85.00	.02	.03	9	336	93.33	.01	.02	8
307	85.28	.02	.03	10	337	93.61	.01	.02	9
308	85.56	.02	.03	7	338	93.89	.01	.02	10
309	85.83	.02	.03	8	339	94.17	.01	.02	7
310	86.11	.02	.03	6	340	94.44	.01	.02	8
311	86.39	.02	.02	7	341	94.72	.01	.02	6
312	86.67	.02	.02	9	342	95.00	.01	.02	7
313	86.94	.02	.02	8	343	95.28	.01	.01	9
314	87.22	.02	.02	10	344	95.56	.01	.01	8
315	87.50	.02	.02	6	345	95.83	.01	.01	7
316	87.78	.02	.02	7	346	96.11	.01	.01	10
317	88.06	.02	.02	11	347	96.39	.01	.01	6
318	88.33	.02.	.02	8	348	96.67	.01	.01	8
319	88.61	.01	.02	9	349	96.94	.01	.01	9
320	88.89	.01	.02	7	350	97.22	.01	.01	7
321	89.17	.01	.02	6	351	97.50	.01	.01	8
322	89.44	.01	.02	10	352	97.78	.01	.01	7
323	89.72	.01	.02	8	353	98.06	.01	.01	8
324	90.00	.01	.02	7	354	98.33	.01	.01	6
325	90.28	.01	.02	9	355	98.61	.01	.01	7
326	90.56	.01	.02	5	356	98.89	.01	.01	10
327	90.83	.01	.02	8	357	99.17	.00	.01	8
328	91.11	.01	.02	6	358	99.44	.00	.01	9
329	91.39	.01	.02	7	359	99.72	.00	.01	7
330	91.67	.01	.02	10	360	100.00	.00	.01	8

5. Adjust the composite monthly curve to equal the annual curve.

   For each of the 360 percentiles (in Tables 13a and 13b), replace the flow value from the composite monthly curve by the flow value of the annual curve (if the two are different).

6. To construct a monthly flow duration curve for the month of interest, extract the 30 flows by means of the flag. This is illustrated for the River Pang for April in Table 14a. Complete Table 14b for the River Roman.

7. Construct a monthly flow duration curve for the River Roman for April and August on the graph paper provided.

Table 14a *River Pang: Calibrated April FDC*

%ile (For Annual Curve)	Flow	%ile (For April Curve)
3.6	2.70	2.0
7.2	2.17	5.3
9.2	1.99	8.7
12.0	1.78	12.0
14.7	1.62	15.4
16.4	1.54	18.7
18.9	1.43	22.0
20.6	1.37	25.4
22.8	1.29	28.7
25.3	1.22	32.1
28.1	1.15	35.4
30.3	1.09	38.8
31.7	1.06	42.1
33.6	1.02	45.5
35.8	.98	48.8
37.2	.95	52.2
39.4	.91	55.5
41.1	.89	58.8
42.8	.86	62.2
44.4	.84	65.5
47.5	.79	68.9
48.9	.78	72.2
51.4	.75	75.6
54.2	.71	79.0
56.9	.68	82.3
60.8	.64	85.6
65.0	.60	89.0
69.2	.55	92.3
74.7	.50	95.6
86.9	.37	99.0

River Pang: Calibrated August FDC

%ile (For Annual Curve)	Flow	%ile (For August Curve)
28.6	1.13	2.0
39.2	.92	5.3
45.8	.82	8.7
51.7	.74	12.0
55.8	.69	15.4
59.7	.65	18.7
62.8	.62	22.0
65.8	.59	25.4
68.9	.56	28.7
71.4	.53	32.1
73.1	.52	35.4
75.6	.49	38.8
76.9	.48	42.1
78.9	.46	45.5
80.6	.44	48.8
81.9	.42	52.2
83.9	.40	55.5
85.3	.39	58.8
86.7	.37	62.2
87.8	.36	65.5
89.2	.34	68.9
90.6	.33	72.2
91.4	.32	75.6
92.5	.30	79.0
93.6	.29	82.3
94.7	.27	85.6
96.4	.24	89.0
97.2	.23	92.3
98.6	.19	95.6
99.4	.18	99.0

Table 14b River Roman: Calibrated April FDC River Roman: Calibrated August FDC

%ile (For Annual Curve)	Flow	%ile (For April Curve)
		2.0
		5.3
		8.7
		12.0
		15.4
		18.7
		22.0
		25.4
		28.7
		32.1
		35.4
		38.8
		42.1
		45.5
		48.8
		52.2
		55.5
		58.8
		62.2
		65.5
		68.9
		72.2
		75.6
		79.0
		82.3
		85.6
		89.0
		92.3
		95.6
		99.0

%ile (For Annual Curve)	Flow	%ile (For August Curve)
		2.0
		5.3
		8.7
		12.0
		15.4
		18.7
		22.0
		25.4
		28.7
		32.1
		35.4
		38.8
		42.1
		45.5
		48.8
		52.2
		55.5
		58.8
		62.2
		65.5
		68.9
		72.2
		75.6
		79.0
		82.3
		85.6
		89.0
		92.3
		95.6
		99.0

8. ESTIMATION OF THE MEAN MONTHLY MINIMA

The Mean Monthly Minima are derived using a general statistical relationship between these statistics and the catchment MAM(7) as a percentage of mean flow and SAAR:

$$MMM(7)_{MON} = a \times MAM(7)^{b} \times SAAR^{c}$$

Table 15 Parameter estimates for mean monthly minimum equations

	Error parameters		Parameter estimates		
MMM(7)	R^2	fse	a const	b MAM(7)	c SAAR
JAN	57	1.20	15.52	0.314	0.038
FEB	65	1.18	39.32	0.303	-0.084
MAR	67	1.18	36.25	0.323	-0.079
APR	73	1.18	31.35	0.359	-0.066
MAY	71	1.16	17.99	0.337	0.035
JUN	78	1.17	39.04	0.398	-0.107
JUL	72	1.22	101.80	0.380	-0.238
AUG	75	1.20	50.04	0.414	-0.157
SEP	77	1.21	55.76	0.446	-0.197
OCT	69	1.21	19.99	0.385	-0.029
NOV	59	1.21	8.82	0.349	0.105
DEC	61	1.20	11.77	0.344	0.059

The parameters a, b, c are selected from Table 15 according to the month in question.

River Pang

The January MMM(7) for the River Pang is calculated as follows:

MAM(7) = 28.4% MF
SAAR = 704 mm
$MMM(7)_{JAN}$ = $15.52 \times MAM(7)^{0.314} \times SAAR^{0.038}$
= $15.52 \times 28.4^{0.314} \times 704^{0.038}$
= 56.94 %MMF

Roman River

MAM(7) = *% MF*
SAAR = *mm*
$MMM(7)_{JAN}$ = *$a \times MAM(7)^{b} \times SAAR^{c}$*
= *( ) x ( )$^{( )}$ x ( )$^{( )}$*
= *%MMF*

To express $MMM(7)_{JAN}$ in flow units, rescale by the January Monthly Mean Flow (MMF_{JAN}) which was calculated in Exercise 5:

River Pang:

MMF	=	1.77 m^3s^{-1}
$MMM(7)_{JAN}$	=	1.01 m^3s^{-1}

Roman River

MMF	=	m^3s^{-1}
$MMM(7)_{JAN}$	=	m^3s^{-1}

The monthly minima for each month for the Pang are given in Table 16a. Complete Table 16b for the Roman.

Table 16a *Mean monthly minima for the River Pang*

	J	F	M	A	M	J	J	A	S	O	N	D
a	15.52	39.32	36.25	31.35	79.99	39.04	101.80	50.04	55.76	19.99	0.385	-0.029
b	0.314	0.303	0.323	0.359	0.337	0.398	0.380	0.414	0.446	8.82	0.349	0.105
c	0.038	-0.084	-0.079	-0.066	0.035	-0.107	-0.238	-0.157	-0.197	11.77	0.344	0.059
$MMM(7)_{MON}$ %MMF	56.94	62.49	63.65	67.62	69.90	73.33	76.26	71.44	68.17	59.95	56.45	54.79
MMF m^3s^{-1}	1.77	1.89	1.86	1.19	0.98	0.70	0.51	0.48	0.53	0.68	1.06	1.46
$MMM(7)_{MON}$ m^3s^{-1}	1.01	1.18	1.18	0.80	0.69	0.51	0.39	0.34	0.36	0.41	0.60	0.80

Table 16b *Mean monthly minima for the River Roman*

	J	*F*	*M*	*A*	*M*	*J*	*J*	*A*	*S*	*O*	*N*	*D*
a	*15.52*	*39.32*	*36.25*	*31.35*	*79.99*	*39.04*	*101.80*	*50.04*	*55.76*	*19.99*	*0.385*	*-0.029*
b	*0.314*	*0.303*	*0.323*	*0.359*	*0.337*	*0.398*	*0.380*	*0.414*	*0.446*	*8.82*	*0.349*	*0.105*
c	*0.038*	*-0.084*	*-0.079*	*-0.066*	*0.035*	*-0.107*	*-0.238*	*-0.157*	*-0.197*	*11.77*	*0.344*	*0.059*
$MMM(7)_{MON}$ %MMF	*41.01*	*46.70*					*54.43*	*48.42*			*38.68*	*38.11*
MMF m^3s^{-1}	*0.32*	*0.30*	*0.26*	*0.15*	*0.10*	*0.04*	*0.03*	*0.03*	*0.05*	*0.07*	*0.15*	*0.21*
$MMM(7)_{MON}$ m^3s^{-1}	*0.80*	*0.80*					*0.00*	*0.01*			*0.06*	*0.08*