LOW FLOW STUDIES

Report No 1

Research report

INSTITUTE OF HYDROLOGY
Crowmarsh Gifford
Wallingford, Oxon

JANUARY 1980

PREFACE

This report summarises the main conclusions of a 5 year study of low flow estimation procedures for United Kingdom rivers carried out at the Institute of Hydrology. The philosophy underlying the study was that low flow indices extracted from flow records could be related statistically to catchment characteristics to yield formulae enabling low flows to be predicted at ungauged sites for preliminary design purposes.

The staff engaged on the study consisted of three hydrologists, Alan Gustard, B.A. (team leader), Stuart Curry, M.Sc. and David Marshall, M.Sc, assisted as required by Ann Sekulin, M.Sc, computer programmer, Carole Webb, Helene Dracos and Sandra Higgs, Cartographic assistants, and Helen Brimacombe, Jacqueline French, Ellie Moore and Margaret Owen, Assistant Scientific Officers. The overall supervisor was Max Beran, B.Sc, and the work was carried out in the Applied Hydrology Division headed by Dr. J. V. Sutcliffe.

The study was funded by the Department of the Environment and their interest and advice at various stages is much appreciated. We are also grateful for the considerable assistance given by Regional Water Authorities, River Purification Boards, and other gauging authorities, government departments and research establishments in the United Kingdom and the Republic of Ireland (see Appendix I for a complete list) for suggesting useful low flow measures, for advice relating to the reliability of flow records and for providing the flow data without which this study would not have been possible.

January 1980.

CONTENTS

*Those wanting an appreciation of the broad scope and main conclusions could restrict their reading to these sections.

ILLUSTRATIONS

FIGURES

TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

ADF	average flow in cumecs
AE	actual evaporation in mm
AMP(D)	annual D day minimum of probability of exceedance P
AREA	catchment area in km^2
ARV	average runoff volume in units of cumec days
BFI	base flow index
CV	coefficient of variation
D	duration over which flow is averaged in FDC and FFC
D_1, D_2	durations of deficit periods (spells)
DVF	dry valley factor
f( ), F( )	probability density and cumulative probability function
FALAKE	proportion of catchment covered by a lake or reservoir
FDC	flow duration curve
FFC	flow frequency curve
fse	factorial standard error
GWP	groundwater pumping
KREC	two day recession constant at discharge of approximately 25% ADF
L	mainstream length in km
MAM(D)	mean annual D day minimum
MAM(10)	mean annual 10 day minimum
P25	probability (expressed as number of standard deviations from the mean) of exceeding 25% ADF
PE	potential evaporation in mm
Q,q	general purpose symbols for discharge
Q95	flow exceeded 95% of the time (duration not specified)
Q95(10) etc	10 day average flow exceeded by 95% of 10 day average discharges
QP(D)	D day average flow exceeded by P% of D day average discharges
r	ratio between potential and actual evaporation
SAAR	standard period (1941-1970) annual average rainfall in mm
S1085	slope between points 10% and 85% up the main stream from the point of interest in m/km
STMFRQ	stream frequency in junctions per square kilometre
TC	type curve for flow duration or flow frequency curves
URBAN	proportion of catchment under urban development
V, V_1, V_2	volumes of deficits or storage requirement
γ, θ	parameters of Weibull distribution
y	reduced variate of Gumbel distribution and Normal distribution
Φ	normal probability integral
W	reduced variate of Weibull distribution
WDU	Water Data Unit

1 Background to the study

1.1 Introduction

This report is the first of a series which documents the work of the Low Flow Study team carried out at the Institute of Hydrology. The complete series of reports is as follows:

Report No. 1 Research report

Report No. 2 Manuals for estimating low flow measures at gauged or ungauged sites

Report No. 3 A manual describing the techniques for extracting catchment characteristics

Report No. 4 River basin and regional monographs describing the relationship between the base flow index and catchment geology.

These reports are being updated and extended following specific requests, 'feedback' from report users, and continuing research. Manuals are written in the form of a step by step guide with completed example and examples to be worked by the user.

It should be emphasised that this study deals with statistical measures of low flows such as are used in design work or in licensing abstractions or effluent discharges, and not with absolute minima, with forecasting methods, nor with time series or rainfall - runoff models. Examples of the low flow measures that are discussed are those concerned with the frequency of low flow events, the length of time spent below a threshold discharge, storage and yield, and the rate of recession. Whilst all these are described and their computation from flow records is given, not all have yet been generalised to the ungauged site.

Successful estimation at an ungauged site was found to depend very largely on the nature of the geology of the catchment. A new index, the base flow index, was developed for the purpose of quantifying catchment geology and the separate regional monographs describe how this index relates to and may be estimated from a knowledge of local geology.

1.2 Summary of report

A brief survey of previous attempts to regionalise low flow indices is given in the next section. Chapter 2 describes the availability of data, the method of assessing its suitability for the study and also the extraction of low flow measures and catchment characteristics.

Chapter 3 is concerned with methods of estimating low flow indices at ungauged sites, describes the statistical analysis used to establish relationships and summarizes the estimation procedure. The final chapters reiterate the availability of other more detailed reports and data, and outline continuing work and future research requirements.

1.3 Bibliography of low flow studies

There is an extensive literature on low flow processes, in particular the surface or groundwater interaction and descriptions of the low flow regime of individual basins. However, relatively little work has been reported on techniques for estimating low flow measures at ungauged sites even for measures that are commonly employed in engineering practice. This survey concentrates on the literature relevant to low flow prediction for ungauged locations.

A comprehensive study by the United States Geological Survey (Thomas and Benson, 1975) concluded that low flows were more difficult to predict than other flow characteristics and a more recent study (Frye and Runner, 1970 reported by Chang and Boyer 1977) concluded that 'low flow characteristics at ungauged sites on natural-flow streams, minor and principal, cannot be estimated accurately by regression'.

On the other hand there are many references to the use of more or less informal techniques of classifying catchments into physiographic types and transferring low flow data in dimensionless or specific form between catchments within the same region. Examples of this technique for different countries of the world are to be found in Martin *et al* (1976) for Ireland, Simmers (1975) for New Zealand, Musiake *et al* (1975) for Japan, Knisel (1963) for south central United States, Midgeley *et al* (1967) for South Africa, Mitchell (1957) for Illinois USA and Hines (1975) for Arkansas which are typical of other State surveys, McMahon (1969) for the Hunter River basin in Australia, Yoon (1975) for the Han River in Korea, and Weyer *et al* (1970) for Munster in Germany. Most of the quoted examples employed catchment characteristics indexing catchment size, shape and climate and most refer to the additional need to consider the geology of the catchment in order to explain more of the variability of low flows.

However very few studies have been carried out in which any direct quantitative allowance is made for the effect of geology. Indirect allowance may be made if geology-sensitive catchment characteristics are used. Those few that do endeavour to quantify geology are described in the following paragraphs.

Wright (1970) presents a prediction equation for the mean lowest flow in a year using catchment slope and area as independent variables. The prediction error was then associated with catchment geology and a table of numerical geological indices for different classes of material was derived. Because this work was based on a rather limited set of catchments, mainly in south-east Scotland, a second paper (Wright, 1974) was written using a more extensive data set and presented a larger table of modified geology indices. This second paper was more concerned with the forecasting of low flows from seasonal rainfall than the prediction problem.

Klaassen *et al* (1975) studied the rate of recession following flood hydrographs on 29 catchments in New South Wales. An index of aquifer and alluvium behaviour is developed from these data and tabulated for different types of material. This index is then used to predict the recession constant.

Armbruster (1976) describes the development of an infiltration index for improving the predictive ability of low flow regression equations. Data from 100 gauging stations in the Susquehanna River basin (USA) were used to derive 10, 20, and 50 year return period 7 day flows. The US Soil Conservation Service soil classification procedure was used with numerical weights assigned to each soil class. Different weights were tried in order to optimise the regression prediction. With the chosen weights a typical standard error of estimate of 50% was achieved compared with 70% for predictions based upon area and rainfall alone.

The estimation of low flows by correlation with neighbouring gauged catchment data is described in U.S. Geological Survey publications, in particular Riggs (1973). Wesche *et al* (1973) and Skelton (1974) make use of the cross-sectional properties of streams. This approach has not been attempted in the Institute's study.

For the United Kingdom more general information on the behaviour of British rivers is given by Ward (1968) and also in Rodda *et al* (1976). Flow duration curves were published in early Surface Water Yearbooks (HMSO, 1959-60) and up until 1975 in many River Authority Annual Reports. The interaction between surface and groundwater for major aquifers is discussed in Ineson *et al* (1965). Much design work has been based on the lowest recorded flow and the Water Resources Board (1970) catalogues a large number of these obtained in many cases from spot gaugings at points not normally gauged.

The Deacon (1910) diagram and the Lapworth (1949) chart have been used for the assessment of reservoir yield and storage. These are both generalised storage yield diagrams but although experience has shown that the Lapworth chart corresponds to about a 1% or 2% drought, it does not quote probabilities. The cumulative inflow curve has been employed at gauged sites based upon a particular recorded low flow period or synthesised by combining records or from a statistical treatment of low flows. This latter technique was developed by Bannerman and reported by Law (1965, 1966). A further development by Watson (1970), for use in regulating reservoir design, allows the 100 year return period cumulative runoff of any duration from 6 months to 3 years to be evaluated for any point, given only the average annual rainfall. Flow duration curves and their applications in the UK are given in Hoyle (1963) and the subsequent work of the IWE/SWTE panel (Mansell-Moullin, 1965). They are also discussed by Boulton (1965) where the concept of a 'Minimum Acceptable Flow' is described and the factors likely to enter into its calculation are considered.

The incidence of droughts in the United Kingdom occasions special studies. A list of the more important droughts from the water supply viewpoint is given in Rodda *et al* (1976). The 1959 drought is discussed in some detail in Rowntree *et al* (1961). The recent 1975/76 drought has been reviewed and described in many articles and papers, with the Central Water Planning Unit documentation discussing river flow aspects in greatest detail (Wright, 1977).

2 River flow and catchment data analysis

This chapter describes the flow and catchment data that were used and also the extraction of the low flow measures. Section 2.1 details the selection of suitable gauging stations according to rating accuracy and the level of artificial influences.

Section 2.2 describes the flow processing used to produce the various low flow measures. Section 2.3 describes the extraction of catchment characteristics from maps and the facilities for handling these data.

2.1 Selection of flow records

Because the relationships were sought between the low flow regime of a river and the catchment 'responsible' for that regime, only catchments whose gaugings represent reasonably natural conditions were accepted. Three criteria were applied to an original list of gauged catchments based upon the Flood Studies Report (NERC, 1975, Vol IV) updated with Water Data Unit and Water Authority catalogues:

(a) the accuracy of the flow measurement;

(b) the extent of artificial influences compared with the natural river flow;

(c) the length of record available in analysed form.

The selection of suitable gauging stations was assisted by discussions with the gauging authority, the scrutiny of water resources publications and lists of abstractions and sewage works, and inspection of the Institute of Hydrology and Water Data Unit station history files.

Flow measurement: The accuracy of a gauging station's stage/discharge relationship (rating) is of less concern for statistical analyses of the type described in this report than for many operational purposes. The accuracy at 25% average discharge (25% ADF) was used to index low flow performance. The two main cases are purpose built gauging structures and natural river sections calibrated by current meter.

Except where field experience indicated that the gauge performance of a purpose built gauge at 25% ADF had been consistently poor, a low factorial standard error (fse), often 1.05, was attributed to the station. A consistent bias such as may be introduced by weed growth was of greater concern than errors that are randomly positive or negative.

Where a least squares procedure had been used to rate a natural section gauging station the fse obtained in the analysis was used. Where the rating was based on an eye fit to the current meterings, the envelope to the scatter of points was assumed to represent 2 fse. This procedure was sometimes employed even if a least squares fit had been used when, as was common, the scatter at low flows was larger than the overall scatter.

Artificial influences: To develop useful relationships between low flows and catchment characteristics the river flow must approximate a natural response to the catchment. It was thus necessary to categorise the data according to the extent of artificial controls on river flows. Table 2.1 lists common influences and summarises their effects and treatment.

These influences were represented by flow paths within and across catchment boundaries and so reduced all effects to a net loss or gain (eg. exporting or importing water from a catchment) or else a redistribution in time (eg. groundwater pumping returned as sewage effluent). The fse was assessed as a function of the size of the loss or gain or redistribution relative to average flows, and the fse from this source was combined with the fse arising from rating error to produce a single error assessment for each record. Factorial standard errors from two independent sources f_1 and f_2 were combined in the standard manner:

TABLE 2.1 ARTIFICIAL INFLUENCES ON LOW FLOWS

Artificial influence	Effect on natural flow regime		Error assumed
Reservoir in catchment (direct supply, regulating, hydro-electric)	Possible bias if supply exported outside catchment Smoothing of annual hydrograph.	i	If flows not naturalised bias used in error calculation based upon proportion of reservoir yield to ADF.
		ii	If flow naturalised effect of redistribution considered to reduce the grade usually to monthly.
Groundwater	Possible bias if pumped water exported outside the catchment. Effect of aquifer management is to smooth the annual hydrograph. Effects depend on degree of confinement of aquifer and the position of the borehole relative to the gauged catchment boundary.		If aquifer unconfined and cone of depletion entirely within catchment then factorial error f assessed as $f = \frac{ADF + GWP}{ADF}$ where GWP is average pumped quantity, ADF is average discharge.
Mine drainage	If pumped then considered as groundwater pumping. Adits can cross boundaries of catchment and so import or export water.		Numerical data seldom available and many gauged catchments in Trent and Yorkshire area downgraded to 'unsuitable' for this reason.
Sewage effluent discharge	Possible bias dependent upon the original source of the sewage water. Some redistribution in time is inevitable even if original source is within catchment.		Bias considered after water balance incorporating all influences. Redistribution allowed for subjectively by reducing the grade one class if sewage discharge is large enough.
Direct abstraction from river	Possible bias dependent upon eventual point of return.		Regional average quantities for ratio of licence to actual abstraction used and estimated factors for irrigation returns and observed values for large water supply abstractions.
Mills, locks, canalised section, tidal influence	Possible redistribution in time.		Subjective assessment, commonly reducing 'daily' graded stations to the 'weekly' class.

$$S_1 = \log (f_1); \quad S_2 = \log (f_2)$$

where S_1, S_2 is the standard error of the logarithms (this being the common form especially with rating curve error)

$$S = \sqrt{S_1^2 + S_2^2}$$

where S is the combined error of the logarithms

and $f = \text{antilog}(S)$

where f is the combined factorial error.

It is possible to combine bias with standard errors in a similar fashion.

The criterion used for accepting a station's record was that the total fse must be less than 10% and this led to a grading of each station according to the minimum time period for which its data was considered as acceptable - daily, weekly, monthly, annual and unsuitable. Thus, to use monthly flow data, the error of monthly flows had to be within 10% and so on. Under this scheme stations with precise low flow ratings and few artificial influences were graded 'daily' but a station, whose record was affected by an unnaturally high discharge on one day of the week offset by a lower discharge on another day in the week, would be graded weekly because the error of average weekly discharge was acceptable.

Period of record: One, two, five and twenty years of data were the minimum length of records suitable for daily, weekly, monthly and annual graded stations. Over 1,400 stations were considered for use in the study. The breakdown of the stations by grade and length of record is shown in Table 2.2. Data were used only if flow records had already been computed so many potentially suitable records could not be employed because mean daily flows had not been worked up from the original chart records.

<u>TABLE 2.2</u> NUMBERS OF GAUGED CATCHMENTS IN VARIOUS CATEGORIES

GRADE	Daily	Weekly	Monthly	Annual	Unsuitable	Total
Total in grade	470	156	177	32	632	1467
Total in each grade with sufficient length of record	396	121	163	7	-	687
Length of record (years)						
< 2	61	-	-	-	-	61
2-5	95	29	-	-	-	124
5-20	221	89	107	-	-	417
> 20	19	3	56	7	-	85

Flow data handling: Computer based data handling facilities had to be developed to process the large quantity of flow information. Most of the flow data were obtained from the Water Data Unit's archive although special steps were taken to fill gaps in their archive by requesting the missing data from the gauging authority. This affected 300 of the stations. A limited number of stations' records in data sparse regions were punched up from manuscript forms. All these data, totalling over two million flow values, were stored in a daily discharge and monthly discharge archive on the Institute's Univac 1108 computer.

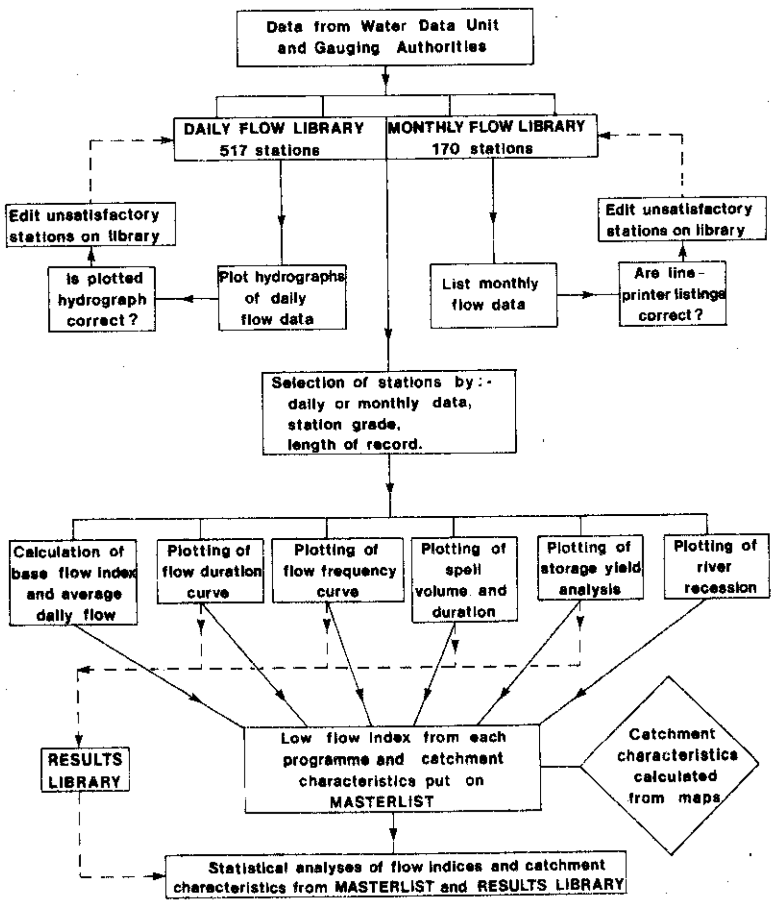
A simple internal quality control system was applied which consisted of plotting on the CALCOMP plotter the daily mean discharges as a flow hydrograph and scrutinising these for unlikely events. A large number of spurious events were detected by this method. Common errors were the use of zero values instead of the missing value symbol for missing data, incorrect flow units and misplaced decimal points. The monthly flow archive was similarly checked from a line-printer listing of the values. Brief periods of missing data were infilled where possible by interpolation between correctly recorded discharges often with advice from the gauging authority.

The final outcome of the data collection programme was a library containing 517 daily and an additional 170 monthly flow data stations.

Figure 2.1 shows the data handling system and represents the computer routine for archiving and accessing data according to station number and required period of record, and the subsequent hydrograph analysis programs.

FIGURE 2.1

DATA PROCESSING FLOW CHART



2.2 Low Flow Measures

The term 'low flow measures' is used throughout this report to describe the many ways that have been developed for summarising, often in diagrammatic form, the low flow regime of a river. The reasons for the proliferation of measures are:

(a) Different definitions of a low flow event - an event can be expressed in terms of a threshold discharge, an accumulated volume, a length of time spent below a threshold or a rate of recession;

(b) Different methods of expressing frequency - the frequency or probability may be thought of as a proportion of time, eg., flow duration curve, or as a proportion of years that a given low flow occurs, eg., flow frequency curve;

(c) different durations or averaging periods; many applications consider low flow not at an instant but over some set period of time such as 7 days or 6 months.

Computer programs have been written to calculate and draw many of the measures described in this section and store the values on the RESULTS LIBRARY (Figure 2.1). A second term 'low flow index' is reserved in this report for particular values obtained from any low flow measure. For example, the flow duration curve is a low flow measure and the 95 percentile 10 day flow is a low flow index drawn from the flow duration curve. These same computer programs derive particular indices and these are stored on the MASTERLIST (Figure 2.1) for further processing. The following paragraphs describe the low flow measures and indices used in this study.

Flow duration curve: This curve shows the relationship between any given discharge and the percentage of time that the discharge is exceeded. Flow duration curves can be derived from daily flow data by assigning daily discharges to class intervals and counting the number of days within each interval. The proportion of the total number of days above the lower limit of any given class interval is then calculated and plotted against the lower limit of the interval.

In the example of Figure 2.2 flows are first expressed as a percentage of average daily flow (ADF) over the recorded period and a logarithmic discharge axis is used. The purpose of expressing discharge in terms of the ADF is that it permits comparison between catchments, by reducing the effect on the slope and location of the flow duration curve of differences in catchment area and higher or lower than average flows during the recorded period.

A normal probability scale is used for the frequency axis. Thus if n days out of a total record length of N days of record are above a discharge q a plotting position on the frequency axis is given by t where:

$$\text{Prob } (Q > q) = n/N = 1 - \Phi(t)$$

where Φ is the normal probability integral $\displaystyle\int_{-\infty}^{t} \frac{1}{\sqrt{2\pi}} e^{-x^2/2}$

which is tabulated in standard texts. The quantity t can be thought of as the number of standard deviations greater or less than the mean, the frequency axis of Figure 2.2 being linear in standard deviations.

If the logarithms of the daily discharges were normally distributed then under this scheme the curves would plot as a straight line. This is approximately the case for most streams and greatly facilitates extrapolation beyond the range of the data.

The slope of a flow duration curve drawn on log-normal paper is a measure of the standard deviation of the logarithms of discharges (SDL). By reading the ordinates of an eye-fit straight line at, for example, abscissae of 5% and 95%, Q5 and Q95, an estimate of the standard deviation is obtained from

$$\log Q5 - \log Q95 = 3.29 \text{ SDL}$$

Furthermore, the standard deviation of the logarithms, SDL, is approximately proportional to the coefficient of variation, CV, of the original data. Thus

$$CV \doteqdot 0.43 \text{ SDL}$$
or
$$CV \doteqdot 0.132 \log (Q5/Q95)$$

It is also possible, and in some cases more convenient, to plot flow duration curves on untransformed axes. In this case the area under the curve is related to the total volume of runoff. However the resultant curve is more difficult to extrapolate and to make comparisons between catchments.

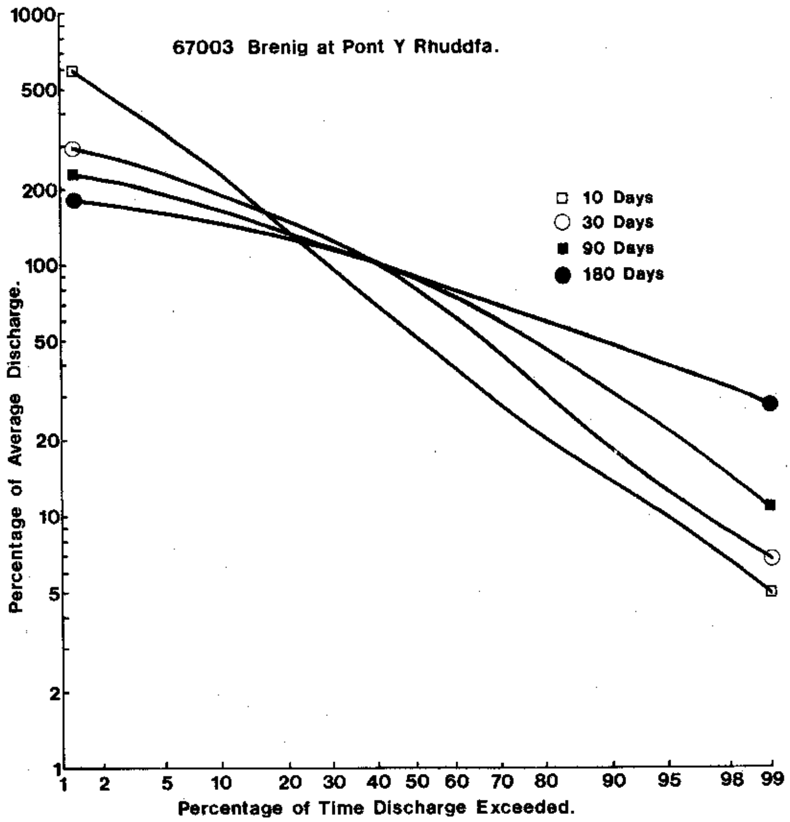


FIGURE 2.2

FLOW DURATION CURVES FOR DIFFERENT DURATIONS

Figure 2.2 also shows curves drawn for D-day consecutive periods. The interpretation of a point on, say, the 10-day flow duration curve is that it gives the proportion of 10-day periods when the average discharge over the period is greater than a certain value. An alternative way of viewing the D-day case is to consider it as a flow duration curve developed from a derived hydrograph obtained by applying a D-day moving average to the original hydrograph. The derived hydrograph is, of course, a smoothed version of the original with higher troughs and lower peaks thus accounting for the flatter slope of the flow duration curves as D increases. For practical purposes the curve drawn for D = 1, ie daily data, may be equated with the curve drawn from continuous data at least when considering low flows. Monthly data can be used in the same way producing 1 month, 3 month and 6 month flow duration curves.

An important area of application of flow duration curves is in sewage works design because they indicate the proportion of time the flow in the river will provide adequate dilution for the effluent. Similarly the design and licensing of direct river abstractions can be judged although if there is any element of storage it will be more appropriate to use a flow duration curve based upon D day flows where D is larger than one. The IH computer program allows up to nine D values between one and 365 days to be plotted on the same set of axes and provides graphical and tabular output.

The low flow index from the flow duration curve used to generalise to ungauged locations was the 95 percentile 10 day discharge, Q95(10). However various other values were entered on the MASTERLIST (Figure 2.1); Q95 (1, 5, 7, 30, 60, 90 and 180 days) and the percentiles conresponding to ADF, 25% ADF (P25), 5% ADF and 1% ADF.

Flow frequency curve: While the flow duration curve is concerned with the proportion of time that a flow is exceeded, the flow frequency curve shows the proportion of years, or equivalently the average interval between years (return period), in which the river falls below a given discharge. As with other measures of low flow it can be derived from one or D daily data, or from monthly data. The moving average interpretation of D-day values given for the flow duration curve applies equally for the flow frequency case where in fact a D-day annual minimum becomes a point minimum of the derived hydrograph.

The method of drawing the flow frequency curve (Figure 2.3) is:
(i) find the lowest flow in each year (from the moving average data where required); (ii) rank them from highest to lowest; (iii) assign a plotting position to each ranking; (iv) plot the discharge against the plotting position; and (v) draw a smooth curve through the points. In this study such curves have been drawn adopting for convenience the Weibull distribution:

$$f(x) = (\gamma/\theta)\ x^{\gamma-1} \exp(-x^{\gamma}/\theta) \qquad 0 < x < \infty$$

$$F(x) = 1 - \exp(-x^{\gamma}/\theta)$$

where $f(x)$ and $F(x)$ are the density and distribution functions; θ, γ are parameters of the Weibull distribution

This can be shown to be identical to the Extreme Value Type III (EV3) distribution (NERC, 1975, I p88) if x is replaced by - x, i.e. if a variable is distributed as EV3 its negative is distributed as Weibull, and is identical to Gumbel's 'limited distribution of the smallest value' (Gumbel, 1958, p 278). The relevant formulae for the plotting position for the ith largest of a sample of N are:

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

$$y_i = - \ln (- \ln P_i)$$

$$W_i = 4(1 - e^{-.25y_i})$$

$$T_i = (1 - P_i)^{-1}$$

where y is the EV1 reduced variate

P_i is the corresponding exceedance probability

W_i is the plotting position for the case of $\gamma = 4.0$

T_i is the corresponding return period.

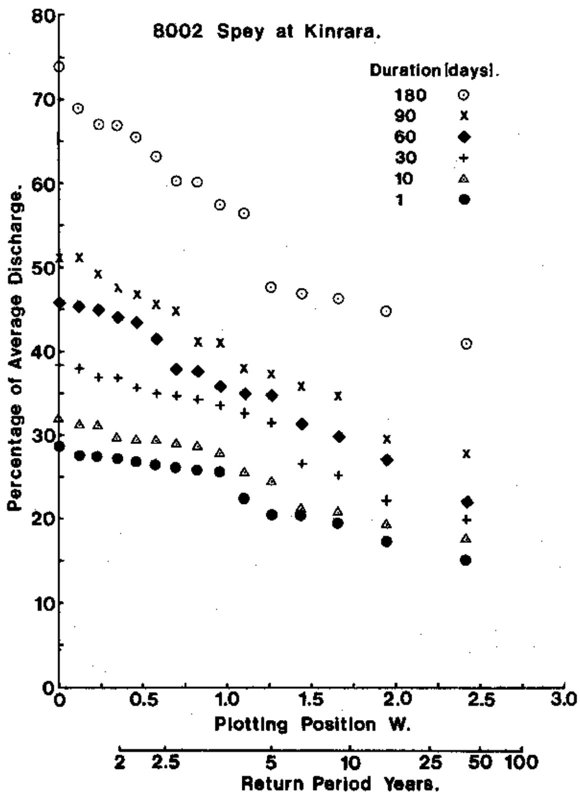


FIGURE 2.3

FLOW FREQUENCY CURVE FOR DIFFERENT DURATIONS

The IH program caters for up to nine values of D and expresses discharge as a percentage of ADF (Figure 2.3). While data that are drawn from the Weibull distribution with appropriate γ value will plot as a straight line this is not assumed in this study and the assumption is to be regarded as providing a convenient plotting scale.

A further program extracts the annual minima of up to nine D values, in the current study 1, 5, 7, 10, 30, 60, 90, 180 and 365 days, and calculates the first four moments of the raw data and of the logarithms of the data. These results were entered onto the results library (Figure 2.1). The low flow index, the mean annual 10-day minimum, MAM(10) was calculated for all stations with more than five years of record and was entered onto the MASTERLIST for further analyses.

The application of the flow frequency curve is similar to the flow duration curve but it is better equipped to describe rarer events and enter into economic evaluations. Note that 90% exceedance on the flow duration curve is a more common event than 90% or 10 year return period low flow from the flow frequency curve. By nesting flows of a given frequency of increasing durations within each other it is possible to construct artificial drought sequences for reservoir design purposes.

Low flow spells: The measures considered so far describe the event in terms of a discharge. However it is of interest both in amenity and water quality work to know for how long a low flow is maintained and how large a deficit can build up. Thus while the 95% flow on the flow duration curve is defined to be exceeded 95% of the time, or in other words, in a period of 100 years there will be 1826 days (5% x 365 x 100) when the flow is lower, no information is available on how these 1826 days occur. These 1826 days may be divided into many short spells or alternatively into fewer long spells. A low flow measure which provides this information is now described.

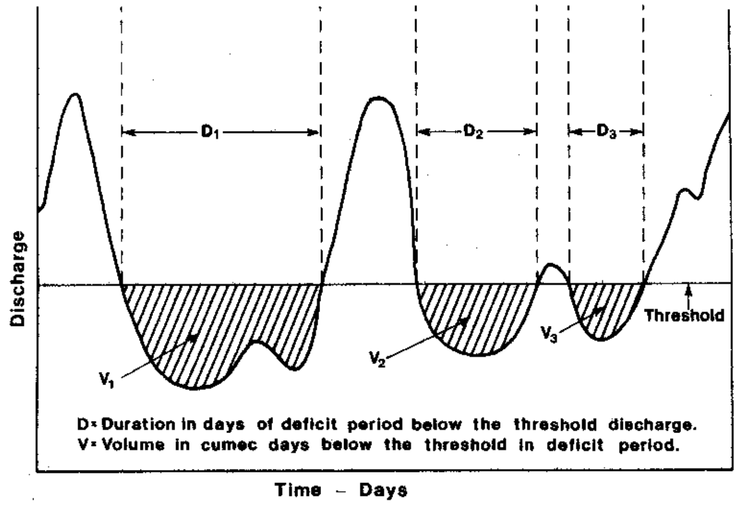


FIGURE 2.4

DEFINITION OF SPELL DURATIONS AND DEFICIENCY VOLUMES

Figure 2.4 shows the definition of low flow spells below a given threshold discharge. The deficit duration D is the length of the period that the river spends continuously below a threshold, and the deficit volume V is that which would be required to maintain the flow at that threshold. The measures described below are all based on the set of durations D_1, D_2 ... and volumes V_1, V_2, ... illustrated in Figure 2.4. The analyses were performed on all stations with more than 20 years of record and at threshold discharges set at 5, 10, 20, 40, 60, 80 per cent of ADF, and at the discharge corresponding to the 95 percentile from the 10-day flow duration curve.

The frequency of spells and volumes is expressed in two ways (a) frequency per 100 years of an event, illustrated in Tables 2.3 and 2.4 and Figures 2.5 and 2.6 and (b) proportion of years in which a deficit duration or volume is exceeded, illustrated in Tables 2.5 and 2.6 and Figures 2.7 and 2.8.

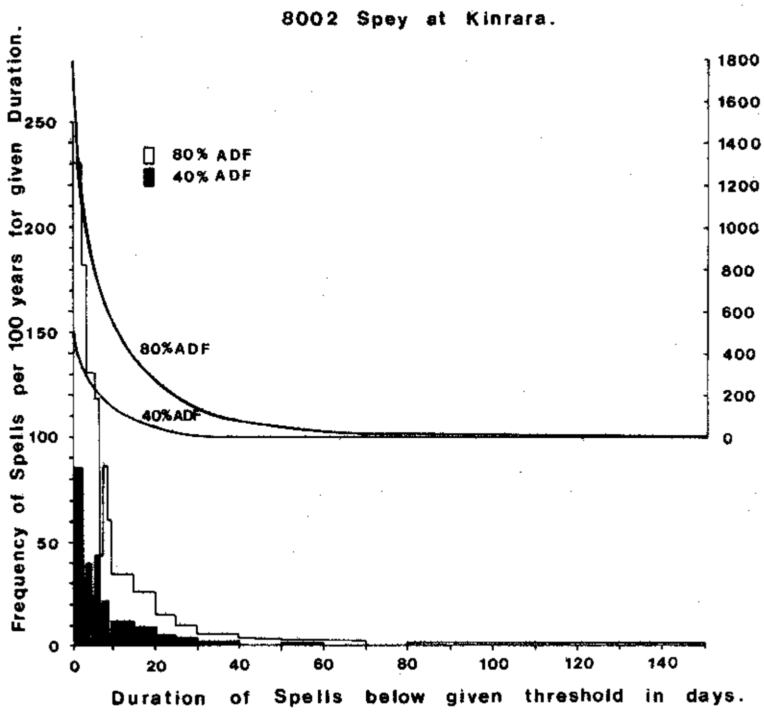


FIGURE 2.5

FREQUENCY OF SPELL DURATIONS

TABLE 2.3 FREQUENCY OF SPELL DURATIONS

STATION NUMBER 8002 PERIOD OF RECORD JAN 1952 TO DEC 1975

AVERAGE DAILY FLOW = 20.514 CUMECS
Q95 = 33.20 % AVERAGE DAILY FLOW
AVERAGE ANNUAL RUNOFF = 7493. CUMEC DAYS

SPELL DURATIONS

THRES-HOLD % ADF	CLASS LIMITS DAYS																										
	LOWER	1	2	3	4	5	6	7	8	9	10	15	20	25	30	40	50	60	70	80	90	100	150	200	250	300	350
	UPPER	1	2	3	4	5	6	7	8	9	14	19	24	29	39	49	59	69	79	89	99	149	199	249	299	349	
5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20		4	13	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40		86	86	30	39	21	43	8	21	4	56	43	21	13	8	0	8	4	4	0	0	0	0	0	0	0	0
60		173	117	139	91	43	47	47	52	56	182	82	69	34	39	13	13	4	4	8	0	4	0	0	0	0	0
80		243	230	182	130	130	117	43	86	60	173	126	69	47	47	30	17	17	17	4	8	13	0	0	0	0	0
Q95		56	47	47	17	26	13	13	4	4	47	8	8	0	0	8	0	4	0	0	0	0	0	0	0	0	0

NOTES: 1. FREQUENCY IS EXPRESSED AS THE NUMBER OF EVENTS IN CLASS INTERVAL PER 100 YEARS
2. ONE EVENT IN PERIOD OF RECORD HAS FREQUENCY OF 4 PER 100 YEARS

TABLE 2.4 FREQUENCY OF DEFICIENCY VOLUMES

STATION NUMBER 8002 PERIOD OF RECORD JAN 1952 TO DEC 1975

AVERAGE DAILY FLOW = 20.514 CUMECS
Q95 = 33.20 % AVERAGE DAILY FLOW
AVERAGE ANNUAL RUNOFF = 7493. CUMEC DAYS

DEFICIENCY VOLUMES

THRES-HOLD % ADF	CLASS LIMITS % ANNUAL RUNOFF																										
	LOWER	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	20.	30.	40.	50.	75.	100.
	UPPER	.1	.2	.3	.4	.5	.6	.7	.8	.9	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	20.	30.	40.	50.	75.	100.	
5		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20		30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40		326	52	26	30	26	13	8	4	0	0	8	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0
60		547	165	65	91	47	52	30	34	17	17	91	34	13	0	4	4	4	4	0	0	0	0	0	0	0	0
80		726	213	130	113	65	26	60	21	39	39	165	69	30	21	21	17	8	4	4	21	0	0	0	0	0	0
Q95		239	39	13	0	4	0	0	0	4	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NOTES: 1. FREQUENCY IS EXPRESSED AS THE NUMBER OF EVENTS IN CLASS INTERVAL PER 100 YEARS
2. ONE EVENT IN PERIOD OF RECORD HAS FREQUENCY OF 4 PER 100 YEARS

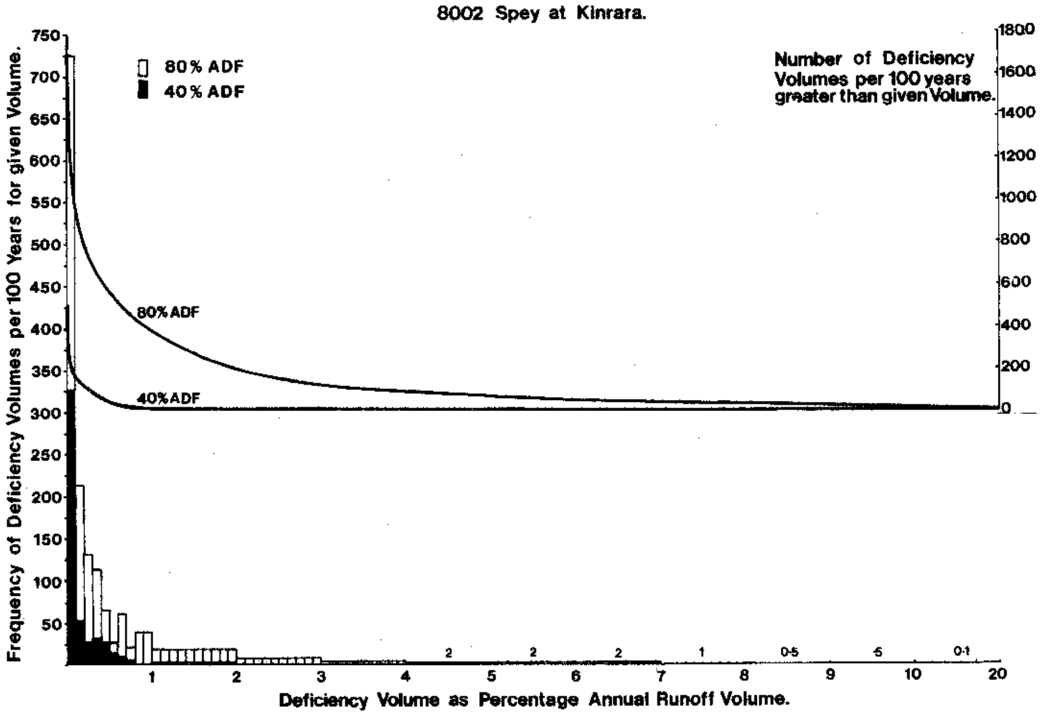


FIGURE 2.6 FREQUENCY OF DEFICIENCY VOLUMES

The first set of tables and figures present the D and V data of Figure 2.4 in histogram form and so may readily be interpreted as the number of occasions in 100 years when, for example, a spell of exactly five days duration occurred. Summation in the tables will yield data for the number of occasions when spells of longer than a given duration occur. Deficit volumes being continuous rather than discrete variables are treated in class intervals; otherwise the interpretation is identical.

The second set of tables and figures present the D and V data using the annual probability method of expressing frequency. Thus for example Figure 2.7 shows the proportion of years in which a spell of, say, 20 days or more is experienced. Such spell frequency curves are drawn by finding the longest deficit period below a given threshold in each of the N years of recorded daily flow data. The deficit periods are then ranked in increasing order and a normal probability plotting position assigned to each one using the Blom plotting position where

$$F_i = \frac{i - 0.375}{N + 0.25}$$

$$y_i = \Phi^{-1} (F_i),$$

Φ^{-1} is the inverse Normal probability integral.

The value of y_i is tabulated in Vol. I, p. 71, of the Flood Studies Report (NERC, 1975).

A logarithmic duration (or deficit volume) axis may be used in which case if the annual maximum spell durations are distributed log-normally then the points would lie along a straight line.

TABLE 2.5 ANNUAL MAXIMUM DURATIONS OF LOW FLOW SPELLS

STATION NUMBER 8002 PERIOD OF RECORD FROM 1952 TO 1971 AVERAGE DAILY FLOW = 20.514 CUMECS
Q95 = 33.20 % AVERAGE DAILY FLOW

AVERAGE ANNUAL RUNOFF = 7493. CUMEC DAYS

	THRES-HOLD % ADF	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971
	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DURATIONS	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
IN	20	0	0	0	11	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DAYS	40	14	4	4	62	16	51	15	50	25	36	15	19	24	0	6	11	18	20	10	31
	60	42	19	19	109	22	81	37	79	41	51	23	51	61	25	24	26	31	51	18	39
	80	82	29	30	133	51	103	58	79	102	62	37	56	93	29	30	67	65	71	20	71
	Q95	6	0	0	49	9	21	10	43	22	4	11	8	11	0	0	6	7	5	5	17
START MONTH	80	5	3	7	5	5	4	10	8	4	5	6	1	5	11	8	6	7	5	6	8
END MONTH	80	8	4	8	10	7	7	12	10	8	7	8	3	8	12	9	8	9	8	7	10
START MONTH	Q95	9			7	7	6	7	9	6	7	7	2	7			8	9	9	6	9
END MONTH	Q95	9			8	7	6	7	10	7	7	7	3	8			9	9	9	6	9

NOTES: 1. START AND END MONTHS REFER TO MONTH NUMBER IN WHICH LONGEST DURATION BELOW THAT THRESHOLD OCCURRED

TABLE 2.6 ANNUAL MAXIMUM DEFICIENCY VOLUME OF LOW FLOW SPELLS

STATION NUMBER 8002 PERIOD OF RECORD FROM 1952 TO 1971 AVERAGE DAILY FLOW = 20.514 CUMECS
Q95 = 33.20 % AVERAGE DAILY FLOW

AVERAGE ANNUAL RUNOFF = 7493. CUMEC DAYS

	THRES-HOLD % ADF	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971
	5	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
VOLUMES	10	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
AS	20	.0	.0	.0	.1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
% ANNUAL	40	.2	.0	.0	2.2	.3	1.5	.3	1.7	.7	.5	.4	.4	.5	.0	.0	.2	.4	.3	.2	.6
RUNOFF	60	2.2	.6	.6	8.1	1.4	5.9	1.8	6.0	2.5	3.2	1.5	2.5	4.0	.8	.9	1.2	1.6	2.4	.9	2.5
	80	6.5	1.9	2.4	15.9	4.4	11.5	5.8	10.4	11.1	7.0	4.2	5.5	9.6	2.3	2.4	5.9	6.6	6.5	7.0	8.0
	Q95	.0	.0	.0	1.1	.1	.5	.1	.9	.3	.0	.1	.1	.1	.0	.0	.0	.1	.0	.0	.2
START MONTH	80	5	3	7	5	5	4	5	8	4	5	6	1	5	11	8	6	7	5	6	8
END MONTH	80	8	4	8	10	7	7	7	10	8	7	8	3	8	12	9	8	9	8	7	10
START MONTH	Q95	8			7	7	6	7	9	6	6	7	2	6			8	9	9	6	8
END MONTH	Q95	8			8	7	6	7	10	7	7	7	3	7			9	9	9	6	9

NOTES: 1. START AND END MONTHS REFER TO MONTH NUMBER IN WHICH LONGEST DURATION BELOW THAT THRESHOLD OCCURRED

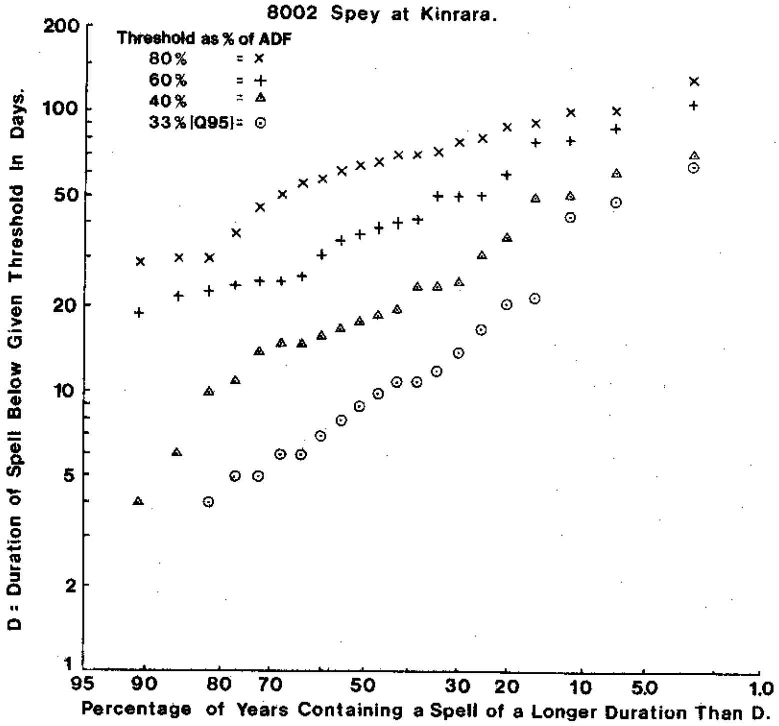


FIGURE 2.7

ANNUAL MAXIMUM DURATION OF LOW FLOW SPELLS

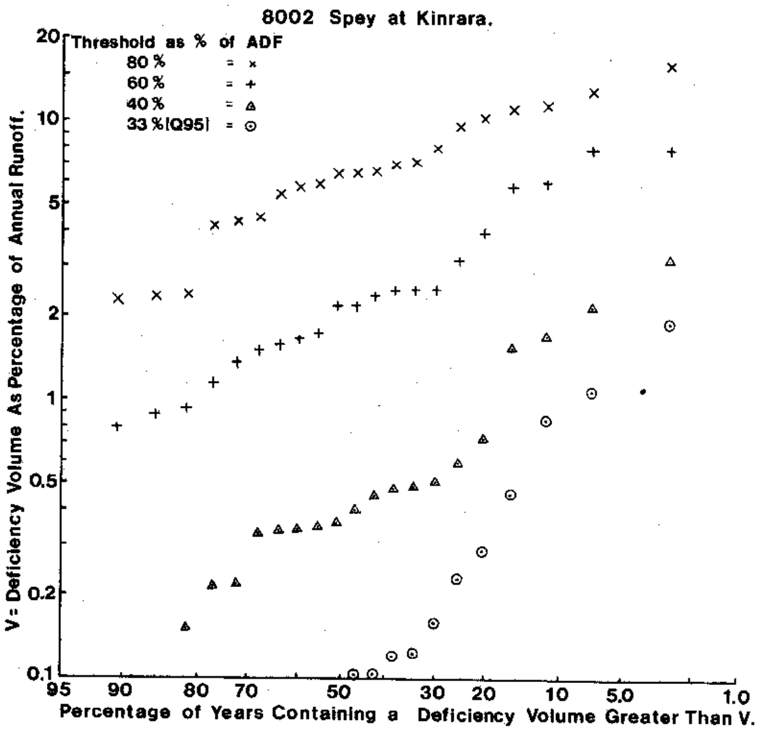


FIGURE 2.8

ANNUAL MAXIMUM DEFICIENCY VOLUMES

This report does not present a method for estimating low flow spell durations and volumes at ungauged sites but experience of many such curves suggests that the curves flatten off at high return periods and that a distribution with less area in the tail than the two-parameter log normal distribution would be a closer fit. One possible explanation is that there is some limiting mechanism presumably related to flow seasonality. However inferences based upon interpolation or moderate extrapolation will not be influenced by this.

Spell frequency has been used to compare synthetically generated flow sequences with recorded data to assess time series models. It could be a useful measure for amenity purposes because it shows the frequency with which the flow is below a threshold for given periods, and may also be more relevant to assessing dilution requirements than the use of the simple flow duration curve. Deficit volume data have been used in regulating reservoir design work, and also in validating the performance of time series models.

Storage yield analysis: The storage yield diagram is used to determine the volume of storage required in a reservoir to yield a given uniform supply rate with a given probability of failure. The deficit volumes described above cannot be used for this purpose because their calculation assumes the reservoir to be full at the start of each deficit period. Figure 2.9 illustrates a form of analysis which allows for the effect of possible 'carry-over' from a previous deficit period.

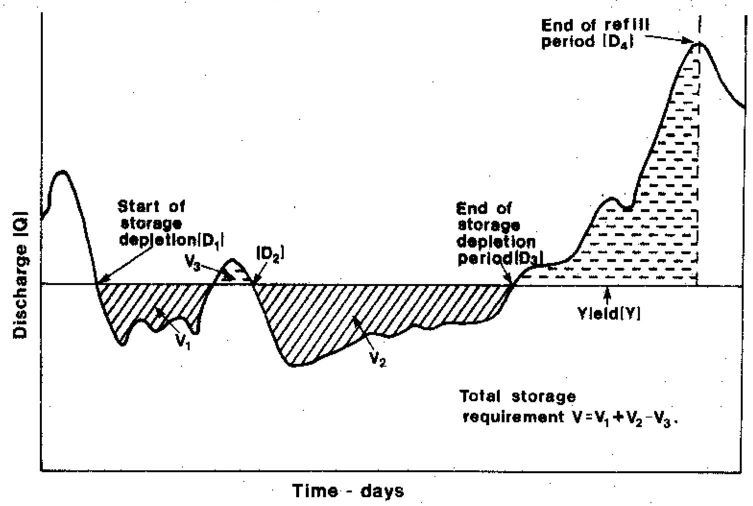


FIGURE 2.9

DEFINITION OF STORAGE YIELD ANALYSIS

Starting at the onset of a deficit period the running accumulation $\Sigma(Q - Y)$ is summed. The maximum value, V, occurs at the end of the second low flow spell as defined in Figure 2.9, i.e. after time D_3; V is therefore the total storage required to maintain yield Y throughout that event. Had the assumption of a full reservoir been made at time D_2, the required volume of storage would have been underestimated. $\Sigma(Q-Y)$ returns to zero in time D_4. D3 is often referred to as the critical duration of the event, other definitions of the term critical period are found in the literature, see McMahon and Mein (1978) for a complete survey.

The J largest values of storage V found in an N year record ($N/4 < J < N$, $N > 20$) were ranked and plotted using a log normal plotting scheme with non-exceedance probability of the ith smallest storage given by

$$F_i = \frac{J}{N}\left[\frac{i - .375}{N + .25}\right]$$

TABLE 2.7 LARGEST RECORDED STORAGE REQUIREMENT FOR GIVEN YIELDS

STATION NUMBER 8002   PERIOD OF RECORD FROM 1952 TO 1974   ADF = 20.514 CUMECS, Q95 = 33.200 %ADF

RANK	YIELD AS A PERCENTAGE OF AVERAGE DAILY FLOW																		
	5%	10%	20%	40%				60%				80%				Q95%			
	VOL	VOL	VOL	VOL	STRT	MMD	DUR	VOL	STRT	MMD	DUR	VOL	STRT	MMD	DUR	VOL	STRT	MMD	DUR
1			.069	3.270	8.972	11.972	103	10.240	6.972	11.972	188	21.585	4.957	10.959	1064	1.910	8.972	10.972	96
2			.034	2.585	6.955	9.955	129	9.768	5.959	10.959	191	18.679	6.972	10.972	564	1.082	7.955	8.955	82
3			.003	1.845	8.959	10.959	80	8.707	5.955	10.955	215	18.330	4.971	10.971	226	.861	9.959	10.959	46
4				1.549	5.957	7.957	66	7.833	4.971	10.971	190	17.953	2.974	10.974	296	.646	5.957	7.957	53
5				.869	8.971	10.971	66	7.063	4.974	9.974	219	17.152	4.955	12.955	560	.291	6.960	7.960	31
6				.836	5.960	7.960	87	6.050	4.957	7.957	212	11.630	4.960	8.960	301	.277	5.960	6.960	24
7				.797	6.964	8.964	62	5.682	5.960	8.960	176	11.319	3.952	9.952	309	.239	8.975	8.975	25
8				.728	5.975	8.975	158	4.734	5.964	8.964	123	10.927	1.964	8.964	342	.230	8.971	8.971	18
9				.638	6.959	7.959	49	4.024	5.961	8.961	103	10.303	5.968	9.969	689	.180	9.971	9.971	30
10				.596	5.961	7.961	55	3.995	6.969	9.969	147	8.890	6.967	9.967	146	.160	8.973	8.973	18
11				.491	6.974	7.974	57	3.545	5.952	9.952	158	8.762	4.961	8.961	198	.155	6.959	6.959	30
12				.486	7.972	8.972	26	3.533	6.968	9.968	132	6.415	5.954	9.954	159	.131	7.971	7.971	12
13				.456	8.973	8.973	24	3.512	6.973	9.973	138	6.137	5.962	8.962	129	.125	6.964	7.964	14
14				.422	2.963	3.963	30	2.877	5.956	7.956	83	5.573	12.962	3.963	77	.121	7.962	7.962	13
15				.406	9.968	9.968	22	2.866	6.967	9.967	119	4.430	7.966	9.966	151	.115	7.964	8.964	19
16				.366	7.971	7.971	27	2.688	5.958	7.958	77	3.384	3.953	10.953	250	.112	7.972	8.972	20
17				.356	7.962	7.962	34	2.680	5.975	8.975	198	2.846	5.970	8.970	86	.111	6.974	7.974	22
18				.344	7.956	7.956	17	2.506	1.963	3.963	55	2.687	2.955	4.955	60	.111	9.968	9.968	14
19				.342	9.969	9.969	21	2.430	6.962	8.962	78	2.659	5.965	7.965	124	.103	7.958	7.958	14
20				.334	7.958	7.958	21	1.984	10.958	12.958	86	2.637	2.968	3.968	54	.096	6.955	6.955	15
21				.274	7.969	8.969	31	1.275	2.969	3.969	39	2.295	11.965	12.965	37	.066	2.963	3.963	8
22				.264	8.952	9.952	33	1.274	2.964	4.964	68	1.856	5.963	6.963	33	.064	7.956	7.956	15

NOTES:
1. VOL. = VOLUME OF STORAGE AS % ANNUAL RUNOFF. FLOW DOES NOT FALL BELOW 5% OR 10% ADF AND ONLY 3 OCCASIONS BELOW 20% ADF
2. STRT. = MONTH IN WHICH STORAGE DEPLETION STARTS
3. MMD. = MONTH OF MAXIMUM DEFICIT
4. DUR. = LENGTH OF CRITICAL PERIOD UNTIL COMPLETE REPLENISHMENT IN DAYS

$\}$ ONLY SHOWN FOR HIGHER THRESHOLDS

Recession behaviour: The rate of decay of river flows in the absence of rain is dependent upon many factors. This study was limited to describing the typical decay pattern using graphs like Figure 2.11 in which the current flow is plotted against the flow N days ago during known recession periods (Langbein 1938). All periods when the flow receded during the entire N day period were used and individual points were linked. N was set at two days for almost all stations, this decision being taken as a compromise between a value of N = 1 for which the recession cannot be estimated accurately and a large value which tends to eliminate many recession periods from consideration. In the majority of cases it was possible to discern a curve just below the enveloping line where the individual recessions run together most densely. This curve is defined to be the master recession and its slope at a discharge of ADF ÷ 4 was used as the low flow index (KREC) in subsequent analyses. Only daily classified stations were used for this low flow measure.

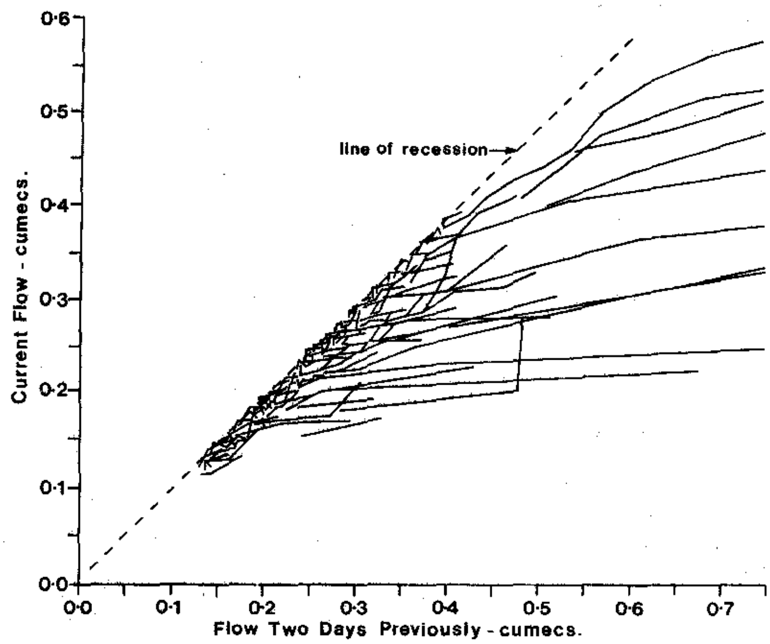


FIGURE 2.11

DERIVATION OF RECESSION CONSTANT

On this method of presentation a straight line is equivalent to an exponential recession rate $Q(t) = ae^{-bt}$. The method was adopted because it is less subjective than procedures entailing the combination of separate recession limbs using transparent overlays, and is simple to program. The master recession that is produced tends to decay more rapidly than the commonly used alternatives of function fitting and combining recessions using a transparent overlay. This is because it is desirable in those methods to have as long a recession as possible so there is a tendency to include 'flats' in the recession. It is felt that subject to the approximation of assuming a constant value for the rate of river recession the adopted method provides the more 'correct' estimation procedure.

The application of the recession constant is in flow forecasting where an estimate of the discharge at some future date is required given the current river discharge and assuming there is no effective rainfall. It is also an important property, used by hydrogeologists, relating to aquifer storage.

Base flow index: The low flow measures discussed so far have all had applications in water resource work. The base flow index (BFI) was developed from an idea of Lvovich (1972) and from its construction can be thought of as measuring the proportion of the river's runoff that derives from stored sources. Its use in this study is as a catchment characteristic.

The computer program applies simple smoothing and separation rules to the recorded flow hydrographs as shown in Figure 2.12 from which the index is calculated as the ratio of the flow under the separated hydrograph, to the flow under the total hydrograph. The program calculates the minima of five day non-overlapping periods and subsequently searches for turning points in this sequence of minima. The turning points are then connected to obtain the separated hydrograph. The precise details of the separation procedure are given in the programmed learning manual for catchment characteristics.

The annual values of BFI have been found to be stable, typically with a standard deviation of 0.04, and furthermore with no systematic variance with likely factors. For example high runoff years do not experience higher or lower BFI values than the average.

This index has been found to be closely related to other low flow indices and can be estimated from catchment geology. Interest in it for purposes of this study has focussed on its use as a catchment characteristic; however a similar quantity has been used in UK water resources work to compare the flow reliability of different rivers (Yorkshire R.A., 1969).

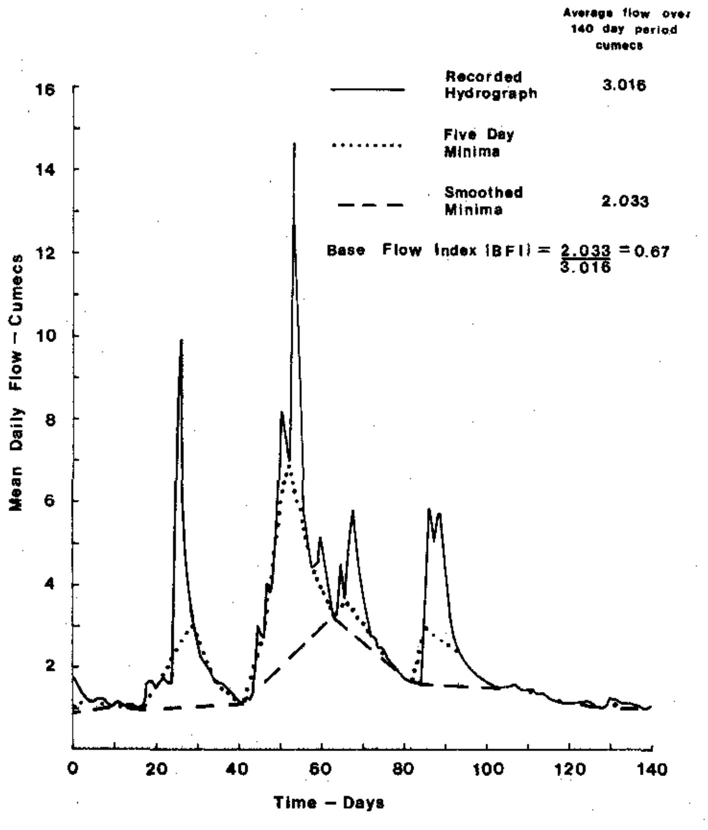


FIGURE 2.12 CALCULATION OF BASE FLOW INDEX FROM DATA

2.3 Catchment Characteristics

The low flow indices described in Section 2.2 were correlated with catchment characteristics to develop prediction formulae for use on ungauged catchments. The selection of catchment characteristics was decided by (i) availability in map form, (ii) the factors thought to affect low flows and (iii) prevention of instability in the regression equations which occur when highly intercorrelated variables are used. The following paragraphs discuss each of the catchment characteristics and Table 2.8 summarises their definitions and method of calculation, a much fuller account of which is given in Report No. 3. All these catchment characteristics were extracted from maps and added to a computer archive ready for statistical analysis.

Catchment size: The primary measures used to represent the size of a catchment were its topographic area (AREA) and the length of the main stream (L). Subsurface area is arguably more relevant but groundwater divides are seldom adequately defined. All other factors being equal, the larger the catchment the larger the low flow. However because the low flow indices such as Q95(10) have been standardised by dividing by the average flow, the influence of catchment size is not clear-cut although intuitively some residual positive effect may be anticipated.

Catchment climate: The only readily available measures of climate were those relating to rainfall. Early experiments made use of a drought related rainfall index, the 5 year return period 6 month rainfall deficit (Tabony, 1977), but a pilot study showed that this was so well correlated with the annual average rainfall that the latter was preferred (SAAR). As with catchment size the influence of wet or dry conditions is not obvious in view of the standisation of flows by the average discharge.

Catchment slope: The influence of slope on low flows is not clear-cut; past experience has shown that its effect is confounded with other independent variables. One measure of channel slope, the slope between points 10% and 85% up the mainstream, was included in the data set (S1085).

Stream frequency: Stream frequency is measured as the number of stream junctions per square kilometre (STMFRQ). It is known that a high stream frequency increases the rate of quick response runoff and might therefore be expected to reduce low flows. Alternatively one could argue that a higher stream frequency increases the effective drainage net and should increase low flows.

Land use: The proportion of catchment area under urban development was included in the data set (URBAN). However most heavily developed catchments were excluded following the gauging station and catchment assessment (Section 2.1). The presence of a town will reduce infiltration into the underlying geology but the artificial drainage network may cancel out this effect. Lake and reservoir storage act like groundwater storage to smooth the hydrograph. The proportion of catchment covered by a lake or reservoir was also included in the data set (FALAKE).

Geology: The more permeable the rock, drift and soil material of a catchment the more sustained is its flow during dry weather. Three variables were used to index this effect: a soil index was developed for use with a five soil-type map and two hydrograph based indices of geology, the recession constant (KREC) and the base flow index (BFI)(Section 2.2). Discussions with the Soil Survey of England and Wales suggested that the Winter Rainfall Acceptance Potential map developed for the Flood Studies (NERC, 1975, Vol I, p 303) could be used to indicate low flow properties too, with the modification that permeable upland soils and raw peat soils are located in different soil classes. Values of BFI and KREC were also included with the soil index in the data set and a comparison of the merits of each of the three variables

TABLE 2.8 CATCHMENT CHARACTERISTICS SUMMARY

Acronym	Method of calculation
AREA	Catchment area in km^2 obtained by planimetering or 'counting squares' on a convenient scale map.
L	Length of main stream in km obtained by stepping up main stream with dividers set at 0.1 km using 1:25 000 scale maps.
SAAR	Annual average rainfall in standard period 1941-1970, published at 1:625 000 scale, square counting provides adequate accuracy.
S1085	The stream channel slope measured between two points 10% and 85% up the main stream above the point of interest on a 1:25 000 scale map and expressed in m/km.
STMFRQ	The number of stream junctions as shown on the first series 1:25 000 map, divided by the catchment area.
URBAN	The proportion of catchment with urban development. Suitable maps are 1:50 000 for small catchments and the Agricultural Land Classification Survey at 1:250 000 for larger catchments, square counting provides adequate accuracy.
FALAKE	The proportion of catchment covered by a lake or reservoir as marked on 1:250 000 scale map, square counting provides adequate accuracy.
BFI	The base flow index - a measure of the proportion of baseflow under the flow hydrograph. It is estimated at the ungauged site from catchment solid and drift geology by making comparisons with analogue catchments having a similar geology and a known BFI calculated from flow data.
KREC	The 2 day recession constant as measured by the ratio of the current flow to the flow 2 days previously and established at a current flow of 25% ADF.
ADF, ARV	Average flow expressed in cumecs and cumec days units respectively.
PE	Potential evaporation in mm estimated from the Meteorological Office 1:2 000 000 map (provisional version).
AE	Actual evaporation in mm derived from PE.
DVF	Dry valley factor. The length of dry valley from the stream head to the watershed, divided by the total length to the divide.

TABLE 2.9 TYPICAL BASE FLOW INDICES FOR VARIOUS ROCK TYPES

Dominant Permeability Characteristics	Dominant Storage Characteristics	Example of rock type	Typical BFI range
Fissure	High storage	Chalk	.90 - .98
		Oolitic limestones	.85 - .95
	Low storage	Carboniferous limestone	.20 - .75
		Millstone Grit	.35 - .45
Intergranular	High storage	Permo-Triassic sandstones	.70 - .80
	Low storage	Coal measures	.40 - .55
		Hastings Beds	.35 - .50
Impermeable	Low storage at shallow depth	Lias	.40 - .70
		Old Red Sandstone	.46 - .54
		Silurian/Ordovician	.30 - .50
		Metamorphic-Igneous	.30 - .50
	No storage	Oxford Clay) Weald Clay) London Clay)	.14 - .45

in a pilot study indicated that BFI was the most useful variable. Details of the estimation of BFI at an ungauged point are included in Report No.4; ranges for drift-free solid geologies are shown in Table 2.9.

Average daily flow: The estimation procedures express low flows either as a percentage of the average daily flow (ADF) or as a percentage of the annual runoff volume (ARV). In either case the average runoff of the catchment has to be estimated. Alternative procedures for doing this are described in Section 3.3; they are also given in detail in the catchment characteristic estimation manual.

3 The low flow estimation procedure

The previous chapter described the derivation of low flow indices and the calculation of catchment characteristics. This chapter describes the development of the external relationships between these low flow indices and catchment characteristics (Section 3.1). Internal relationships are used (Section 3.2) to work from the basic low flow indices to estimate discharges of other durations and frequencies. The practical estimation procedure is outlined in Section 3.7.

The development of predictive equations for estimating low flows made use of the MASTERLIST data base (Figure 2.1) which stored all the low flow indices and catchment characteristics. Data were read from the MASTERLIST and used as input to a statistical programming package ASCOP (National Computing Centre, 1971) which had facilities for transforming data and carrying out standard statistical routines such as correlation and multiple regression.

3.1 Relationships between low flow indices and catchment characteristics

It was described in Section 2.2 how, for each low flow measure such as the flow duration curve, a particular 'low flow index' was extracted, for example the 95 percentile 10 day flow, Q95(10). This section describes the development of external relationships between such indices and catchment characteristics.

These external relationships take the form of regression equations and adjustment factors and this section describes the various issues and options that were explored before finalising the form of the equations and choice of variables. Details of this process are given for Q95(10); however some information is also presented for the other basic indices. The steps in the procedure are:

(1) the transformation of the variables to obtain linearity and constant error variance, (2) the selection of a useful subset of catchment characteristics from the initial set described in Section 2.3, and (3) the development of regional equations.

Variable transformation: Preliminary inspection of the data indicated that a single variable, the base flow index, would be of overriding importance in any eventual relationship. The 'scatter diagram' Figure 3.1 between Q95(10) and BFI showed that with increasing BFI there was an increase in both scatter and the slope of the trend line. Both observations suggested the data needed transforming.

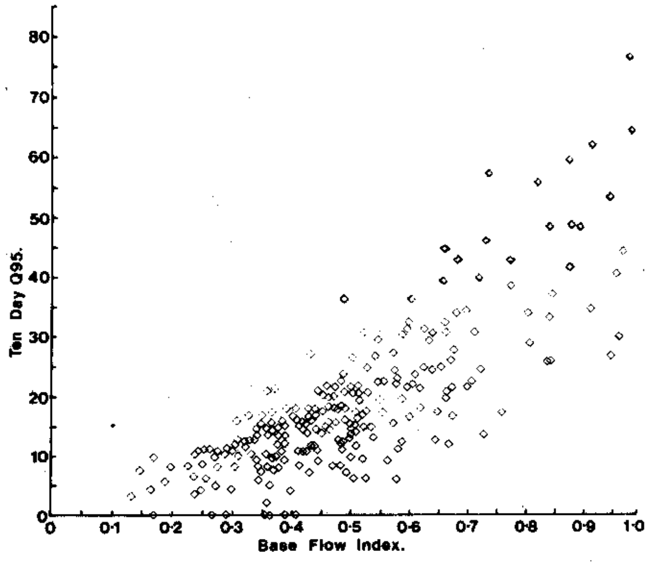


FIGURE 3.1

RELATIONSHIP BETWEEN BFI AND Q95(10)

A number of different transformations of the data set were carried out using a procedure due to Box and Cox (1964) in which $X_T = (X^T-1)/T$ which for different values of T encompasses powers, square root (T=0.5) cube root (T=0.33), logarithm (T=0) and reciprocal powers (T<0). By inspecting the skewness and kurtosis of the transformed variables and by examining the distribution of residuals from pair-wise scatter diagrams and the ability of the equation to predict the complete range of Q95(10) the best transformations were selected. The square root transformation offered the best compromise and was applied to all variables except URBAN and FALAKE which were to be treated by separate adjustment factors.

TABLE 3.1 CORRELATION MATRIX FOR SQUARE ROOT TRANSFORMATION APPLIED TO ALL VARIABLES (456 stations)

	Q95(10)	MAM(10)	BFI	AREA	STMFRQ	S1085	L	DVF	SAAR
Q95(10)	1.000	0.899	0.724	0.131	- 0.207	- 0.181	0.108	0.052	- 0.155
MAM(10)	0.899	1.000	0.814	0.123	- 0.307	- 0.242	0.081	0.064	- 0.292
BFI	0.724	0.814	1.000	0.129	- 0.479	- 0.373	0.085	0.067	- 0.419
AREA	0.131	0.123	0.129	1.000	- 0.122	- 0.453	0.904	0.255	- 0.017
STMFRQ	- 0.207	- 0.307	- 0.479	- 0.122	1.000	0.502	- 0.097	- 0.017	0.528
S1085	- 0.181	- 0.242	- 0.373	- 0.453	0.502	1.000	- 0.495	- 0.039	0.616
L	0.108	0.081	0.085	0.904	- 0.097	- 0.495	1.000	0.121	0.005
DVF	0.052	0.064	0.067	0.255	- 0.017	- 0.039	0.121	1.000	- 0.106
SAAR	- 0.155	- 0.292	- 0.419	- 0.017	0.528	0.616	0.005	- 0.106	1.000

Regression equation development: Table 3.1 shows the correlation matrix between the square roots of the variables. Of the correlations with Q95(10), BFI is clearly the largest. Intercorrelations among the independent variables, while present, are not sufficiently high to introduce serious instability problems in multiple regression equations. This was confirmed using ridge regression. After exploring a number of combinations of independent variables it was decided to use BFI, AREA and SAAR as a basic subset to test whether there were important regional variations. These national regression equations for this case are shown below.

$$\sqrt{Q95(10)} = 8.60\sqrt{BFI} + .00377\sqrt{AREA} + .0414\sqrt{SAAR} - 3.22$$

$$R^2 = .552 \quad se = .956$$

$$\sqrt{MAM(10)} = 9.39\sqrt{BFI} + .00199\sqrt{AREA} + .0144\sqrt{SAAR} - 2.89$$

$$R^2 = .667 \quad se = .855$$

Regionalising the regression equation: A computer program was written to plot the residuals from the regression equation (difference between observed and estimated value of $\sqrt{Q95(10)}$) on a map of the United Kingdom. This showed a tendency for the 'national' equation to overpredict in some areas and underpredict in others. The United Kingdom was divided into six regions on the basis of this pattern. An analysis of variance showed that five regions were sufficient, it being possible to treat catchments in Ireland with catchments in South-West England and Wales.

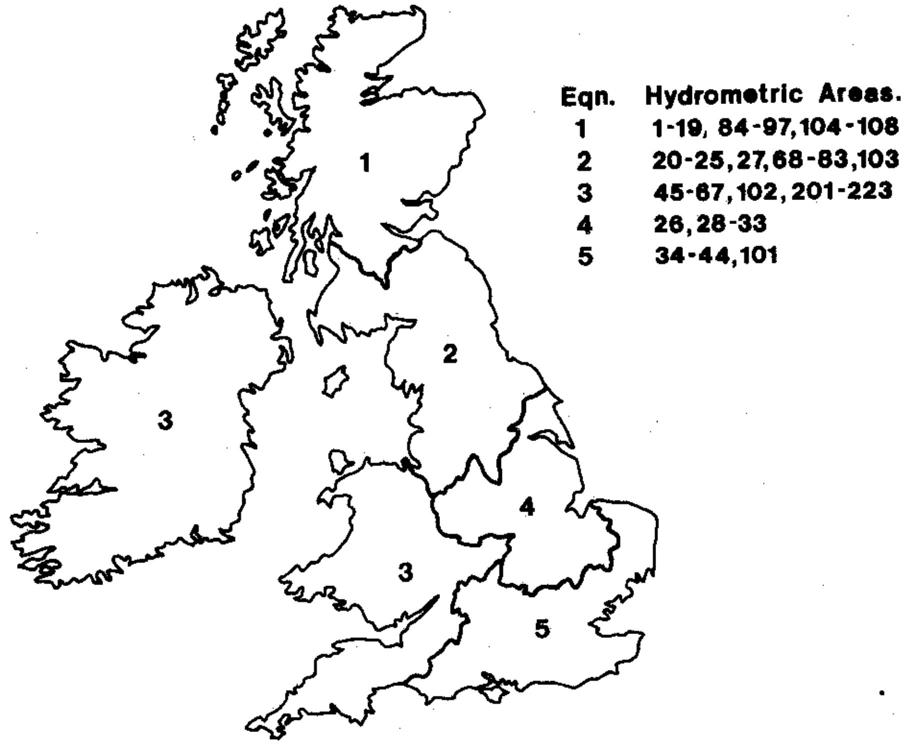


FIGURE 3.2 ESTIMATION EQUATION TO USE IN DIFFERENT REGIONS

Of these five regions (Figure 3.2), three could be described by equations differing in the constant term and regions 4 and 5 required two totally different equations (Table 3.2).

TABLE 3.2 REGIONAL ESTIMATION EQUATIONS FOR Q95(10)

Region	Hydrometric areas	Equation $\sqrt{Q95(10)}$ =
1	1-19, 84-97, 104-108	$7.60\sqrt{BFI} + .0263\sqrt{SAAR} - 1.46$
2	20-25, 27, 68-83, 103	$7.60\sqrt{BFI} + .0263\sqrt{SAAR} - 1.84$
3	45-67, 102, 201-223	$7.60\sqrt{BFI} + .0263\sqrt{SAAR} - 2.16$
4	26, 28-33	$11.9\sqrt{BFI} + .115\sqrt{SAAR} - 8.03$
5	34-44, 101	$8.51\sqrt{BFI} + .0211\sqrt{L} - 1.91$

Having used the basic three variables BFI, AREA and SAAR to identify the regions, separate regressions were then performed as a check to identify which characteristics could improve the prediction equation for each of the chosen regions. Table 3.2 and Figure 3.2 show the final equations to use for different areas of the country; it can be seen that three regional equations with different intercepts remain, the fourth region has different coefficients and the equation for south east England replaces SAAR with main stream length as the second catchment characteristic. BFI was significant at the 99% confidence level in all 5 equations.

It has been found that catchment characteristics are also of value in estimating the BFI for particular rock types; in the case of Carboniferous Limestone for example catchments with a higher stream frequency have a lower BFI. Relationships such as these will be described in detail in the separate regional monographs.

Flow frequency regression: The flow frequency curve was treated in a similar way to the flow duration curve, the mean annual minima, MAM(10), being used in regression analysis as the basic low flow index. The square root transformation was used and the correlation matrix (Table 3.1) showed similar results to the flow duration curve with the exception that correlation coefficients were generally higher for MAM(10) than Q95(10). A three variable national equation confirmed this finding with the error in estimating MAM(10) (R^2 = .667, se = .855), being less than for Q95(10). A map of residuals calculated from this national equation showed a tendency to under and overpredict in the same areas as did the Q95(10) equation. It was therefore decided to adopt the same regions as were used for the flow duration curve, and to use an equation with a different intercept for regions 1, 2 and 3 but two separate equations for regions 4 and 5. The final equations are shown on Table 3.3. where BFI was significant at the 99% confidence level in each region and SAAR was significant at the 95% level in Region 4.

TABLE 3.3 REGIONAL ESTIMATION EQUATIONS FOR MAM(10)

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

3.2 Internal relationships between low flow indices

To restrict the number of regression equations, only one low flow index from each low flow measure had been the subject of 'external' relationships with catchment characteristics. But of course in applications any duration and frequency may be needed. In this section the following topics are discussed which enable the entire set of curves to be built up from the basic low flow index:

(a) relationships between different durations;

(b) relationships between different frequencies;

(c) comparison of statistics based on daily mean and monthly mean discharges.

As with the previous descriptions most of the details presented here relate to the flow duration curve with a briefer description of the flow frequency curve. In the former case the investigation of duration and frequency relationships reduces to the study of the spacing between the curves such as in Figure 2.2 and their slopes.

Duration relationships: To enable the flow duration curve of other than a 10-day moving average to be estimated a study of the relationship between flow duration curves derived from different durations such as shown on Figure 2.2 was carried out. The approach adopted was to analyse the way in which Q95(D)/Q95(10) varied with the duration D. Sample graphs of r(D) = Q95(D)/Q95(10) plotted against the duration D showed some variety of behaviour between catchments. Attention was focussed on the behaviour of the gradient (GRADQ95(D)) of the graph of r(D) versus D. The smooth trend of increasing r(D) with D enabled a function to be fitted with high accuracy and its gradient GRADQ95(D) was determined at D = 1, 5, 7, 10, 30, 60, 90 and 180 days. The function employed was

$$r(D) - r(1) = b(D-1)^n$$

differentiating w.r.t D

$$\mathrm{GRADQ95}(D) = \frac{dr(D)}{dD} = nb(D-1)^{n-1}$$

It was initially thought that it might be possible to estimate n, b and r(1) from catchment characteristics, but this was not practical as there is considerable intercorrelation between these variables, giving rise to a 'trading off' between pairs of values and poor prediction from catchment characteristics. However this does not affect the accuracy with which GRADQ95(D) can be obtained from the function.

Regression equations linking GRADQ95(D) with catchment characteristics were obtained, SAAR and Q95 being the most significant variables. In general, the regression coefficients did vary with D; however the prediction of curvature in the r(D).V. D relationship was poor and nothing more elaborate than a straight line relationship having a constant gradient (= GRADQ95) could be justified. The main difficulty encountered was with dry catchments with a low BFI (and hence low Q95(10) where the assumption of a constant gradient leads to under prediction of r(D) for durations longer than 10 days. To some extent this is offset by a tendency to overpredict Q95(10) from catchment characteristics for these very dry impermeable catchments. This can be seen by considering the relation Q95(D) = r(D).Q95(10).

The adopted relationship for the flow duration curve is

$$\log_{10} \mathrm{GRADQ95} = 0.023\sqrt{\mathrm{SAAR}} - 0.19\sqrt{\mathrm{Q95(10)}} - 2.11$$

and from the straight line relationship between Q95(D) and D, with slope GRADQ95 we obtain;

$$\mathrm{Q95}(D) = \mathrm{Q95}(10).\left[1 + (D-10)\mathrm{GRADQ95}\right]$$

A similar analysis was carried out for the flow frequency curve substituting MAM(D) and MAM(10) for the flow duration curve indices. The corresponding equations are:

$$\log_{10} \mathrm{GRADMAM} = 0.0084\sqrt{\mathrm{SAAR}} - 0.14\sqrt{\mathrm{MAM(10)}} - 1.61$$

and

$$\mathrm{MAM}(D) = \mathrm{MAM}(10).\left[1 + (D-10)\mathrm{GRADMAM}\right]$$

Frequency relationships: To estimate discharges other than the 95 percentile from the flow duration curve it is necessary to use an internal relationship between the discharges of different frequencies. Catchments were assigned to one of 16 classes according to their BFI value and a computer program drew all the flow duration curves for a given class of catchment on common axes. The curves were then averaged by finding the mean value of t (the plotting position on the frequency axis: see section 2.2) for a given discharge Q. There were a total of 144 possible average curves (16 BFI classes and 9 durations) of which 48 were based upon a sufficient number of station years for reliable averaging. It was found that these averaged curves formed a single family such that, for example, a 180 day curve from a catchment with a low BFI might have the same shape and position as a 1 day curve from a catchment with a high BFI.

The computer program which was used to average the flow duration curves within a BFI interval was also used to average curves within Q95(10) intervals. It was observed that this grouping gave more stable results and the final family of type curves were obtained from this latter standardisation procedure.

A family of twenty type curves was then interpolated between the average curves such that they were equally spaced (in mm) at Q95 (type curve 20 had a Q95 value of 100% and curve 1 had a value of 1%) and had the same shape as the averaged curves. A consequence of the finding that any flow duration curve can be adequately described as one of a limited set of curves is that the shape of the flow duration curve is determined entirely by the value of Q95. The curve number to use can be calculated from

$$\text{curve number} = \text{nearest integer } (10 \log_{10} Q95(D)).$$

For convenience in application the ordinates of the curves were divided by the ordinate at 95% (Q95), and as shown on Figure 3.3 yield the factor by which Q95 is multiplied to give the flow of any other percentile, QP.

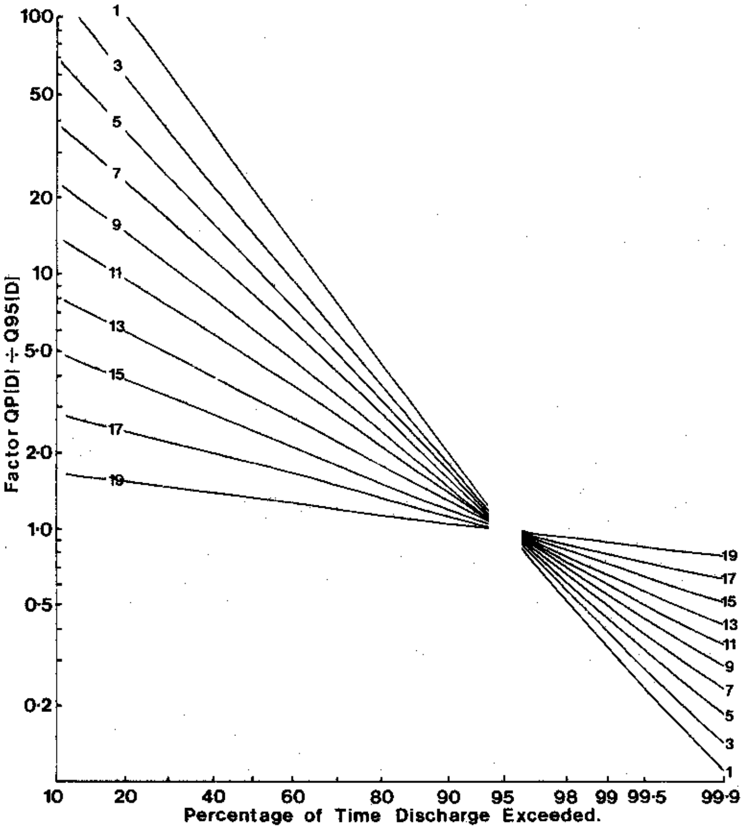


FIGURE 3.3 FLOW DURATION TYPE CURVE

This averaging procedure may have masked possible dependence on catchment characteristics and this was investigated by correlating the slope of the 10 day flow duration curve (as measured by Q99 ÷ Q50) with AREA, STMFRQ, SAAR etc. It was found that catchment rainfall, SAAR, was the most significant catchment characteristic, dry catchments having flatter curves. This was tested by further subdividing the Q95(10) groups into 3 rainfall bands and again obtaining averaged curves. These new curves only partly supported the correlation analysis; many either did not show the effect or the degree of flattening was not consistent throughout.

To incorporate the effect of SAAR on the frequency relationship it would be necessary to use different type curves for different SAAR bands. As the error is less than one type curve number it was felt that a single set representing average catchment conditions was adequate.

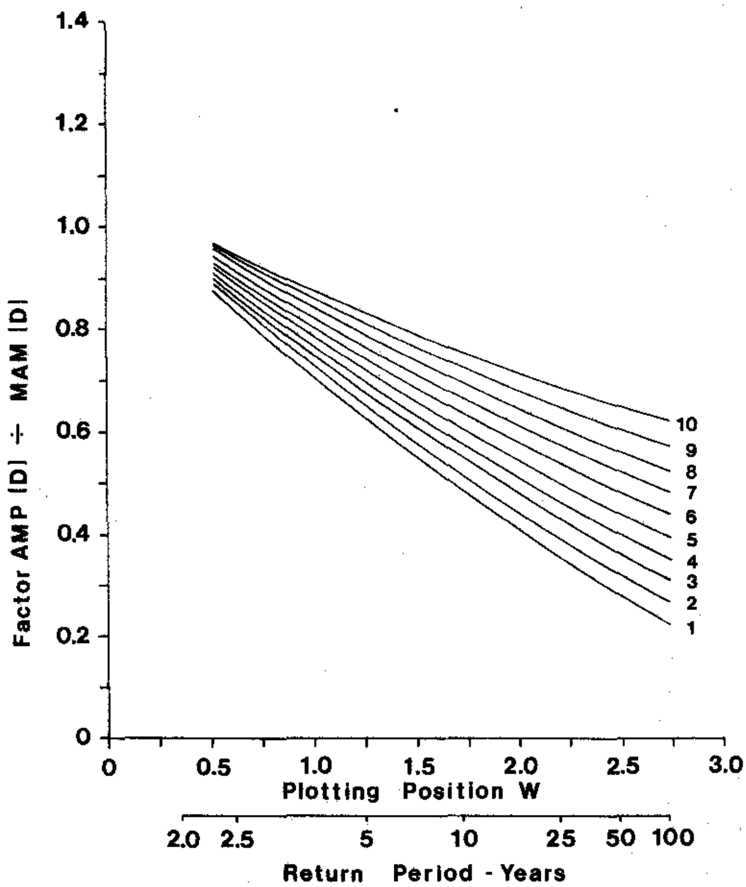


FIGURE 3.4

FLOW FREQUENCY TYPE CURVES

A family of standardised type flow frequency curves (Figure 3.4) were produced in a very similar way to the type flow duration curves. In this instance the choice of curve did not depend solely on the magnitude of MAM(D). In general flatter curves are found with more permeable catchments; however there is a tendency for longer durations to follow steeper curves, and for the very longest durations to tend towards a single curve irrespective of catchment type. This latter trend may be anticipated because over longer durations the major influence is the climate and its year to year variation, catchment response playing a smaller role. Table 3.4 shows these trends and allows the particular type curve to be chosen for any required catchment.

TABLE 3.4 CURVE NUMBER FOR REQUIRED DURATION AND 10 DAY MEAN ANNUAL MINIMUM

MAM(10) %ADF	Duration D in days 1	10	30	60	90	180
5	1	1	1	1	2	3
10	2	2	2	2	2	3
15	4	4	3	2	2	4
20	5	5	3	2	2	4
25	6	6	4	2	3	5
30	8	8	6	4	4	5
40	10	9	8	6	6	5
50	10	10	9	8	7	6
60	10	10	10	9	8	7

3.3 Estimation of average flow ADF

Results of the estimation procedures derived in Sections 3.1 and 3.2 expressed discharge as a percentage of average flow and volumes as a percentage of annual runoff volume. The final stage in the estimation procedure is to convert these percentage estimates to absolute units by scaling by the ADF or ARV. The two basic procedures explained in following paragraphs entail estimating evaporation from maps or from neighbouring gauged catchments. Report Number 3 describing the estimation of catchment characteristics details the procedures for calculating ADF and AVF.

Using rainfall and potential evaporation maps: Catchment runoff over the long term can be assumed to be equal to the difference between annual average rainfall (SAAR) and actual evaporation (AE). SAAR is estimated from the 1:625,000 annual average rainfall map for the 1941-1970 standard period and potential evaporation (PE) from a 1:2,000,000 map of annual average potential evaporation (provisional version) based on the Penman equation. Both maps are available from the Meteorological Office. Actual evaporation (AE) is then estimated from potential by using AE = r x PE where the adjustment factor r depends on catchment rainfall. Table 3.5 shows r for given values of SAAR. These values have been obtained by selecting stations with more than 10 years of flow data and calculating their average runoff in mm. Runoff was then subtracted from the SAAR of each catchment and this 'loss' figure was assumed to be equal to the actual evaporation. Potential evaporation was calculated from the 1:2,000,000 Meteorological Office map and the ratio(r) of Actual to Potential evaporation was plotted against catchment rainfall.

TABLE 3.5 ADJUSTMENT FACTOR FOR ESTIMATING ACTUAL EVAPORATION

SAAR	500	600	700	800	900	1 000	> 1 100
r	0.88	0.90	0.92	0.94	0.96	0.98	1.00

For catchments with annual average rainfall in excess of 1100 mm it is assumed that actual evaporation is equal to potential. This is justified because periods when actual evaporation is limited by a soil moisture deficit may be compensated by periods when actual evaporation is in excess of potential. This greater loss rate can occur because PE is defined to relate to a freely transpiring grass surface and other vegetation types are able to exceed this rate of loss (Calder 1977).

Using local runoff data: Rather than estimate losses from mapped PE and an adjustment factor, losses may be assessed directly from a neighbouring similar gauged catchment. If the annual average rainfall at the site of interest and nearby gauged sites are similar then estimates of runoff in mm can be used directly. If a difference in rainfall exists then it is preferable to calculate losses in mm from the nearby catchment and subtract this loss value from SAAR of the catchment of interest.

Using short runoff record at site of interest: A short runoff record can often be usefully adjusted by using a nearby long runoff record and multiplying by the ratio of long to short period runoff from the key station.

Using daily evaporation and soil moisture deficit data: Although requiring more time and data, improvements on the above estimates can be made by calculating daily potential evaporation rates from meteorological data. Assumptions about the relationship between actual and potential evaporation as soil moisture deficit becomes a limiting factor can then be used to estimate actual evaporation based on potential evaporation and soil moisture deficit data (Grindley 1970). Estimates of daily actual evaporation are available from the Meteorological Office and because the annual variability of evaporation is low (less than rainfall and discharge) then a record of between 5 and 10 years would be sufficient.

Published values of ADF: The Water Data Unit and Institute of Hydrology flow archives hold the calculated average daily flow for over 1000 gauging stations in the United Kingdom. In addition useful information is available from the Water Data Unit for estimates of average discharge for the midpoint of some 16,000 river stretches, calculated when compiling the River Pollution Survey (Moore *et al*, 1978). A map of average runoff of the UK although not produced for estimating runoff is also available from the WDU and is useful as a guide to checking estimates by other techniques.

The most suitable technique to use will depend on the data availability and the average rainfall and evaporation of the catchment. The more detailed techniques are of particular value in low rainfall areas where the proportional error in estimating runoff is highest because of the greater error associated with estimating the difference between two similar quantities. In the drier parts of the country long period runoff data will give the best estimates; where rainfall is in excess of about 1,500 mm then rainfall and evaporation data are more reliable and preferred to a short runoff record

3.4 Use of local data

Local data, partial, or short records can be used in a number of ways at different points in the estimation procedure. The most obvious cases are in estimating BFI when the relationship between BFI and geology of neighbouring gauged catchments is investigated, or in calculating ADF when local data is preferred to using rainfall and evaporation maps. Uses of local data are described in detail in the relevant estimation manual and are only summarised below.

(a) It has been found that BFI can be estimated from a year's record with an standard error of .04 and that the value of BFI is insensitive to above or below average runoff during the year. BFI could usefully be calculated from a short record at the site of interest in preference to a value estimated from geological maps.

(b) If only annual minimum data have been calculated at the site of interest a good estimate of Q95 is possible from the following equation:

$$\sqrt{Q95(10)} = .935 \sqrt{MAM(10)} + .0299 \sqrt{SAAR} - .693 \quad R^2 = .867, \; se = .52$$

It is then possible to build up the complete flow duration curve using the duration and frequency relationships described in section 3.2.

(c) If a correlation can be established between a short or partial record at the site of interest and a long record at a nearby similar catchment then this can be used essentially to re-label the flow axis of the long record flow duration curve.

(d) Current meterings can be taken at the site of interest and plotted against the frequency experienced on the same day at a nearby long recording station for which a flow duration curve has been developed.

3.5 Conversion of monthly data based results to daily form

For some stations only monthly runoff totals are available and if low flow statistics based on daily data are required an adjustment is necessary. The reason for the difference may be seen most readily with reference to the flow frequency curve. The lowest 30 day period in a year would generally overlap two calendar months and as a result would have a lower mean discharge than the lowest calendar month discharge. Annual minima based on monthly data would therefore always be higher than that based on the equivalent length of daily data. The amount of adjustment has been investigated by analysing 50 'daily' graded stations with 20 or more years of data in both daily and monthly modes. Flow duration curves, flow frequency curves, and storage yield analyses were then performed on the daily and the monthly data sets and statistics from each form of analysis were compared. Flow duration curves were comparable when derived from either data set, a 30 day flow duration curve being equivalent to a 1 month flow duration curve. This may have been anticipated because when treating all data without specifically sampling for minima no bias is introduced by any random sampling scheme. In the case of the annual minimum series however, the mean of the 1 month flow frequency curve was greater than the mean from a 30 day moving average. The 1 month mean is equivalent to the mean derived from a 45 day moving average; the corresponding numbers for 2, 3 and 6 months were 79, 109 and 195 days.

Results from the storage yield analysis has shown that the storages derived from monthly data are always underestimated when compared with daily derived storage requirements. The difference (when expressed as a percentage of ARV) between monthly and daily based storages does not appear to depend either on the yield or the probability of failure and a constant value of 2% of ARV can be assumed. A constant value is to be expected because the difference is due to the geometry of the hydrograph at the start and end of the event and not to the magnitude of the event (which is a result of the yield and probability). For large reservoirs with a high degree of regulation this may be unimportant but where perhaps only 20% of the runoff volume is stored then using monthly data without an adjustment would lead to a noticeable underdesign of the required storage by about 10%.

3.6 Errors in estimation

The complete estimation procedure for an ungauged site consists of a number of steps each of which will entail some error. The only accurate method of error assessment would be to carry through the estimation procedure at each gauged point 'blind'. This has not yet been done although a programme of investigation along these lines is planned. An approximation to the total error has been obtained by making certain simplifying assumptions, notably that errors from different sources are independent and that an overall representative error is obtained from average values of all variables. The following paragraphs describe the assessment and combination of errors for the various steps.

External relationship and BFI estimation: The error in estimating Q95(10) from catchment characteristics must combine the error in estimating BFI from maps (average se = 0.05) with the regression equation error (se = 1.0 in square root units), in order to allow for the fact that recorded BFI values were used when calibrating the regression equations. On the other hand the quoted standard error is itself an overestimate because it is based upon values of Q95(10) which are subject to observation and sampling error. The degree of overestimate was assessed by comparing regressions based upon long and short records and by subdividing long records into shorter subsets. It was thus found that the reduced standard error of the regression equation was 0.90 which when combined with the error in BFI estimation gave a total error of 0.91 in square root units for estimating Q95(10), equivalent to a factorial standard error (fse) of 1.6 for an average catchment with Q95(10) equal to 18% ADF.

Duration relationship: The additional error that derives from the relationship between Q95 of one duration and another depends on the duration considered; the further from 10 days the larger the error. The total error of estimating Q95 for any duration can be estimated by combining the errors of estimating Q95(10) having an fse of 1.6 with the error of the ratio Q95(D) to Q95(10). For durations less than 30 days this extra error can be ignored and for longer durations the total fse is 1.7.

Frequency relationship: The type curve estimated from Q95 determines a multiplying factor which when applied to Q95(D) gives the flow of any other frequency. Two processes were used to develop the type curves; (1) combining individual flow duration curves into categories, and (2) pooling these curves into a standard set of type curves. The error of each of these procedures is estimated as equivalent to 1 type curve giving a combined error of 1.4 type curves equivalent to an fse of 1.38.

The total fse when combined with those due to the other sources can be expected to be 1.61 for durations up to 30 days and 1.73 for longer durations equivalent to 2.1 and 2.4 type curves respectively. The following equation can be used to convert from fse terms to type curve terms

$$\text{Type Curve error} = 10 \times \log_{10} \text{fse}$$

ADF estimates: The final step in the estimation procedure converts the quantities expressed as %ADF to cumecs and entails estimating the average discharge in the river. The assessment of ADF is obtained as a subtraction between rainfall and evaporation and is proportionately less accurate when the two quantities are similar in magnitude as in low rainfall areas. In a region where rainfall is less than about 1000 mm the factorial standard error is about 1.5; in a region with rainfall in excess of 2000 mm the error is about 1.1. However, the quoted high level of error is probably unrealistic in view of the relatively good gauging and other information in low rainfall regions of the UK. On the other hand the site effects that can dominate in high rainfall areas would mean that the fse of 1.1 understates the true error. It is felt that an fse of 1.25 in estimating ADF is

4 Further research requirements

This report has described a continuing project and it is planned that as further results are obtained additional estimation manuals will be produced and the main report will be revised to include the new results.

The main gap in the current results is that no techniques are presented for estimating low flow spells and storage yield diagrams at an ungauged site. This will entail the extraction of low flow indices from the diagrams and relating them to catchment characteristics. Although experience in the UK and overseas indicates that, after standardizing, curves vary little from catchment to catchment, initial indications are that storage yield properties do vary with catchment type. A further task arising from the current study is the production of the regional memoranda outlining the base flow index variation in particular basins or in regions. It is planned to produce these following requests from users. In addition it has been found that the estimation of ADF is critical to the estimation procedure and it is thought that more work is required to define the best estimation method for given annual rainfall and evaporation.

New research is, in the first instance, directed to the following objectives

- (i) to develop short and long term low flow forecasting procedures
- (ii) to develop a pollution orientated low flow measure
- (iii) to study the annual and seasonal variation of the flow duration curve and relate it to catchment characteristics

Low flow forecasting differs from the predictive tools presented in this report in its concern with the actual occurrence of a low flow at a particular future time rather than a statistical statement about the 'rate' of occurrence of an event over some design horizon. It will be apparent though that flow forecasting beyond the time scale of weather forecasting is not possible and practical low flow forecasts will be expressed in terms of probabilities, or alternatively be made contingent on intervening rainfall. For short term forecasting the recession curve may be used so long as no effective rainfall occurs.

When applying low flow measures to pollution studies (for example when determining the effluent standard to achieve a given water quality in the river downstream of the discharge point), it is commonly assumed that the upstream river and effluent quantities are constant and so is the effluent quantity. This allows a simple mass balance to be used and the 95% exceedance (say) effluent concentration will occur as a result of the 95% flow on the flow duration curve. The result of (i) relaxing these steady state assumptions, and (ii) recognising that a low concentration if extended over a sufficient duration may be as critical as a greater concentration over a short period, will be explored.

Some interest has been expressed in the seasonal and annual variability of the flow duration curve. It is possible to describe a flow duration curve for the data of one year. The 95% point, for example, on this annual curve can itself be viewed as a variable and its variation from year to year can be studied. Similarly flow duration curves can be drawn for particular seasons of the year. A typical application would be to determine the consent conditions for abstracting waters for irrigation. This ideally should be based upon the frequency of inadequate river flow during the irrigation season and not on 'whole-year' frequencies.

The exploration of the use of the base flow index in water resource studies is more realistic and this can be applied to all catchments. The total error combining this and the other sources is thus 2.3 type curves for short durations and 2.6 for longer durations.

Conclusions: The error assessment for low flow estimation is approximate as it has been obtained from a lengthy sequence of steps each with its own error structure. The major sources of error have been found to be the external relationship and ADF assessment. In general terms the standard error is about 2.4 type curves for QP(D)/ADF and nearer 2.6 type curves for QP(D) expressed in cumecs. For the common case where Q95 is itself the value to be estimated the error is factorial standard 1.6 when expressed in %ADF and 1.7 when expressed in cumecs.

The error structure for the flow frequency curve is similar to that of the flow duration curve for the external, duration and ADF error assessment stages. The frequency error can also be expressed in terms of type curves (Figure 3.5) and because an error due to the frequency relationship alone of 1.4 type curves can also be assumed, then the errors quoted above for the flow duration curve can be applied to the flow frequency curve.

3.7 Summary of estimation technique

The estimation techniques are described fully in the estimation manuals for low flow measures, catchment characteristics and the BFI regional monographs. The procedure for the flow duration curve entails the following steps:

(a) Calculate mapped catchment characteristics; AREA and SAAR are always required and L and STMFRQ may be required depending on the location of the catchment;

(b) Estimate the base flow index BFI from nearby gauged catchments and knowledge of the solid and drift geology of the catchment;

(c) Calculate the low flow index Q95(10) using the appropriate regional equation (Table 3.2);

(d) Use the duration relationship to estimate Q95(D) from Q95(10) where D is the duration of interest (Section 3.2);

(e) Use the frequency relationship to estimate, for example, the 99 percentile D day discharge from the 95 percentile D day discharge (Section 3.2);

(f) Estimate average daily flow in cumecs using catchment area, rainfall and evaporation;

(g) Convert discharge from percentage of ADF to cumecs.

These steps assume that a frequency and duration other than the 10 day 95 percentile is required and that there are no data available at or near the site of interest. If only Q95(10) is needed then steps d and e are omitted and if flow data are available then the procedure can be modified accordingly. The ways of using limited data are explained in the estimation manuals; they include estimating BFI from a short record, correlation between short and long record stations and estimating the flow duration curve from current meterings.

another area where further study is planned. Now that flow data has been assembled for most of England and Wales a detailed investigation of the 1975/76 drought, including an appraisal of the best statistical distribution to describe annual minima, is feasible.

5 Conclusions

The Low Flow Study has investigated a variety of ways of describing the low flow properties of rivers. All of these different ways have been programmed and the analyses performed on flow data for up to 750 gauging stations. Two of these measures have been related to catchment characteristics and procedures developed for estimating them at an ungauged site are now available. The duration aspect of low flows has led to the need for estimating flow measures from different moving averages. Preliminary results from storage yield and spell analysis indicate that these measures also can be related to catchment characteristics.

When low flow measures are standardized by dividing by the average daily flow then the effect of catchment area and rainfall is largely removed and geology has been found to be the most important remaining characteristic. The study has developed a method of indexing this characteristic using flow data and of estimating it from maps of solid and drift geology.

The need to estimate average runoff expressing discharge in absolute units highlighted the errors involved in runoff estimates from flow data or from rainfall and evaporation in dry areas. It is thought that the average runoff calculation is a significant source of error in the estimating procedure and that additional research effort could be expended on this aspect. In addition the questioning of the flow duration curve as a valid measure relevant to water quality and the need for probability based low flow forecasts have instigated further research objectives.

References

Armbruster, J.T. 1976 An infiltration index useful in estimating low-flow characteristics of drainage basins. *Journal Research U.S. Geological Survey*, 4, 5, 533-538.

Boulton, A.G. 1965 Minimum acceptable flow. *Journal of the Institution of Water Engineers*, 19, 59-80.

Box, G.E.P. and Cox, D.R. 1964 An analysis of transformations (with discussion). *Journal of the Royal Statistical Society, Section B*, 26, 211-252.

Calder, I.R. 1976 The measurement of water losses from a forested area using a 'Natural' lysimeter. *Journal of Hydrology*, 30, 311-325.

Deacon, G.F. 1910 Water Supply. *Encyclopaedia Britannica (1910-26) 10th-14th Editions*.

Frye, P.M. and Runner, G.S. 1970 A proposed streamflow data program for West Virginia. *U.S. Geological Survey, Open File Report* 61.

Grindley, J. 1970 Estimation and mapping of evaporation. *Symposium on World Water Balance*, I, 200-213. *(Publ. No 92 AIHS, IASH-UNESCO)*.

Gumbel, E.J. 1958 Statistics of Extremes. *New York and London: Columbia University Press*.

Hines, M.S. 1975 Flow-duration and low-flow frequency determinations of selected Arkansas streams. *U.S. Geological Survey, Water Resources Circular No. 12*.

H.M.S.O. 1959-60 Surface Water Yearbook.

Hoyle, N. 1963 Frequency curves and applications. *Journal of the Institution of Water Engineers*, 17, 1963, No. 6.

Ineson, J. and Downing, R.A. 1964 The ground-water component of river discharge and its relationship to hydrogeology. *Journal of the Institution of Water Engineers*, 18, 7, 519-541.

Klaassen, B.E. and Pilgrim, D.H. 1975 Hydrograph recession constants for New South Wales streams. *The Institution of Engineers, Australia. Civil Engineering Transactions*, 1975, 43-49.

Knisel, W.G. 1963 Baseflow recession analyses for comparison of drainage basins and geology. *Journal of Geophysical Research*, 68, 12, 3649-3653.

Lapworth, C.F. 1949 Reservoir storage and yield. *Journal of the Institution of Water Engineers*, 3, 269.

Law, F. 1965 Reservoir yield/storage relationships. *The Institution of Civil Engineers, Introductory Paper to the Hydrological Group Informal Discussion*.

Langbein, W.B. 1938. Some channel storage studies and their application to the determination of infiltration. *Trans. Amer. Geophys. Union* 19, 435-447.

Law, F. 1966 Methods of determination of safe yield and compensation water from storage reservoir. *International Water Supply Congress, Barcelona. Manual of British Water Engineering Practice, Fourth Edition, Vol II.*

Lvovitch, M.I. 1972 Hydrologic budget of continents and estimate of the balance of global fresh water resources. *Soviet Hydrology*, No. 4. pp. 349-360.

McMahon, T.A. 1969 Water resources research: aspects of a regional study in the Hunter Valley, New South Wales. *Journal of Hydrology,* 7, 14-38.

McMahon, T.A. and Mein, R.G. 1978 Reservoir capacity and yield. *Developments in Water Science, Elsevier Scientific Publishing Company: Amsterdam-Oxford-New York.*

Mansell-Moullin, M. 1965 The application of low-flow frequency curves and recession curves to the design of catchwaters. *I.W.E./ S.W.T.E. Engineering Research Sub-Committee, Panel 5: Recession Curves and Frequency Diagrams.*

Martin, J.V. and Cunnane, C. 1976 Analysis and prediction of low-flow and drought volumes for selected Irish rivers. *The Institution of Engineers of Ireland.*

Midgeley, D.C. 1967 Generalized drought sequence probabilities for storage draft frequency analysis. *International Hydrology Symposium, Fort Collins,* 443-450.

Mitchell, W.D. 1957 Flow duration of Illinois streams. *Dept. of Public Works and Buildings, State of Illinois.*

Moore R.J., Marsh T.D. and Smith, D. 1978 Method of flow computation in the river pollution survey. *Water Data Unit Technical Memorandum No. 12 (In Press).*

Musiake K., Inokuti S., Takahasi, Y. 1975 Dependence of low flow characteristics on basin geology in mountainous areas of Japan. *Publication No 117 de L'Association Internationale des Sciences Hydrologiques de Symposium de Tokyo,* 147-156.

National Computing Centre Limited 1971 ASCOP statistical programming package. Science Research Council, Manchester.

Natural Environment Research Council 1975 *Flood Studies Report* 5 vols. Available from Institute of Hydrology .

Riggs, H.C. 1973 Regional analyses of streamflow techniques. *Techniques of Water Research Investigations, Book 4, Chap B3, U.S. Geological Survey, Washington, D.C.,*

Rodda J.C., Downing R.A. and Law, F.M. 1976 Systematic Hydrology *London: Newnes Butterworths,*

Rowntree N.A.F., Bleasdale A., Law F. and Burgess, J.S. 1961 Conference on surface water resources and the drought of 1959: Leeds Symposium of Papers. *Journal of the Institution of Water Engineers,* 15, No. 3.

Sharp, R.G. and Watson, D. 1970 Correlation of river flow data for yield assessment. *The Institution of Civil Engineers. Introductory Paper to the Hydrological Group.*

Simmers, I. 1975 The use of regional hydrology concepts for spatial translation of stream data. *Publication No. 117 de L'Association Internationale des Sciences Hydrologiques de Symposium de Tokyo, 109-118.*

Skelton, J. 1974 Estimating low-flow frequency for perennial Missouri Ozarks streams. *U.S. Geological Survey, Rolla, Missouri.*

Tabony, R.C. 1977 The variability of long-duration rainfall over Great Britain. *Meteorological Office, Scientific Paper No. 37.*

Thomas, D.M. and Benson, M.A. 1970. Generalization of streamflow characteristics from drainage basin characteristics. *Geological Survey Water Supply Paper.* No.1975

Ward, R.C. 1968 Some runoff characteristics of British rivers. *Journal of Hydrology* 6, 358-372.

Water Resources Board 1970 Dry Weather Flows. *Technical note 12.*

Wesche, T.A. and Rechard, P.A. 1973 Parameters influencing minimum streamflow. *Hydraulic Engineering and the Environment, Proceedings of the Hydraulic Division Speciality Conference, Bozeman, Montana,* 21-30.

Weyer, K.U. and Karrenburg, H. 1970 Influence of fractured rocks on the recession curve of limited catchment areas in hill country: A result of regional research and a first evaluation of runoff at hydrogeological experimental basins. *Journal of Hydrology (NZ),* 9, 2, 177-191.

Wright, C.E. 1970 Catchment characteristics influencing low flows. *Water and Water Engineering, November 1970,* 468-471.

Wright, C.E. 1974 The influence of catchment characteristics upon low flows in South East England. *Water Services, July 1974,* 227-230.

Wright, C.E. 1977 The 1975-76 drought: A hydrological review. *Central Water Planning Unit, Annual Report 1976-77.*

Yoon, Y.N. 1975 Correlation of the stream morphological characteristics of the Han river basin with its mean daily and 7-day 10 year low flows. *Publication No. 117 de L'Association Internationale des Sciences Hydrologiques Symposium de Tokyo,* 169-180.

Yorkshire Ouse and Hull River Authority 1969 Survey of Water Resources 1963, *Leeds, Table 7.*

Appendix I

Organizations who have assisted in the study.

Northumbrian Regional Water Authority
Yorkshire Regional Water Authority
Severn Trent Regional Water Authority
Anglian Regional Water Authority
Thames Regional Water Authority
Southern Regional Water Authority
Wessex Regional Water Authority
South West Regional Water Authority
Welsh National Water Development Authority
North West Regional Water Authority
Highland River Purification Board
North East River Purification Board
Tay River Purification Board
Forth River Purification Board
Clyde River Purification Board
Tweed River Purification Board
Solway River Purification Board
Strathclyde Regional Council
Lothians Regional Council
Grampian Regional Council
Tayside Regional Council
North of Scotland Hydroelectric Board
Hull University
Exeter University
Lancaster University
Water Data Unit (Great Britain and Northern Ireland)
Department of Environment (Northern Ireland)
Department of Finance (Northern Ireland)
Office of Public Works Dublin
Institute of Geological Sciences
Soil Survey of England and Wales
British Waterways Board
Central Water Planning Unit
Meteorological Office
Institute of Terrestrial Ecology
Scottish Development Department