Institute of Hydrology

Annual Report for GREAT-ER

January 1998

This report is an official document prepared under contract between ECETOC and the Natural Environment Research Council. It should not be quoted by third parties without permission of both ECETOC and the Institute of Hydrology

---

Institute of Hydrology
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB

Tel: 01491 838800
Fax: 01491 692424
Telex: 849365 Hydrol G

January 1998

1. Annual Review

This review summarises the activities undertaken by the Institute of Hydrology during the first two years of the GREAT-ER project.

1.1 YEAR 1 – FEBRUARY 1996 TO JANUARY 1997

Reporting Period 1

The first reporting period, February to May 1996, was an inception phase with the emphasis on:

1. the identification of available hydrological data within the UK;
2. securing permission to use the UK Environment Agency's WWTP and river quality monitoring data held on the LOIS database at IH and making this data available to consortium members;
3. discussions with other consortium members regarding their requirements from the IH work programme;
4. refinement of the Institute of Hydrology's work programme to define time scales and deliverables for the next six month reporting period, the subsequent nine months and, in outline, for the remainder of the project.

These activities were presented in the Institute of Hydrology's Working Notes No.s 1 to 4 and the four month progress report covering the period February to May 1996.

Reporting Period 2

During the second reporting period, June to September 1996, IH's main activities were:

1. a literature review of methods for estimating river velocities and/or channel geometry's from hydrological and catchment characteristic indices;
2. initiation of the artificial influence data collation programme for the Yorkshire rivers in collaboration with the UK Environment Agency;
3. on site installation of the WIS and Micro LOW FLOWS software at the University of Osnabrück and associated setting up of remote log in and SQL accounts on IH's computing facilities for University of Osnabrück staff;
4. a field visit to the Lambro catchment with associated meetings regarding the acquisition of requisite hydrological data and identification of a suitable hydrological modelling approach for the Lambro basin.

These were reported in the progress report for the period June to September 1996.

Reporting Period 3

During the third reporting period, October 1996 to February 1997, IH has been primarily concerned with:

1. populating Micro LOW FLOWS databases with artificial influence data;
2. developing a method for estimating velocity at ungauged sites.

These activities were presented in the Institute of Hydrology's Working Notes No. 5.

1.2 YEAR 2 – FEBRUARY 1997 TO JANUARY 1998

The activities undertaken by the Institute of Hydrology during the second year of the GREAT-ER project may be summarised into three reporting periods.

Reporting Period 1

Within the first reporting period, February to May 1997, activities were concentrated on the hydrological analysis associated with incorporating variations in the timing of low flow events into the low flow model and using local data to improve the flow estimates derived from the model, including:

1. Investigation of seasonal variations in flows;
2. Developing techniques for incorporating the timing of low flow events;
3. Development of code to implement techniques within the Micro LOW FLOWS software;
4. Preliminary evaluation of the revised method;
5. Initial investigations of strategies for incorporating local data into the estimation procedure.

These activities are described in detail in "GREAT-ER quarterly progress report: February to May 1997" (Croker and Young, 1997).

Reporting Period 2

During the second reporting period, June to September 1997, the main activities were:

1. The development of a summary document describing the availability of hydrological and climatic data across the European Union. This document "Hydrological and Climate data in Europe" (Croker and Young, 1997) has been presented as a draft report.

2. A review of the RUG discussion document on sewer flow modelling presented at the Enlarged Task Force meeting held in Milan in June 1997.

3. The development of the natural hydrological model for the Yorkshire pilot study region. This has primarily focussed on:

    i. The incorporation of the variation in the timing of low flow events at a monthly resolution through distributing the standardised Q95 model

    ii. Improving the implementation of the mean flow estimation model by distributing the model on a 1km^2 resolution grid

4. The enhancement of the estimates of natural mean flow at ungauged sites through the incorporation of mean flow measured at natural catchments within the basin gauged at stations of good hydrometric quality

5. The incorporation of the impact of artificial influences within the basin on the natural flow regime as estimated by the model. This has concentrated on developing a generic top down approach that seeks to make optimum use of an incomplete characterisation of the complex artificial influences within the basin.

Reporting Period 3

During the third reporting period, October 1997 to January 1998, the principal activities have been:

1. Initiating the provision of flow estimates to support the monitoring program which is now near completion. This provision of these estimates by the end of January is dependent on the EA providing information of the locations and dates of the sampling programme and the gauged flows on the sampling dates.

2. Building on the work initiated under item five in the previous reporting period, the calibration of the software for the impact of artificial influences has been refined based on a re-evaluation of the available data.

3. Initiation of the acquisition of data from the Environment Agency to calibrate the hydrological model for the Don and Rother catchments.

1.3 WORK PLAN FOR 1998 - 1999

The main activities within this reporting period will be associated with:

1. Assessing the extent of the Italian hydrological data and undertaking quality of the data.

2. Calibration of a semi-distributed rainfall-runoff model for the Lambro. This will be organised into two components:

    i. The rainfall-runoff model will be used to extend the short hydrometric records within the catchment and subsequently extrapolated to ungauged locations using catchment

Institute of Hydrology

Working Note No.6

The timing of low flow events

C. Round & A. Young

This report is an official document prepared under contract between ECETOC and the Natural Environment Research Council. It should not be quoted by third parties without permission of both ECETOC and the Institute of Hydrology

---

Institute of Hydrology
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB

Tel: 01491 838800
Fax: 01491 692424
Telex: 849365 Hydrol G

January 1998

Executive Summary

For the purpose of the GREAT-ER project the Institute of Hydrology is required to produce flow estimates with the necessary confidence for use by non hydrologists. To improve the confidence of flow estimates the necessity to incorporate both the dependency of the seasonality of low flows on the hydrogeology and rainfall, and the available local hydrometric data was recognised.

The assumption that flows are temporally coherent over all parts of the upstream network underlies the existing low flow estimation techniques. This is unlikely to be the case in large catchments given the diversity of geology and distribution of rainfall across such catchments. The implications of this assumption for the GREAT-ER project would be an underestimation of dilution at the catchment scale. Previous work, undertaken by the Institute of Hydrology, has demonstrated that differences in the timing of low flows can be identified at a monthly resolution.

As GREAT-ER is focussing on the daily variation in flows, Working Note No. 6 aims to determine whether the timing of the Q95 flow differs in geologically and climatically heterogeneous catchments at a daily resolution, and to quantify the effect of the differences in the timing on Q95 estimates.

A number of analyses were undertaken using case study catchments and UK wide catchments. The use of case study catchments enabled a preliminary investigation of the dependency of the timing of the Q95 on climate and hydrogeology. A larger set of UK wide catchments were used to investigate the regional variations in the timing of low flows and to quantify the Q95 under different assumptions of the timing of low flows.

The analyses identified differences in the day of occurrence of the Q95 flow, which were shown to be a function of variations in climate and geology. However, when considering the inter-annual variability in the timing of the Q95 flow, these differences were not statistically significant in most nearest neighbour catchments.

The Q95 estimates, derived under the assumption of temporal coherence, are mostly smaller than those estimates derived under the assumption that the low flows occur at the time of one of the upstream catchments. 96% of the estimates derived under the assumption of temporal coherence are within a factor of three of the estimates derived under the assumption that the low flows occur at the time of one of the upstream catchments. Those differences which are larger than a factor of three are associated with wetter and more impermeable catchments. This is due to the large variability that is observed in the daily flows over a small period of time.

The recommendation of the study is that, since the timing is not significantly different at a daily resolution in these wet and impermeable catchments, it is not practicable to incorporate the effect that the flow variability exerts on the estimated Q95. However, the timing of the Q95 at a monthly resolution, which has previously been found to be significant, should be incorporated into the hydrological model.

Contents

1. Introduction

In the GREAT-ER proposal, it was recognised that to produce flow estimates with the necessary level of confidence for use by non hydrologists in water quality modelling activities, it would be necessary to incorporate into the existing low flow estimation methods:

1. the dependence of the seasonality of low flows on hydrogeology and rainfall;

2. the available local hydrometric data.

In estimating low flow statistics at a site, the existing model (Gustard *et al*, 1992) contains the implicit assumption that the temporal distribution of flows is coherent over all parts of the upstream network. This implies spatial and temporal coherence of rainfall, evaporation and, most importantly, catchment response (principally hydrogeological response in the case of UK low flows). Whilst these conditions may potentially be met in small catchments it is unlikely to be the case in larger catchments. For example; within the UK Thames basin (9948 km^2), given the diversity of geology and the temporal variations in the phasing and magnitude of rainfall distributions across the basin, it is highly improbable that all gauging stations within the basin will measure flows corresponding to the same percentile exceedance at the same instant in time. Even assuming that rainfall is temporally coherent across the catchment the permeable catchments within the basin will experience their low flows later in the year than the impermeable catchments.

Within the GREAT-ER project, the implications for the water quality modelling would potentially be an underestimation of dilution at the catchment scale due to the variations in the timing of the Q95 within the river network. Therefore, it is essential that the seasonality of low flows and their dependence on geology and the seasonal nature of rainfall is accounted for in the estimation of the flow regime.

It has previously been demonstrated (Bullock *et al*, 1994) that on a monthly time scale variations in the timing of low flows occurs between different hydrogeological units. The monthly time resolution, which was used in the study, is a useful management unit but is not a hydrologically significant one. Therefore, three principal objectives of the study, discussed in this Working Note, were to:

1. Determine whether the timing of the Q95 flow differs significantly in geologically and climatically heterogeneous catchments at a daily resolution, as the fate modelling activities are being undertaken at this resolution.

2. Quantify the effect of the differences in the timing of low flows on the precision of the estimated Q95 flows.

3. Provide recommendations of the necessity for and/or feasibility of incorporating the probability of occurrence of low flow events into the development and application of regional multivariate hydrological modelling.

In order to meet these objectives three analyses were undertaken:

1. A small number of case study catchments were used in a preliminary investigation of the dependency of the timing of low flows on climate and hydrogeology. This analysis is presented in Chapter 2.

2. A larger set of catchments were used to build on the preliminary investigation to investigate the regional variations in the timing of low flows. Together, analyses one and two enabled the requirements of objective one to be met. This analysis is presented in Chapter 3.

3. The larger set of catchments were used to quantify the Q95 under different assumptions of the timing of low flows and thus determine the precision of the estimated Q95 flows derived using the current assumption of temporal coherence. This third analysis enabled the requirements of objective two to be met. This analysis is presented in Chapter 4.

2. Preliminary investigation of the timing of low flows

2.1 INTRODUCTION

Seven case study catchments were selected so that a preliminary investigation of the variations in the timing of low flows could be made. The selected case study catchments, given in Table 2.1, have the following properties:

(i) they are of good hydrometric quality and are relatively natural;

(ii) they have 20 years of coherent period of record (1976 to 1995), with less than 31 days missing for any one month throughout the period of record;

(iii) The catchments are hydrogeologically homogenous, defined as 75% of the catchment area comprising of two or less similar hydrological response classes (based on a hydrological classification of soils). The range of hydrological response is typical of that for the UK;

(iv) The catchments have either low (<850mm) or high (>1000mm) Standard period (1941 - 70) Average Annual Rainfall (SAAR).

Table 2.1 *Hydrogeologically representative catchments*

Station number	LFG	Geology	SAAR (41-70) (mm)	Area (km^2)	BFI
39019	AB	Chalk	737	234.1	0.97
39043	BA	Chalk	800	295	0.95
44006	AA	Chalk	1098	12.4	0.87
55029	AA	Old Red Sandstone	1001	354	0.59
41025	AA	Weald Clay	806	91.6	0.23
39054	AA	Weald clay	827	31.8	0.24
55026	AA	Metamorphised Silurian sediments	1618	174	0.36

The catchments are described in detail below.

Stations 39019, Lambourn at Shaw, 39043, Kennet at Knighton, and 39054, Mole at Gatwick Airport, are all located in the Thames catchment of southern England. The flows at station 39019 are occasionally influenced by a downstream sluice and also by the West Berkshire Groundwater Scheme which has occasionally provided low flow support to the Lambourn. Artificial influence is otherwise limited in this rural catchment and the flow pattern is baseflow dominated. The flow regime at station 39043 is also base flow dominated although flows are slightly diminished by groundwater abstraction. Some of the pre 1980 flows are uncorrected and there is some bypassing during floods. The catchment is mainly rural but there is some urban growth in the valley. There is very little disturbance to the responsive, natural flow regime at station 39054. Gatwick Airport is not in the catchment, thus the catchment is predominantly rural with only a small export of water.

Stations 55029, Monnow at Grosmont, and 55026, Wye at Ddol Farm, are situated in south Wales. Station 55029 is a natural catchment draining the relatively permeable Old red Sandstone of the Black Mountains. Station 55026 is characteristic of a wet upland impermeable catchment. The flow regime is unaffected by the large water supply reservoir which flows from the Elan valley.

Station 41025, Loxwood Stream at Drungewick, is an impervious clay catchment located in the south-east of England. The abstractions and discharges have a negligible impact on overall runoff, but there is occasional anomalous behaviour at low flows.

Station 44006, Sydling Water at Sydling St. Nicholas, is a predominantly rural, Lower Chalk catchment situated in the south west of England. The station is modular under all flow conditions.

The flow duration curve (FDC) graphically represents the relationship between any given discharge and the percentage of time that the discharge is exceeded. The FDC reflects the geology of the catchment. For example, a permeable catchment has a characteristically low gradient FDC, reflecting the relatively low flow variability of flows about the median flow. Conversely, an impermeable catchment has a characteristically steep FDC, indicative of a flashy flow regime and a high variance of daily flows. The standardisation of discharge by mean flow facilitates comparisons between catchments by reducing the differences in the location of the flow duration curve which are caused by differences in the mean annual runoff.

Figure 2.1 shows the annual FDCs associated with each of the case study catchments. The gradients of the FDCs of the catchments generally increase with increasing impermeability, indicating that greater variability exists in the daily flows in impermeable catchments, as would be expected. The FDCs are typical of the type of catchments that they are assumed to represent.

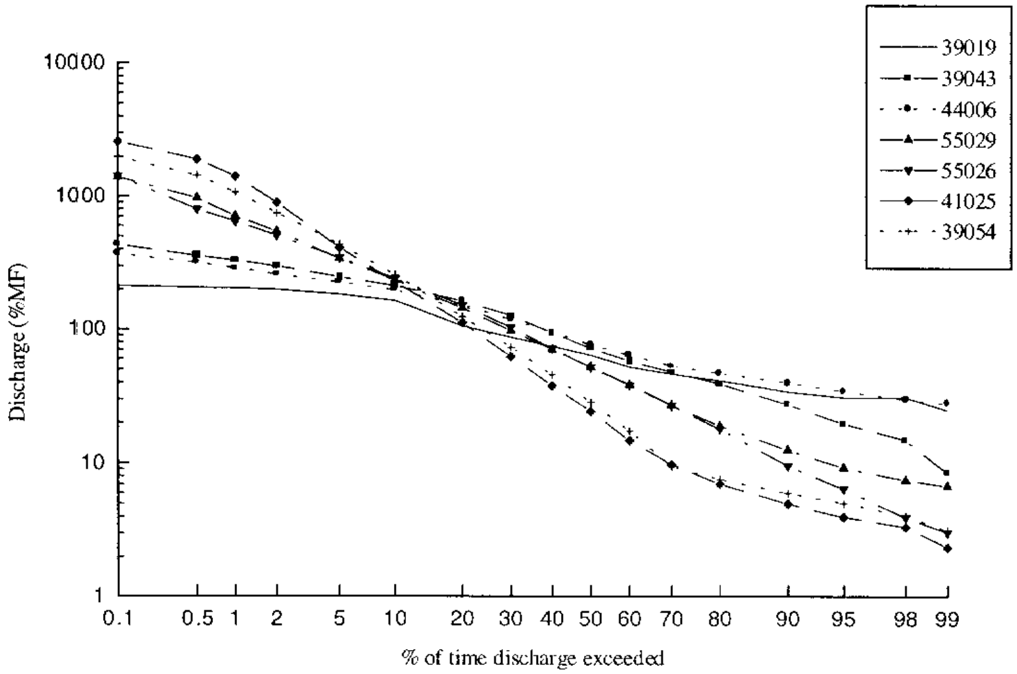

Figure 2.1 *Annual flow duration curves*

An investigation of the timing of low flows was made using these case study catchments. Since the objective of this study was to determine the effect of different permeability and/or rainfall in upstream catchments on the timing of the downstream Q95, hypothetical flow time series were derived by combining the time series of paired catchments with differing hydrogeological and/or rainfall characteristics. Linear combinations of the flow time series were made in the ratios of 100%:0%, 75%:25%, 50%:50%, 25%:75%, and 0%:100% to represent different stages in the transition of a hypothetical catchment with the characteristics of the first catchment in the pair to one with the characteristics of the second.

The paired catchments are given in Table 2.2. Pairs one and two were intended to act as control catchments. Only minimal changes in the timing of the Q95 flow would be expected as the catchment progressed from 100% of catchment one to 100% of catchment two, as in each case the pairs are both climatically and hydrogeologically similar. The stations in pairs three and four were used to investigate the effect of an decreasingly permeable catchment, in areas of low and high rainfall respectively. Pairs five and six were used to identify the effect of increasing rainfall in permeable and impermeable catchments respectively.

Table 2.2 *Paired catchments*

Pair	Station 1	Station 2	Investigation
1	39043	39019	Two dry permeable catchments
2	39054	41025	Two dry impermeable catchments
3	39043	41025	Decreasing permeability in catchments with low rainfall
4	55029	55026	Decreasing permeability in catchments with high rainfall
5	39043	44006	Increasing rainfall in permeable catchments
6	39054	55026	Increasing rainfall in impermeable catchments

The time of occurrence of the Q95 and standard deviation were derived for each of the time series associated with the pairs. These were plotted and analysed graphically to determine the effect of decreasing permeability or increasing wetness. The mean day of occurrence of the two paired catchments was statistically analysed to determine whether on average the Q95 occurred on significantly different days. Details of this analysis are given in Section 2.2.

2.2 ANALYSIS OF THE TIMING OF THE Q95 IN THE CASE STUDY CATCHMENTS

For every time series associated with each of the paired catchments the day of the annual Q95, i.e. the day on which the 18th lowest flow occurred, was extracted for each year over the period of record. Calculating the mean day of the annual Q95 over the period of record presents the problem that the 31st of December and the 1st of January have adjacent values in the time series but will not be considered as such if day numbers are used (Bayliss, A. & Jones, R.).

For example, if the Q95 occurs on days 20, 258 and 293 in three consecutive years then the arithmetic mean of the day of occurrence is 190, thus implying that on average the Q95 occurs in the middle of the year. This is clearly a mis-representation of when the Q95 actually occurs. To avoid this problem the following approach was adopted (Mardia, 1972) to calculate the mean day of occurrence of the

Q95 and the corresponding standard deviation.

Mean Q95 day of occurrence

The day number is expressed as an angle, where:

$$\theta_i = \left(\text{day of occurrence}.\frac{2\pi}{\text{LENYR}} \right) - \text{ADJUST} \tag{2.1}$$

where:

$$\text{ADJUST} = \frac{1}{2}\left(\frac{2\pi}{365} \right)$$

LENYR is 365, or 366 for a leap year.

The x-axis is chosen as an arbitrary starting point and all angles are calculated in an anti-clockwise direction from this point (Figure 2.2). The occurrence of the Q95 values are assigned to the day on which they occur, but in reality the flow is the mean of the flows logged at various times within that day. Therefore, an adjustment (ADJUST) is made to each value so that the Q95 is represented by the angle occurring at its mid point.

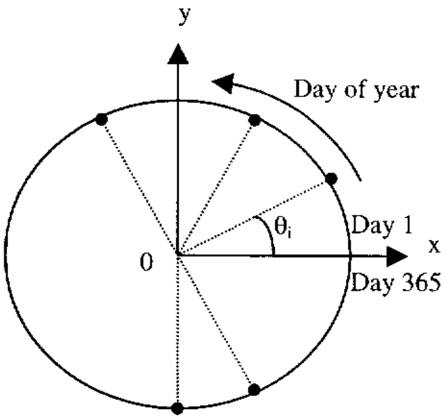

Figure 2.2 *Calculating the mean Q95 day using directional statistics (Source: Bayliss and Jones, 1993)*

Following the approach adopted by Mardia (1972), the mean Q95 day is obtained by representing all the days as weights of unit mass, sited on the circumference of a circle of unit radius, and then calculating the centroid of these weights.

Thus the mean of the x-co-ordinates and the mean of the y-coordinates are calculated:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n}\cos\theta_i \qquad \bar{y} = \frac{1}{n}\sum_{i=1}^{n}\sin\theta_i \tag{2.2}$$

Thus, the mean direction is given by:

$$\bar{\theta} = \tan^{-1}\left(\frac{\bar{y}}{\bar{x}}\right) \tag{2.3}$$

If $\bar{\theta}$ is negative then 2π should be added to $\bar{\theta}$. Finally, the mean direction is converted back to a day number using:

$$\text{MQ95D} = \left(\bar{\theta}.\frac{365}{2}\right) + 0.5 \tag{2.4}$$

A half is added to the MQ95D to compensate for the earlier adjustment (ADJUST) during the conversion of day numbers to angles. The value is rounded to the nearest day.

Standard deviation of the mean Q95 day of occurrence

The 'mean resultant' $\bar{r}$ gives some indication of the spread of data:

$$\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2} \tag{2.5}$$

If $\bar{r}$ is close to unity then the data displays a strong direction, which is likely to indicate strong seasonality in the case of the day of occurrence of the Q95 flow. If $\bar{r}$ is close to zero then the data are not strongly seasonal and the value of MQ95D is less meaningful.

The standard deviation, S_o, of circular data is defined by Mardia (1972) as:

$$S_O = \sqrt{-2\ln\bar{r}} \tag{2.6}$$

This standard deviation, in radians, can be converted to a standard deviation in days about the mean Q95 day, MQ95D, by:

$$SDQ95D = S_o . \left(\frac{365}{2\pi}\right) \tag{2.7}$$

This value is rounded to the nearest day.

The resultant mean day and standard deviation were plotted as a function of the degree of permeability or wetness of a catchment and analysed graphically to determine the effect of decreasing permeability or increasing wetness.

A two sample T-test was used to determine whether on average the Q95 occurred on significantly different days in the paired catchments, listed in Table 2.2. The assumption is made that the two independent samples originate from Normal distributions $N(\mu_1, \sigma_1^2)$ and $N(\mu_2, \sigma_2^2)$. Therefore, the hypothesis that the two populations have the same mean was put forward. The null hypothesis $H_0{:}\mu_1=\mu_2$ was tested, i.e. the mean day of occurrence of the Q95 is equal in the two catchments associated with each pair. Since the population variances were unknown there was a choice of two test statistics, based on the equality of the variances of the two sample populations.

Significance test statistics

The first, given in equation 2.8, is used when the population variances are unknown but equal.

$$T_1 = \frac{\bar{x}_1 - \bar{x}_2}{s_p\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}} \tag{2.8}$$

Where: $$s_p^2 = \frac{(n-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}$$ i.e. the pooled variance

$\bar{x}_1$ and $\bar{x}_2$	are the two sample means
$\bar{s}_1^2$ and $\bar{s}_2^2$	are the two sample variances
n_1 and n_2	are the sample sizes

The second, given in equation 2.9, is used when the variances are unequal and known.

$$T_2 = \frac{\bar{x}_1 - \vec{x}_2}{\sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}}} \tag{2.9}$$

To determine the equality of the variances of two populations, and thus enable the correct choice of test statistic, an F-test was undertaken. The assumption was made that the two independent samples originate from Normal distributions $N(\mu_1, \sigma_1^2)$ and $N(\mu_2, \sigma_2^2)$, and the population mean and variances were unknown. Thus to test the null hypothesis that H_0: $\sigma_1^2 \neq \sigma_2^2$ the value of $F=s_1^2/s_2^2$ was compared to the tabulated value of the F-distribution with n_1-1 and n_2-1 degrees of freedom. Since the F-distribution is tabulated for the upper tail only, for a 5% significance test the larger variance based on n_1 observations was used as the numerator. The observed F value was then compared with the tabulated F value at the 2.5% point. If $F \leq F_{\alpha/2}\,(n_1 - 1, n_2 - 1)$ then it was assumed that the variances were not significantly different.

The sample number for all stations was 20, except for station 41025 where n = 17 and station 39054 where n = 19. Therefore, depending on the sample sizes, the critical values for comparing the variances of the catchments in each pair were:

$F_{19,19}(2.5\%) = 2.58$
$F_{18,19}(2.5\%) = 2.60$
$F_{19,16}(2.5\%) = 2.75$

2.3 RESULTS AND DISCUSSION OF THE CASE STUDY INVESTIGATIONS

For each of the pairs of catchments the mean day of occurrence and the corresponding standard deviation were plotted for each of the linear combinations representing the transition of a catchment with the response of the first catchment in the pair to that of the second. Thus, Figures 2.3a to f are graphical representations of the mean day of occurrence of the Q95 and corresponding standard deviation as a function of catchment geology or rainfall.

T-tests were also undertaken to identify whether the mean day of occurrence of the of the Q95 was different for catchments one and two in each pair. The critical values for comparing the means of the catchments in each pair, depending on the sample size of each station within a pair, are:

$t_{35}(5\%) = 2.032$
$t_{37}(5\%) = 2.027$
$t_{38}(5\%) = 2.025$

The t-statistics are given in Table 2.3.

Table 2.3 *t-statistics for differences between mean day of occurrence*

Pair	Stations	t-statistics
1	39043, 39019	0.15
2	39054, 41025	0.09
3	39043, 41025	2.78
4	55029, 55026	3.94
5	39043, 44006	1.96
6	39054, 55026	3.51

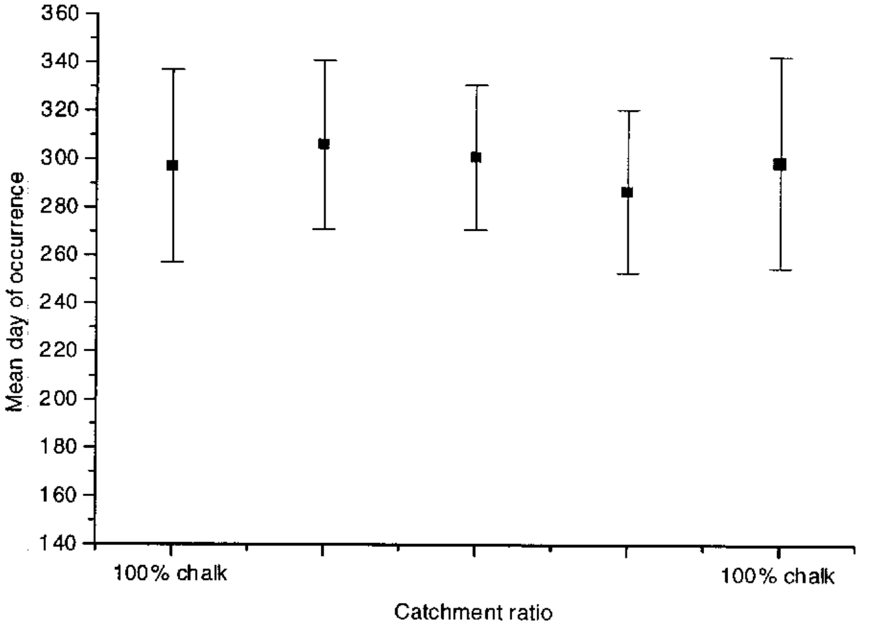

Figure 2.3a Mean day of occurrence of Q95 ± 1 SD for catchments with high permeability and low rainfall (Pair 1)

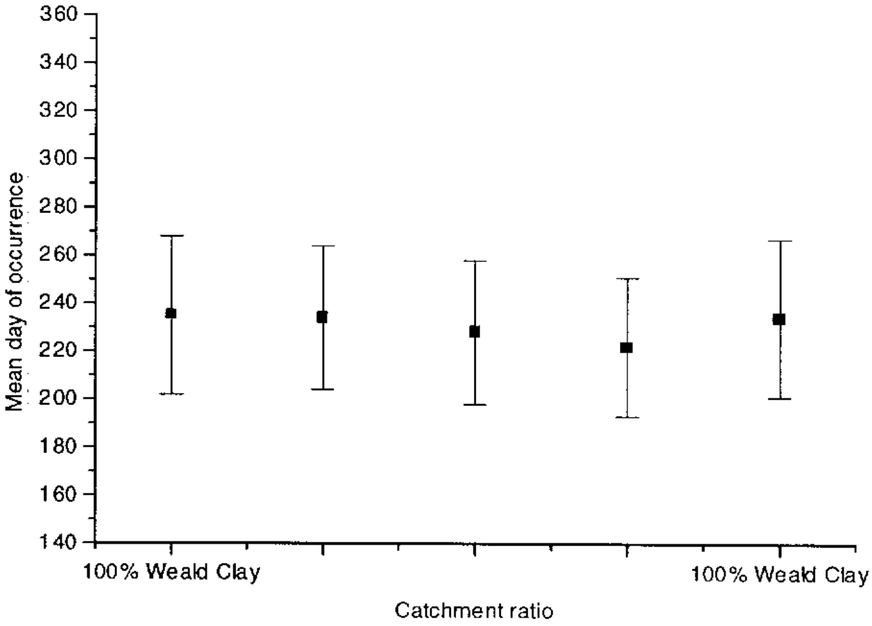

Figure 2.3b Mean day of occurrence of Q95 ± 1 SD for catchments with low permeability and low rainfall (Pair 2)

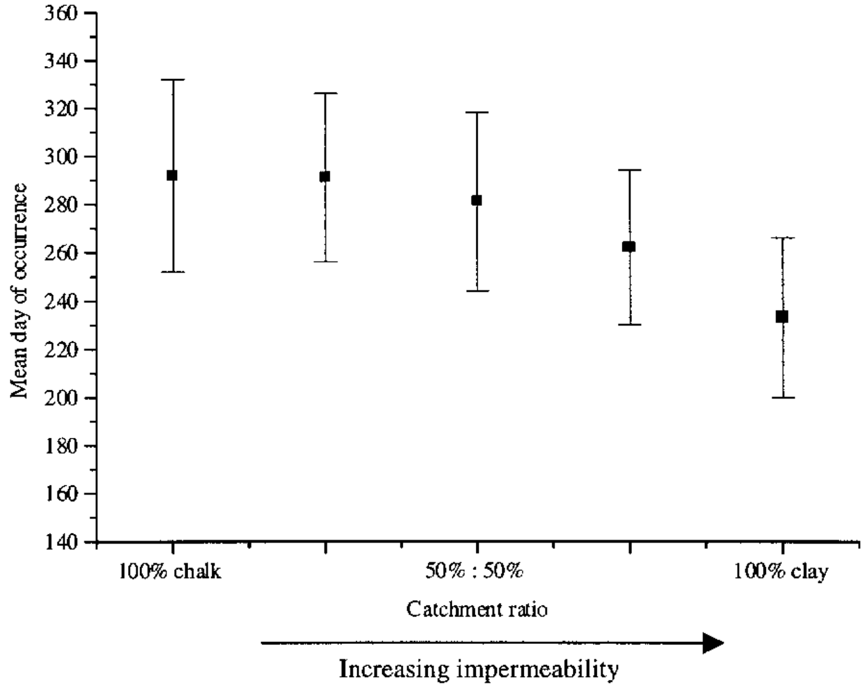

Figure 2.3c Mean day of occurrence of Q95 ± 1 SD for catchments with low rainfall and decreasing permeability (Pair 3)

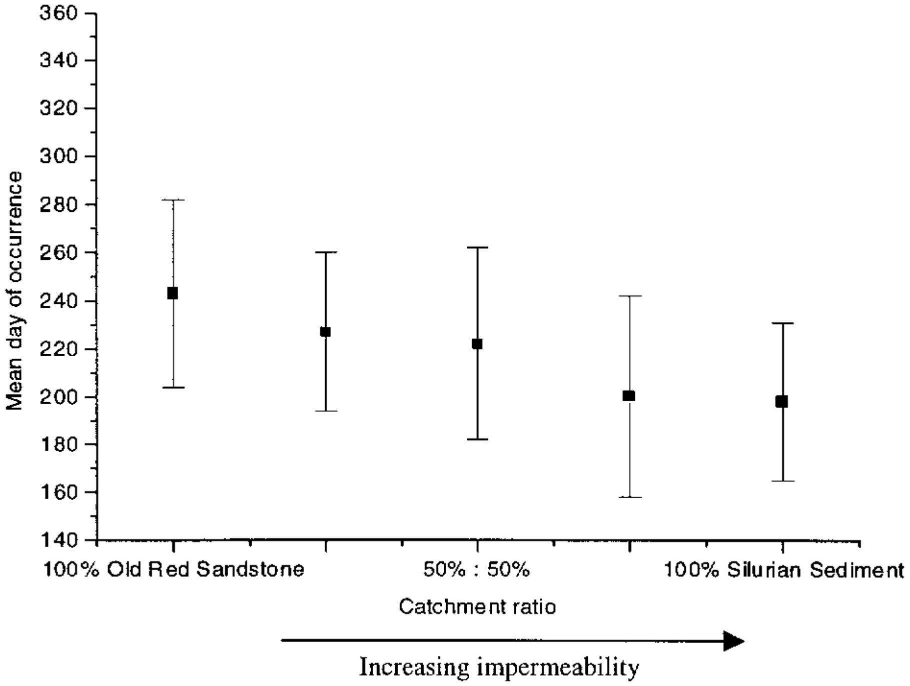

Figure 2.3d Mean day of occurrence of Q95 ± 1 SD for catchments with high rainfall and decreasing permeability (Pair 4)

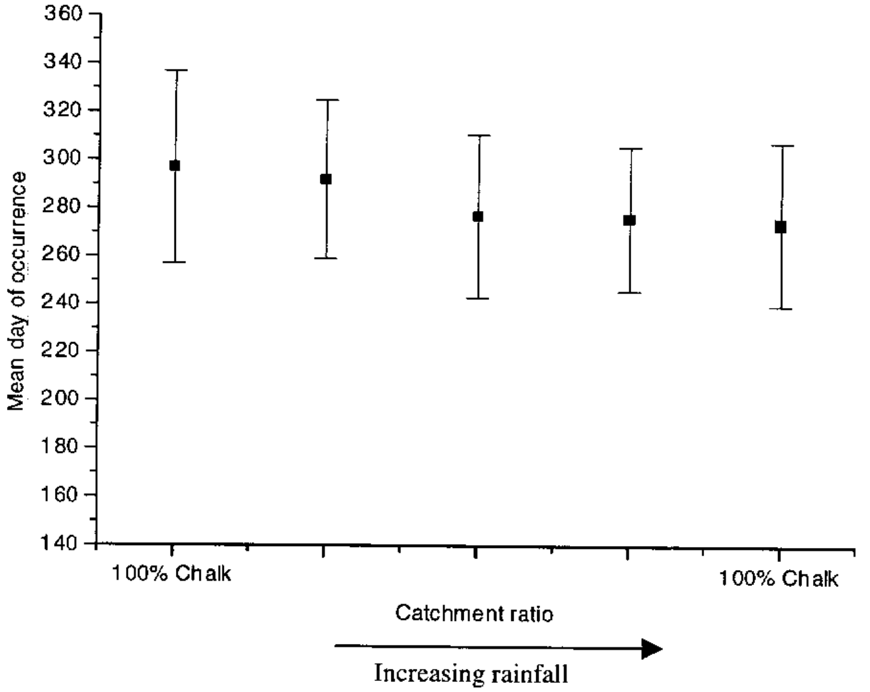

Figure 2.3e Mean day of occurrence of Q95 ± 1 SD for catchments with high permeability and increasing rainfall (Pair 5)

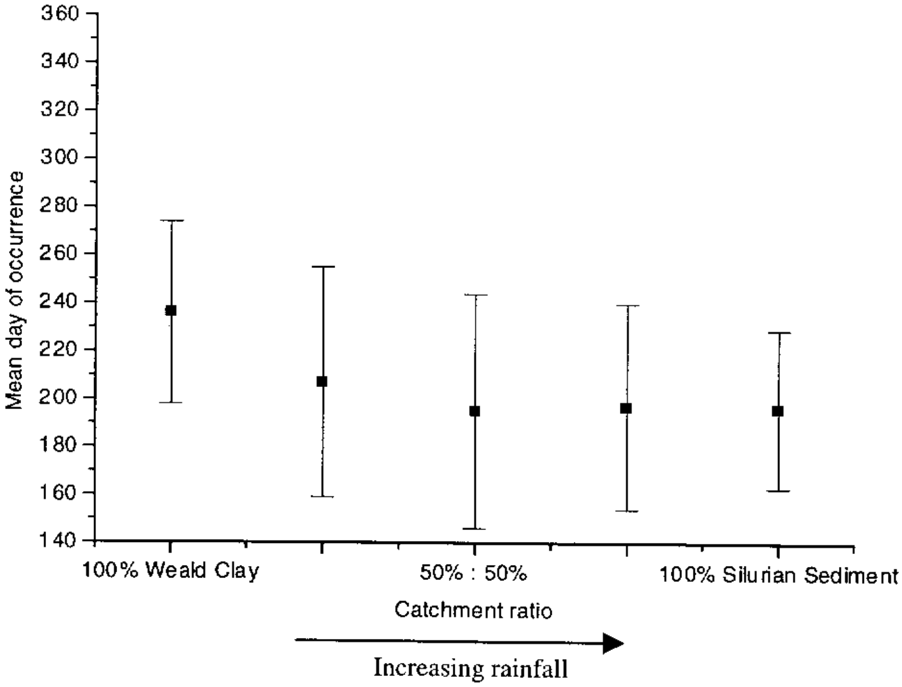

Figure 2.3f Mean day of occurrence of Q95 ± 1 SD for catchments with low permeability and increasing rainfall (Pair 6)

1. Control catchments

Figures 2.3a and b show the mean day of occurrence of the Q95 and the corresponding standard deviations for the dry chalk and dry clay catchments. There appears to be very little difference in the timing, as expected in catchments with similar characteristics. The t-statistics of 0.15 and 0.09 confirmed that the mean day of occurrence associated with the two pairs of catchments are not significantly different.

2. Decreasing permeability in wet and dry catchments

Dry

Figure 2.3c shows that the Q95 occurs progressively earlier as the permeability decreases in the dry catchment pairing. The rate at which the mean day becomes earlier is slower than the rate of increase in percentage area of clay. This is due to the buffering effect that the groundwater discharge has on the river flows. This even occurs when only a small percentage of the contributing catchment consists of a permeable geology. It should be noted that the confidence intervals around the mean day overlap at either extreme. The t-statistic of 2.78 indicated that the mean day in the 100% chalk catchment is significantly different to the mean day in the 100% clay catchment.

Wet

A similar pattern is evident in Figure 2.3d as permeability decreases in wet catchments. However, the rate at which the mean day becomes earlier is more constant than that observed in the dry catchments. This may be attributable to the different characteristics of the Chalk and Old Red Sandstone catchments used in pairs three and four to represent permeable catchments. Whilst both are associated with large storage capacities, the Old Red Sandstone has a higher transmissivity and is consequently more responsive to rainfall. Therefore, the groundwater buffering effect may be less important due to the flashier response of the Old Red Sandstone catchment and the greater contribution to flow that rainfall has in wetter catchments. The t-statistic of 3.94 showed that the mean day in the 100% Old Red Sandstone catchment is significantly different to the mean day in the 100% Silurian Sediment catchment.

3. Increasing wetness in permeable and impermeable catchments

Permeable

Figure 2.3e shows that the Q95 occurs earlier as the catchment becomes progressively wetter. Is likely to be attributable to the complex hydrogeology of the chalk and the fact that the two catchments are associated with different chalk outcrops, which are known to behave differently (Bullock *et al*, 1994).The t-statistic of 1.96 showed that the mean day in the dry chalk catchment is not significantly different to the mean day in the wet chalk catchment. This suggests that rainfall may not significantly influence the timing of the Q95.

Impermeable

Figure 2.3f demonstrates that a similar effect occurs in the impermeable catchments as they become wetter. However, the effect is more noticeable perhaps due to the greater influence that rainfall has on river flows in impermeable catchments. The t-statistic of 3.51 indicated that the mean day in the dry impermeable cathment is significantly different to the mean day in the wet impermeable catchment.

Contrary to the permeable catchment, this result implies that rainfall may influence the timing of the Q95 in impermeable catchments.

3. Investigation of regional differences in the timing of low flows across the UK

3.1 INTRODUCTION

The paired catchment analysis was useful for investigating the dependency of the differences that may occur in the timing of low flows on climate and geology. However, the hypothetical catchments were derived by combining catchments with geological and rainfall characteristics of opposite extremes and sometimes from different regions of the UK. In reality such extremes are unlikely to occur in a catchment.

Therefore, a second subset of 388 natural catchments of good hydrometric quality and flow records covering the period 1976 to 1995 were selected. This second set was used within a regional analysis to determine whether the patterns observed within the paired catchments are replicated across the UK.

3.2 ANALYSIS

3.2.1 Analysis of the timing of the Q95

Using the procedure outlined in Section 2.2, the mean day of occurrence of the Q95 and corresponding standard deviation were calculated for each of the 388 catchments. The mean day of occurrence of the Q95 and the mean resultant are plotted for each catchment on a UK map. The mean resultant is used as opposed to the standard deviation in days in order to give visual weight to those stations which have strong seasonality of low flow events. A visual analysis of the map was undertaken in the context of the distribution of geological units throughout the UK.

Linear stepwise multivariate regression analysis was used to identify the most important variables which determine the mean day of occurrence of the Q95. Potential controlling variables were BFI, SAAR and catchment area. The dependent variable, day of occurrence, was regressed against the independent variables, BFI, SAAR and catchment area.

Stepwise regression was utilised, which is based upon the forward selection of variables, with a backward look at each stage. The first variable that produces the optimum one variable subset (i.e. the variable with the largest R^2) is identified, to which the second variable is added, such that the largest increase in R^2 occurs. Following each addition of a variable a backward elimination may be implemented.

Similar to the determination of the existence of significant differences in the timing of the Q95 in the paired case study catchments (Section 2.2), each of the 388 stations was paired with its nearest neighbour and analysed to determine whether significant differences occur in the timing of the Q95 between nearby catchments. The choice of T-test was based on the equality of the variances, as discussed in Section 2.2.

3.3 RESULTS AND DISCUSSION OF THE VARIATIONS IN TIMING ACROSS THE UK

Figure 3.1 shows the mean day of occurrence of the Q95, as indicated by the direction of the tail, and the strength of the seasonality, as indicated by the length of the tail. In association with Figure 3.2, which shows the distribution of Low Flow HOST Groups in the UK, it was possible to observe regional differences in the timing of the Q95 that occur as a result of regional variations in hydrogeology. Most of the Q95 flows occur between the 1st of July and the 1st of October. In the north west, where catchments are characterised by the impermeable geologies associated with LFHGs 9 and 10, the flows occur in early July, whilst those which occur after October can be associated with LFHG 1, which is primarily comprised of chalk. More generally, Figure 3.1 indicates that there is more variability in the timing of the low flows between gauging stations in areas of more permeable geology, which demonstrates the complex controls of hydrogeology in permeable systems. However, the at station variability, indicated by the length of the tail, is small. This reflects the strong seasonality of low flow events in all regions of the UK.

The results of the multivariate regression analysis, which was undertaken to determine the variables which influence the timing of the Q95, are given in Table 3.1. It is evident that the dominant factor in influencing the day of occurrence of the low flow statistics is the BFI.

Table 3.1 *Multivariate regression results*

Significant variables	Partial R^2	Model R^2	Standard Error	Parameter estimate
INTERCEPT				221.71
BFI	0.4776	0.4776		77.83
SAAR	0.1759	0.6534		-0.0293
AREA	0.0167	0.6701	16.12	-0.0049

BFI accounts for almost 50% of the variability observed in the mean day of occurrence, whilst SAAR accounts for less than 20%. Therefore, a linear regression between the mean day of occurrence and BFI was undertaken. Figure 3.3 shows the linear relationship between BFI and the mean day of occurrence of the Q95. The trendline represents the mean day of occurrence that would occur at a given BFI. The standard error for the distribution around the mean at any given BFI is equal to approximately 20 days. It was therefore possible to estimate the difference in BFI required for the associated mean days of occurrence to be significantly different using the following test statistic:

$$T = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\sigma_1^2 + \sigma_2^2}} \tag{3.1}$$

where: $\bar{x}_1$ and $\bar{x}_2$ mean day of occurrence of Q95

σ_1^2 and σ_2^2 variance associated with $\bar{x}_1$ and $\bar{x}_2$

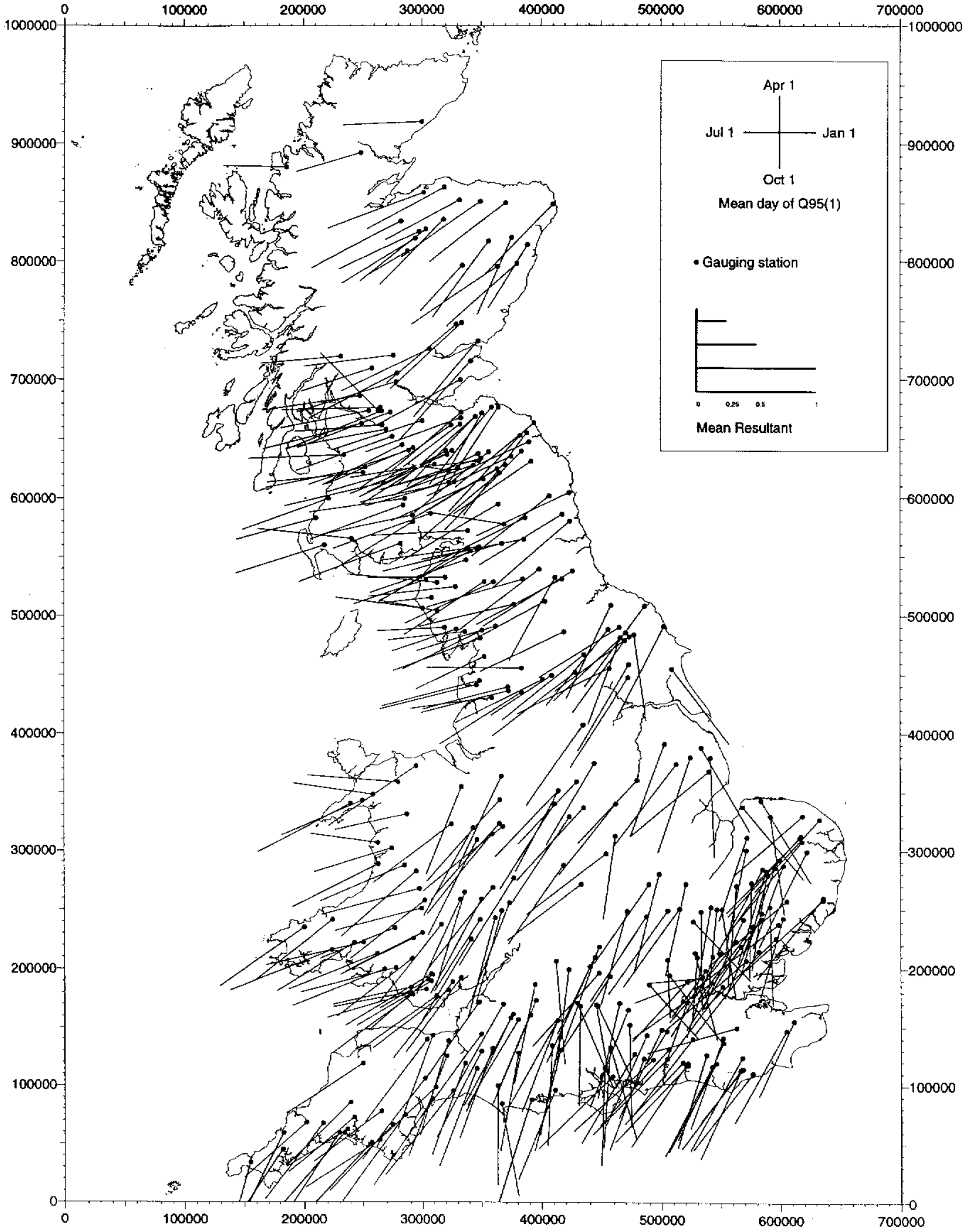

Figure 3.1 *Mean day and seasonality of occurrence of Q95*

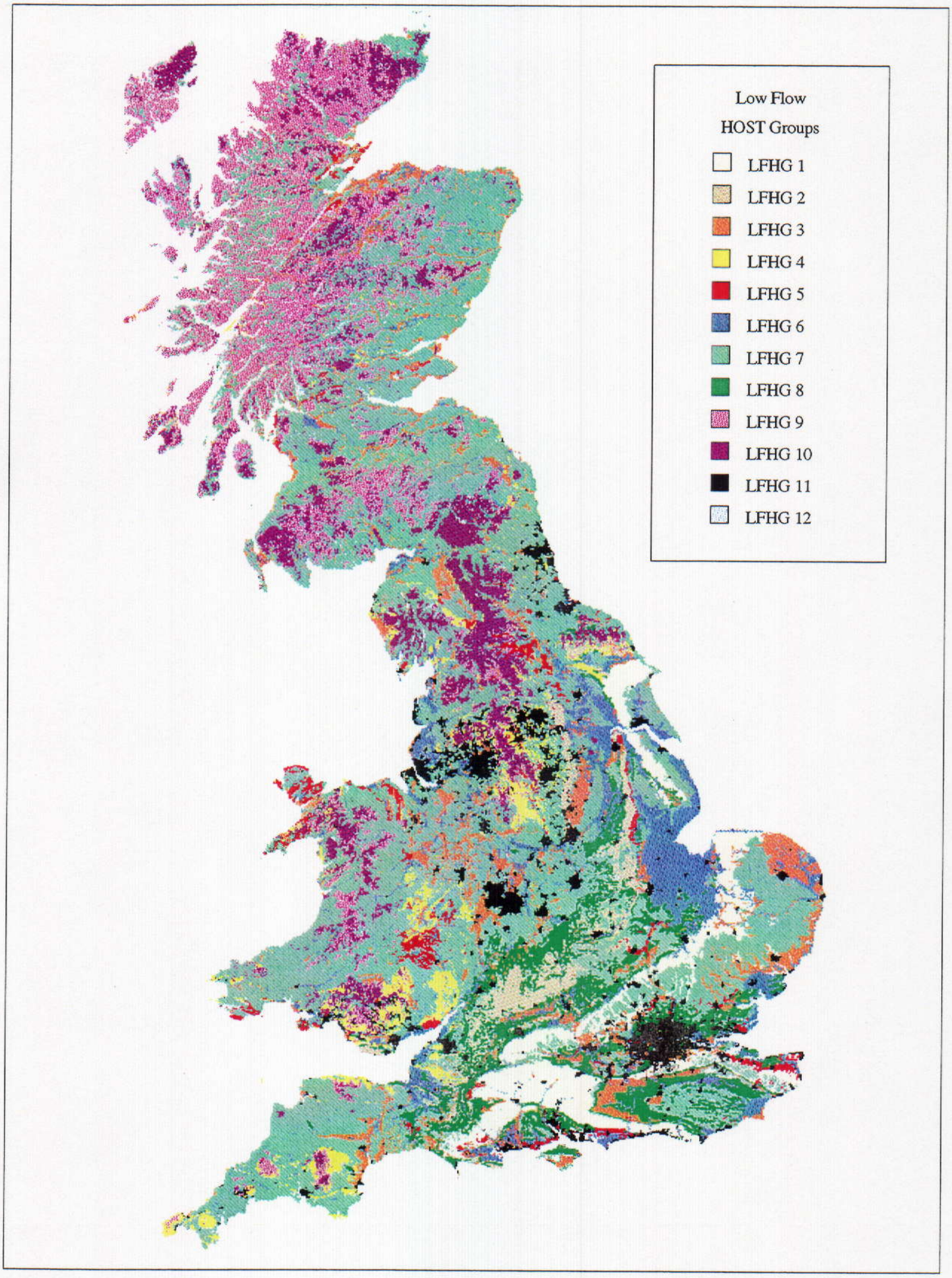

Figure 3.2 *Distribution of LFHGs in Great Britain*

At the 5% significance level, if T exceeds 1.96 then the mean days of occurrence are significantly different. A BFI of 0.2 has a corresponding mean day of occurrence of 194, as calculated from the regression equation given in Figure 3.3.

σ_1^2, σ_2^2 and $\bar{x}_2$ are all known and were therefore substituted into equation 3.1 to determine $\bar{x}_1$:

$$1.96 = \frac{\bar{x}_1 - 194}{\sqrt{20.24^2 + 20.24^2}}$$

Therefore, $\bar{x}_1$ is equal to 250 which, given the pooled variance, is significantly different (95% confidence) from day 194. The BFI associated with day 250 was determined from the regression equation, and is equal to 0.72. Therefore it may be implied, with 95% confidence, that on average a difference in BFI of 0.52 is required before a significant difference is observed in the mean day of occurrence. This compares to the approximate range of BFI values in the UK of 0.2 to 0.98, which represents a difference of 0.78.

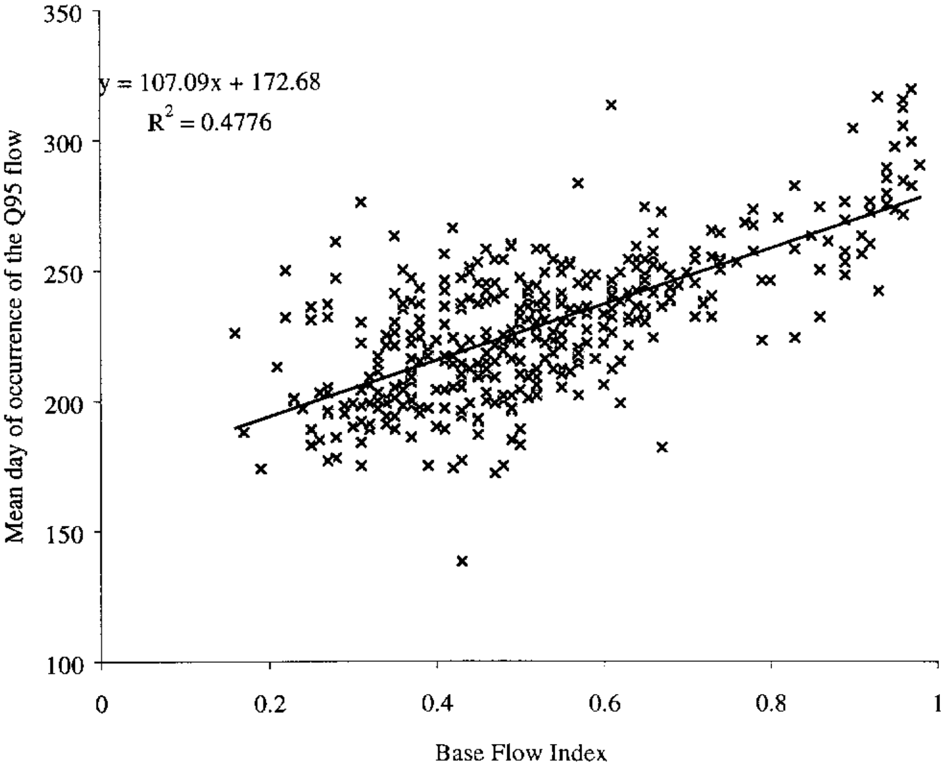

Figure 3.3 *Linear relationship between BFI and mean day of occurrence of the Q95 flow*

The nearest neighbour analysis was undertaken to determine the variations in the timing of the Q95 that are likely to occur over small distances. Therefore, the distances between the nearest neighbour stations was calculated to ensure that the pairs of stations were within a small distance of each other. The frequency distribution of the distance between these nearest neighbour stations is given in Figure 3.4 and shows that approximately 90% of the paired lay within a distance of 20km of each other.

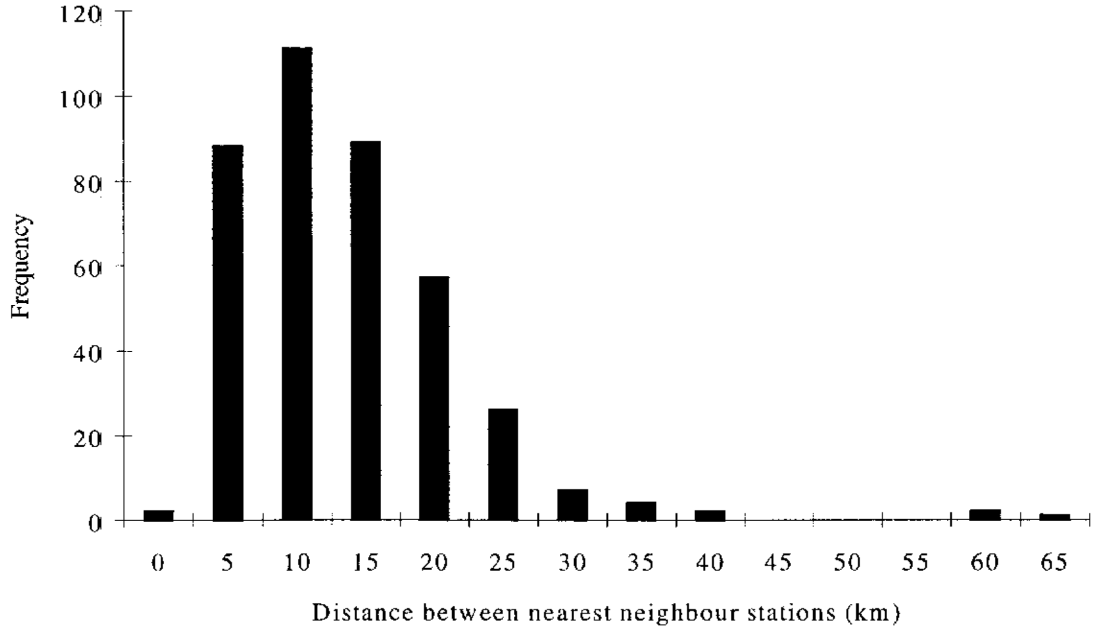

Figure 3.4 *Frequency distribution of distances between nearest neighbour stations*

The T-tests, which were used to test for a significant difference in the mean day of occurrence of the Q95 associated with the pairs of nearest neighbour stations, indicated that only two pairs of stations had significantly different mean days of occurrence. The two pairs of stations (36003 & 36005, 76011 & 23011) with significantly different days are detailed in Table 3.2.

Table 3.2 *Information of paired stations*

Nearest neighbour stations	SAAR (mm) (1941-1970)	Catchment area (km^2)	BFI	Distance between nearest neighbour stations (km)
36003	602	53.9	0.63	6.48
36005	602	156	0.46	
23011	1401	58.8	0.33	17.60
76011	1163	1.5	0.19	

The first pair of catchments represent the two driest catchments in the UK, where the effective rainfall is approximately 100mm. Therefore, the timing of the Q95 flow is more likely to be driven by climatic factors as opposed to the hydrogeological response. The second pair of catchments may have significantly different days of occurrence of the Q95 as a consequence of the large differences in the size of the catchments.

There are two possible explanations for the lack of significant differences in the mean day of occurrence in the remaining pairs of catchments:

1. There are only small differences in SAAR and BFI between the paired catchments. Approximately 90% of the paired catchments have a difference in BFI of less than 0.2 and a difference in SAAR of less than 350mm.

2. The magnitude of the variability around the mean day of occurrence, associated with each gauging station, is large compared to the magnitude of the difference between the mean day of occurrence of the paired catchments.

4. Quantification of the Q95 flow in the UK

4.1 INTRODUCTION

In Chapter 3 it was shown that significant differences in the mean day of occurrence of the Q95 do not generally occur in catchments with different rainfall and hydrogeological characteristics. This is due to the small differences in SAAR and BFI that occurs between nearby stations and also due to the magnitude of the variability around the mean day of occurrence. Since the ultimate concern of this study is to determine the effect of assuming that the Q95 is temporally coherent over all parts of the upstream network the Q95 was estimated for each pair of nearest neighbour catchments using various assumptions of the timing.

4.2 ANALYSIS

The Q95 was estimated for the hypothetical catchments, which derived by taking the nearest neighbour stations (Chapter 3), using the following three assumptions:

1. the Q95 occurs at the same time in both catchments;
2. the Q95 occurs on the mean day of occurrence of catchment one in both catchments;
3. the Q95 occurs on the mean day of occurrence of catchment two in both catchments.

In each case the Q95 was expressed as runoff with units of mmyr^{-1}, thus minimising the influence of catchment area on the scale of the runoff processes in each catchment. Under assumption one, the Q95 flows in each catchment were simply summed. Under assumption two, the Q95 in catchment one was added to the average flow that occurred in catchment two on the mean Q95 day of catchment one, and vice versa for assumption three.

Since assumption one is used in current low flow estimation procedures, the Q95 derived under this assumption was used as a benchmark to determine the percentage difference between the Q95 derived using assumption one and using assumptions two and three. Where a large percentage difference occurred in the Q95 estimates, the catchments were investigated to determine reasons for the differences.

4.3 RESULTS AND DISCUSSION OF THE QUANTIFICATION OF THE Q95

Figure 4.1 shows the frequency distribution of the percent difference between the Q95 derived using assumption one and the Q95 derived using assumptions two and three.

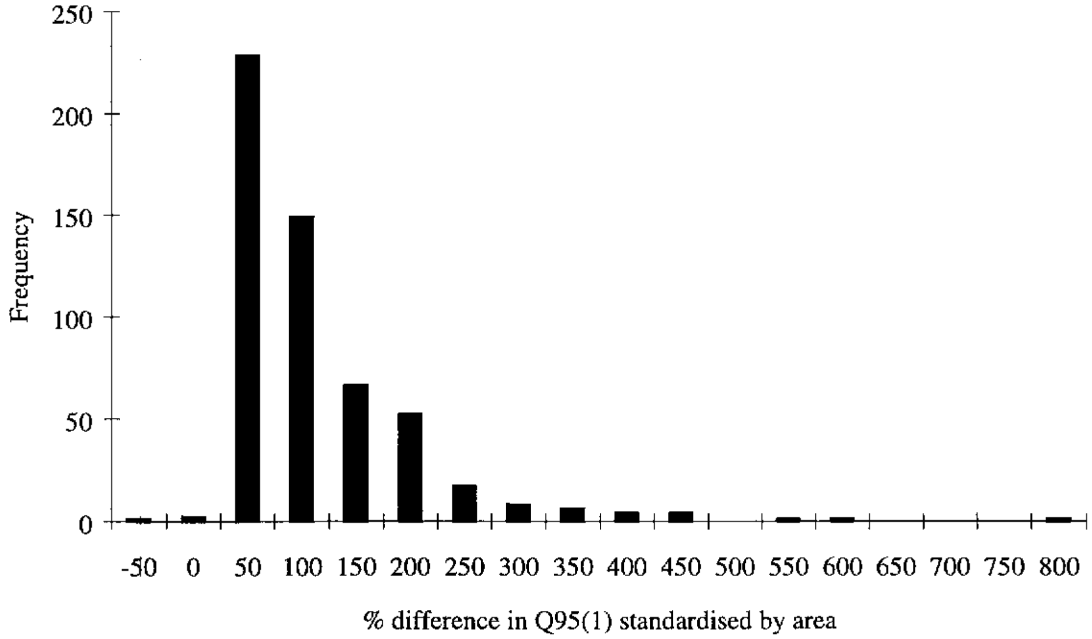

Figure 4.1 *Frequency distribution of differences in Q95*

Figure 4.1 shows that the distribution of percent differences in the Q95 is highly skewed, which indicates that most of the differences are small. The median percent difference is 56.19, and the 68% and 95% confidence limits are (25.86, 154.76) and (12.39, 324.47) respectively. It should be noted that only three of the percent differences are negative, which indicates that the assumption of temporal coherence usually results in an underestimate of the Q95.

Since the GREAT-ER project is concerned with a target accuracy of a factor of three, the pairs of catchments were split into two subsets based on differences in the Q95 of (1) less than 300%, and (2) more than 300%. Approximately 96% of the percent differences lie within a factor of three. Approximately 96% of the nearest neighbour pairs displayed a difference in Q95 of less than 300% (i.e. a factor of three). The mean BFI and SAAR values were derived for the catchments in both classes in order to identify whether the larger differences are associated with a certain type of catchment. Table 4.1 presents the results and implies that those nearest neighbour stations where a difference of more than 300% was observed in the estimates are generally wetter and more impermeable catchments.

Table 4.1 *Average BFI and SAAR for catchments with a < 300% and > 300% difference in estimated Q95*

Characteristic	Difference < 300%	Difference > 300%
BFI	0.54	0.37
SAAR (mm)	1057	1604

5. Conclusions

1. Differences in the timing of the mean day of occurrence of the Q95 flow can be identified. Significant differences do occur in the timing of low flows between catchments with different hydrogeological and rainfall characteristics. Low flows occur earlier in impermeable catchments, although there is some evidence of low flows also occurring earlier in wet permeable catchments.

2. However, this difference in timing at a daily resolution is not observed in the majority of nearest neighbour stations due to their similarity in SAAR and BFI and also the magnitude of the variability around the mean day.

3. The assumption of temporal coherence of low flows results in mostly smaller estimates of Q95 than those derived under the assumption that the low flows occur at the time of one of the upstream catchments.

4. 96% of the Q95 estimates derived using the assumption of temporal coherence are within a factor of three of the Q95 estimates derived the assumption that the low flows occur at the time of one of the upstream catchments. Those differences which are larger than a factor of 3 are generally observed in wetter and more impermeable catchments.

5. Assuming temporal coherence of the Q95 flow over all parts of the upstream network results in the largest underestimates of the Q95 in impermeable and wet catchments due to the large variability in daily flows that occurs over a small time scale. Since the timing is not significantly different at a daily resolution in such catchments, it is not practical to incorporate the effect that the flow variability exerts on the estimated Q95.

6. The recommendations of the study are to incorporate the timing of the Q95 at a monthly resolution, which Bullock *et al* (1994) found to be a significant unit of time.

References

Bayliss, A. & Jones, R. 1993. Peaks-over-threshold flood database: Summary statistics and seasonality. Institute of Hydrology Report No. 121.

Bullock, A., Gustard, A., Irving, K.M. & Young, A.R. 1994. Low flow estimation in artificially influenced catchments. National Rivers Authority R&D Report No. 257.

Gustard, A., Bullock, A. & Dixon, J.M. 1992. Low flow estimation in the United Kingdom. Institute of Hydrology Report No. 108.

Mardia, K. 1972. Statistics of directional data. Academic Press.

GREAT-ER

Working Note No.7

Low flow estimation in Yorkshire Final report

K. Croker, A. Young,
A. Sekulin and C. Round

This report is an official document prepared under contract between ECETOC and the Natural Environment Research Council. It should not be quoted by third parties without permission of both ECETOC and the Institute of Hydrology

---

Institute of Hydrology
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB

Tel: 01491 838800
Fax: 01491 692424
Telex: 849365 Hydrol G

January 1998

Executive Summary

The overall objective of the GREAT-ER project is to develop a geographically referenced risk assessment tool that can be applied to European rivers for estimating flows at ungauged sites, facilitating the simulation of the behaviour of pollutants along rivers. It has been recognised that, in order to produce flow estimates with the necessary level of confidence for use by non hydrologists in water quality modelling activities, it is necessary to incorporate the following into the existing low flow estimation methods:

1. The dependence of the seasonality of low flows on hydrogeology and rainfall;
2. The available local hydrometric data.

Significant differences in the timing of low flow events occur between catchments with different hydrogeological and rainfall characteristics. Previous studies (Bullock *et al,* 1994) had found that variations in timing were significant at a monthly resolution. However, the results of the analysis presented in Working Note 6 concluded that these variations in timing are not significantly different at a daily resolution due to the large variability in daily flows that occurs over a small time scale. It was recommended that the timing of the Q95 should be incorporated into the estimation procedures at a monthly resolution.

The objective of the hydrological modelling work in the UK is to improve the reliability of the flow estimates. This report presents the implementation of this objective through:

1. The development and implementation of techniques for incorporating the variation in the timing of low flow events into the existing estimation procedures, based on the conclusions of Working Note 6, to enhance the estimation of Q95;
2. The incorporation of a distributed approach, on a $1km^2$ grid cell basis, to improve the estimation of natural mean flow;
3. The development of techniques for incorporating measured flow statistics from nearby natural gauging stations into the estimation procedure;
4. The development of procedures for optimising the characterisation of complex artificial influences within the Yorkshire pilot study region, based on a generic top-down approach and incorporating the artificial influenced data from influenced gauging stations.

Techniques for enhancing the natural low flow estimation procedure are based on the aggregation of areas with similar hydrogeological characteristics in a catchment. For each similar hydrogeological unit, seasonal low flow statistics can be determined, making use of existing techniques for estimating monthly low flow statistics. The monthly statistics for each hydrogeological unit can then be recombined to derive a composite response for the whole catchment, thus incorporating the timing of low flows in different parts of the catchment. Using this technique, it was found that the differences in low flow estimates could be attributed to the climatic variations across the catchment.

Techniques were developed for fitting these revised low flow estimates to the flow values measured at natural gauging stations within the river network. The structure of the river network within Micro LOW FLOWS allows the locations of all upstream and downstream gauging stations to be identified. For each stretch, differences between the gauged and estimated mean flows can then be calculated and used to correct the natural estimates at gauged sites using a scheme based on weighting by differences in estimates of mean flow.

For the final calibration of the software, artificial influence data were provided by the North East Region of the Environment Agency and Yorkshire Water Services. This included details of 3000 abstraction licences, the 50 principal sewage treatment plants in the Region and the supply and compensation reservoirs in the Region. These data were quality controlled, re-formatted and loaded onto the Micro LOW FLOWS databases and artificial influenced estimates generated for key gauging station locations. It was assumed that the differences between the estimated and measured flow statistics were a result of an incomplete characterisation of the artificial influences. Therefore, techniques were developed to optimise the influenced estimates based on the artificially influenced flow statistics measured at gauging stations.

The calibrated model provides a significant improvement to the original estimation procedures. The artificial influence data available for Yorkshire can, in the European context, be thought of as being both readily available and of good quality. However, a significant amount of time was expended on quality controlling and correcting the many errors and inconsistencies found within these data before they could be used. This experience and the amount of effort required should be recognised when extending the coverage of GREAT-ER to other catchments within Europe.

Contents

1. Introduction

Variations in river flow regimes are dependent upon three key factors. On a regional scale, the flows will vary as a result of the synoptic weather patterns. In particular, the flows will be controlled by variations in rainfall, temperature and evaporation. On a local scale, the flows will be controlled by the physical properties of a catchment, including geology, channel and hill gradient, vegetation cover and the presence of lakes, marshes and glaciers. However, these climate and physical characteristics govern the natural flow regime. River flow regimes are also affected directly and indirectly by human activities such as reservoir impoundment, abstraction of water, effluent discharges and land use change. The impacts of these activities vary considerably and are dependent to a certain extent on the characteristics of the catchment.

Existing methods which are available for estimating flow statistics at ungauged locations are incorporated into Micro LOW FLOWS (© Institute of Hydrology). Simple conceptual models relate climate to mean annual runoff to obtain estimates of mean flow, while statistical models are used to determine low flow statistics from catchment hydrogeology.

There are several limitations associated with the current estimation procedures. Within the existing Micro LOW FLOWS V2.1 software it is assumed that the low flows occur at the same point in time for all stretches within a catchment, irrespective of hydrogeology and climate. In large catchments especially there are potential great spatial variation in the hydrogeology and both the timing and magnitude of rainfall. This presents the first of the potential limitations to the estimation procedures.

Within Micro LOW FLOWS V2.1 the locations of gauging stations and artificial influences are archived. This provides an invaluable geographic reference system within which the locations are highlighted on the river network. Associated with each gauging station are summary flow statistics derived from the flow records. Associated with each artificial influence are details of the abstraction, discharges or reservoir releases. Whereas the artificial influence data are used within the software to adjust the natural low flow statistics, there are no equivalent algorithms to take into account of the measured flow data. In the past, it has been the responsibility of the operational hydrologist to validate the natural low flow statistics using local data and hydrological experience. This presents the second of the limitations to the estimation procedures.

Therefore, with the aim of improving the reliability of the flow estimates within the GREAT-ER project and thus reduce the need for the input of an experienced hydrologist in interpreting the results, the objectives were to:

1. Develop techniques for incorporating the gauged flow statistics into the estimation procedure.
2. To investigate the timing of low flow events across the UK and to develop a technique for incorporate the variation in the timing of low flow events.
3. Calibrate the software for the Yorkshire region and assess the performance of the final model.

This report presents details of the refinements made to the Micro LOW FLOWS V2.1 software and the calibration of the software within the Yorkshire region. Chapter 2 presents details of existing methods which are available for estimating natural low flow statistics at ungauged locations. The quantification of the artificial influences is described in Chapter 3, which also presents the existing techniques used for deriving influence profiles. The implementation of the natural low flow estimation procedures and artificial influence adjustment techniques are summarised in Chapter 4. The incorporation of local hydrometric data from natural and artificially influenced gauging stations in the Yorkshire Region are discussed in Chapters 5 and 6. Finally, Chapter 7 provides an overview of the enhanced estimation procedures and conclusions from the present study.

2. Existing methods for estimating natural low flow statistics

The hydrological models within Micro LOW FLOWS are based on a simple conceptual water balance model for estimating mean flow (MF), and a statistical multivariate model for estimating the Q95 statistic (i.e. the flow equalled or exceeded for 95% of the time) from the hydrological response of soil types. The existing techniques for estimating annual and monthly low flow statistics are summarised in the following sections.

2.1 ANNUAL FLOW STATISTICS

The mean and Q95 flow statistics estimated from catchment characteristics are used to determine the flow duration curve (FDC) for an ungauged catchment. The overall estimation procedure is summarised in Figure 2.1. The following sections briefly summarise the individual stages in the estimation procedure.

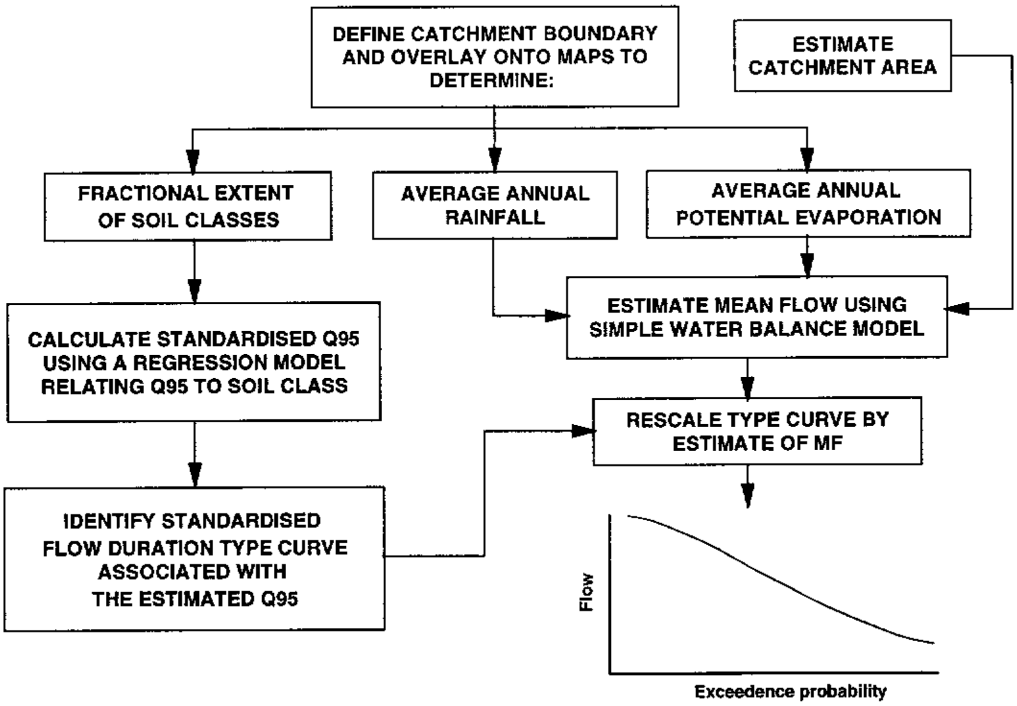

Figure 2.1 *Procedure for estimating natural long-term statistics*

2.1.1 Mean flow

The primary climatic variables used to estimate the mean flow are the Standard period (1941-70) Average Annual Rainfall (SAAR) and the average annual potential evaporation (PE) within the catchment. Digital databases of these variables are available from the UK Meteorological Office, which enables catchment boundaries to be overlain onto the grids and catchment average values of rainfall and evaporation to be determined. In the UK the average annual runoff depth is derived using a simple water balance given by:

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

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

The actual evaporation is equal to the potential evaporation in catchments with annual average rainfall in excess of 850mm since there are more likely to be only short periods when evaporation is limited by soil moisture deficit. Where evaporation is limited by rainfall (of less than 850mm), an adjustment factor (r) is applied to the potential evaporation. These simple relationships have been derived using climatic data and gauged runoff data from 687 catchments within the UK.

The long-term mean flow can be estimated from the average annual runoff depth in mm per year (AARD) over the whole catchment (AREA in km^2) using the equation:

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

2.1.2 Low flow statistics

The key low flow statistic used to characterise the low flow regime is the Q95. The standardised Q95 (%MF) is used in order to minimise the control of the catchment area and variations in the average rainfall and PE on the magnitude of the low flow statistic. Standardising the Q95 is an essential step prior to regionalisation.

A statistical multivariate regression model has been derived to relate the Q95 statistic to the hydrological characteristics of soils within gauged catchments. Within the UK, these hydrological characteristics of soils are represented by the Hydrology of Soil Types (HOST) classification (Boorman *et al*, 1992) which are grouped into Low Flow HOST Groups (Gustard *et al*, 1992).

2.1.3 Flow duration curve

The FDC represents the complement of the cumulative distribution of daily mean flows over a specific period. Using the FDC it is possible to identify the percentage of time that any given flow is equalled or exceeded. The gradient of a FDC is principally controlled by the catchment low flow response, as represented by the magnitude of the standardised Q95.

The procedure for deriving the long term flow duration curve at an ungauged site utilises natural long-term annual Q95 (as described above) to select a flow duration curve from a family of type curves (standardised by the mean flow) (Gustard *et al*, 1992). These type curves are illustrated in Figure 2.2.

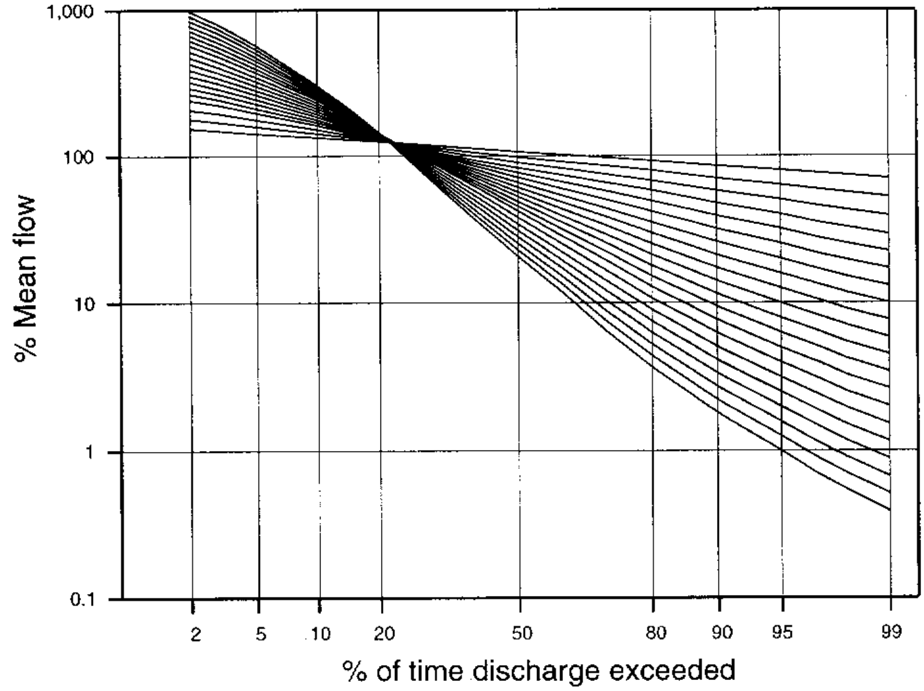

Figure 2.2 *Annual flow duration type curves*

2.2 MONTHLY STATISTICS

The overall estimation procedure for monthly statistics is summarised in Figure 2.3 and the individual steps in the estimation procedures are briefly discussed in the following sections. In common with the long term flow statistics and the key monthly statistics that need to be determined are the mean flow, the Q95 and the FDC.

2.2.1 Monthly mean flow

The derived monthly FDCs are normally expressed as a percentage of the monthly mean flow. In order to identify daily flow values (in cumecs) from the FDC, the monthly mean flow is required to re-scale the FDC.

The variability of monthly runoff volume (MRV) can be linked to the magnitude of the standardised Q95 statistic (i.e. the permeability of the catchment) (Bullock et al, 1994). In Great Britain, the more impermeable catchments (i.e. those with Q95 values of less than 30 % of the mean flow) demonstrate significant regional as well as seasonal variations in the magnitude of monthly runoff. Figure 2.4 illustrates the seasonal and regional variations in monthly runoff volumes for months May and November. For more permeable catchments in Great Britain (with Q95 flows greater than 30% of mean flow) and for catchments in Northern Ireland the spatial variability of MRV is not significant. The seasonal variations in monthly runoff volume for these catchments are presented in Tables 2.1and 2.2.

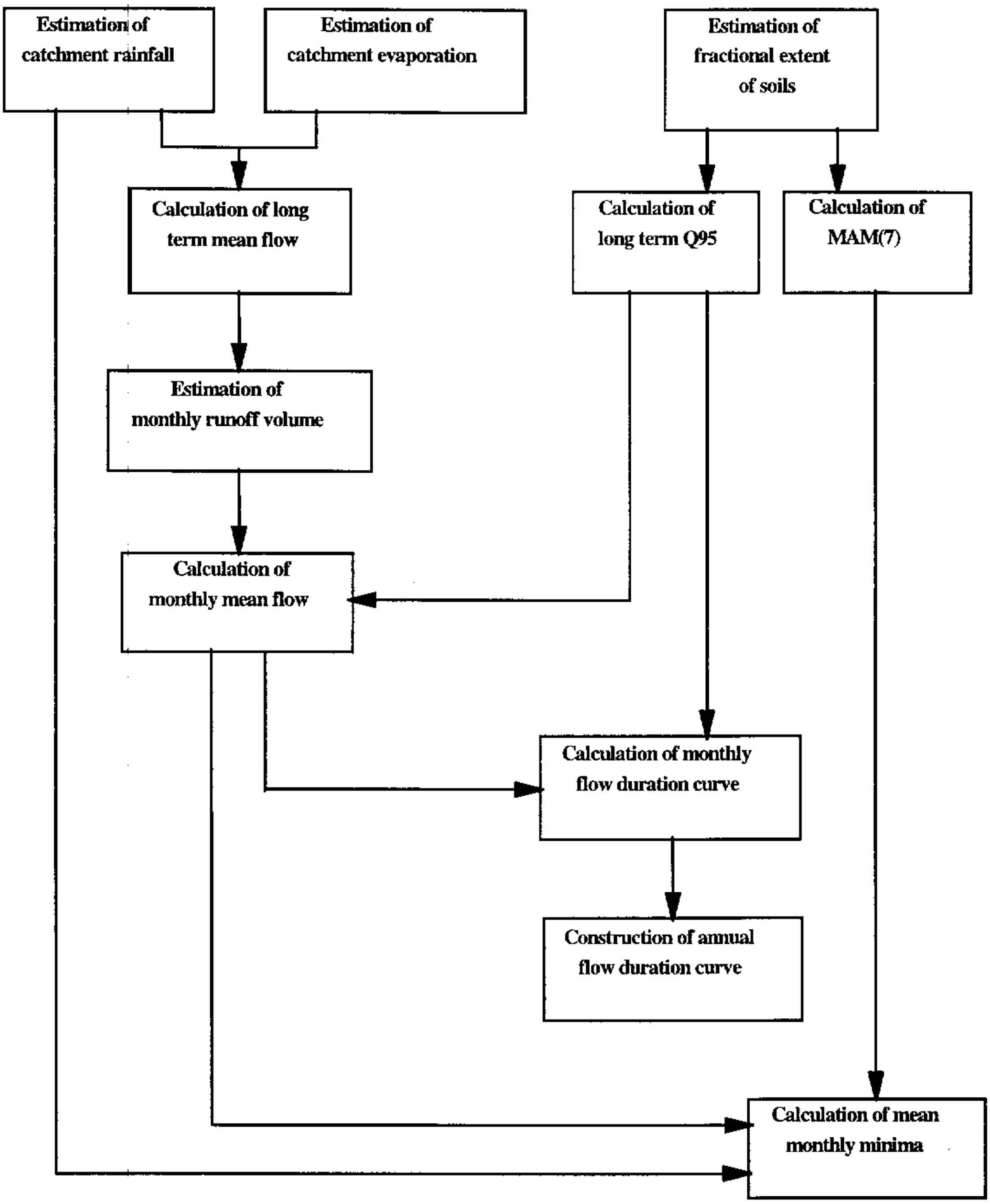

Figure 2.3 *Procedure for estimating natural monthly statistics*

Table 2.1 *Monthly runoff volume for catchments in Great Britain with Q95 >30%MF*

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

Table 2.2 *Monthly runoff volume for Northern Ireland catchments*

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

Having obtained the monthly runoff volume, the monthly mean flow (MMF) is calculated in cumecs within each month using the equation:

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

2.2.2 Monthly and reconstructed annual flow duration curve

The seasonal variations of the flow regime are lost when the flows are represented using the long-term annual FDC. However, Bullock *et al* (1994) identified that the functional form of the monthly curves, when expressed as a percentage of the monthly mean flow is consistent with the family of type curves used for estimating the annual FDC at an ungauged site. Therefore the existing type curves can be used to derive monthly FDCs.

In common with the annual FDC, the estimation of the standardised monthly FDCs requires the estimated natural long term Q95 to identify the appropriate type curves for the individual months. The most suitable type curve is selected from a matrix, given in Table 2.3, which represents the annual type curve which most closely matches the pooled monthly FDCs.

In order to make use of the monthly curves, it is important to ensure that the monthly curves can be combined to determine an annual curve, and that the composite curve is the same as that produced using the annual type curves directly to avoid inconsistencies. Therefore, this can be done by making corrections to the individual points of each curve.

Table 2.3 *Matrix of type curves for monthly pooled flow duration curves*

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

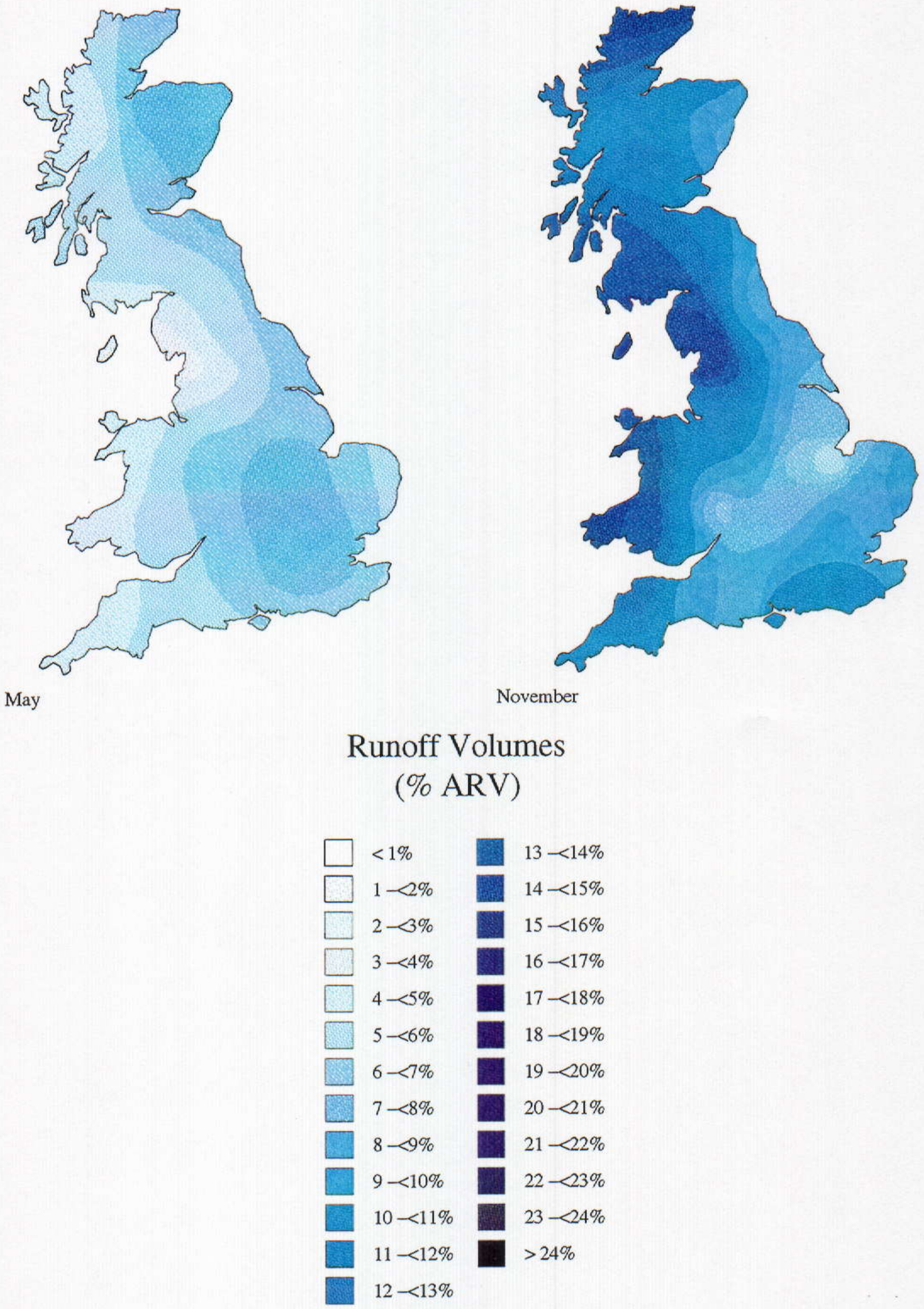

Figure 2.4 *Monthly runoff volumes (as a percentage of annual runoff volume) for May and November for catchments with a Q95 between 15-30% of the mean flow (Source: Bullock et al, 1994)*

3. Estimating artificial influence profiles

The historical level of river and catchment development for water resource purposes means that few rivers display natural flow characteristics. It has been estimated that in England and Wales fewer than 20% of gauged flow regimes represent 'natural' conditions (Bullock *et al*, 1994).

In order incorporate the impact of artificial influences on the natural flow estimates within the catchment, it is necessary to identify all upstream influences and quantify their cumulative impact at the site. Using the artificial influence data available, it is possible to generate net monthly influence profiles which can be applied to the natural monthly mean flow statistics and monthly FDCs discussed in Chapter 2. The impact of artificial influences is most severe during periods of low flows when the absolute volumes of water transfers represent a higher proportion of the natural flow regime. Therefore, using monthly profiles enables the seasonal variations in the natural flow regime and the seasonal operation of some influences to be taken into account.

This Chapter discusses some of the complexities in quantifying the artificial influences and ways in which profiles can be predicted in the absence of actual data.

3.1 TYPES OF ARTIFICIAL INFLUENCE

3.1.1 Abstraction licences and discharge consents

Simple abstraction licences can authorise fixed volumes of water transfer at fixed locations. However, in many cases, a licence can contain complex conditions for different seasonal periods, different locations and different purposes. The Environment Agency holds information on complex licences that permit the licence holders to abstract water under given constraints.

Within Micro LOW FLOWS these complexities are minimised by dividing the licence into an overall licence and a site licence. The key abstraction licence information required for establishing the monthly influence profile include:

(i) The source of the abstraction (Surface or groundwater abstraction). If the abstraction is from groundwater, then the aquifer unit needs to be specified.

(ii) The grid reference of each abstraction site.

(iii) The purpose(s) of the abstraction, which is important in determining the way in which monthly profiles are predicted (refer to Section 3.2).

(iv) The authorised annual abstraction quantity at each site and for each purpose, along with the period of abstraction during the year. If available, actual abstraction rates should be used.

(v) For certain purposes such as cooling water, some of the abstracted water is returned. If this returned water is not covered by a separate discharge consent, then a percentage return factor is required.

In general, in the UK, consents to discharge water to rivers are less complex than abstraction licences. In common with the abstraction licences, any complexities can be taken into account through an overall licence and a site licence. In addition the database structure allows for 12 monthly annual discharge rates to be included for each site. The key discharge consent information required for establishing the monthly influence profile include:

(i) The grid reference of each site and the river to which the discharge is made.

(ii) The type of consent, such as cooling water (returns) and domestic sewage.

(iii) The consented average and maximum discharge rates at each site and for each type. If available, actual discharges should be used.

(iv) The population equivalent.

(v) The Dry Weather Flow.

3.1.2 Impounding reservoirs

Abstractions and discharges represent simple outputs and inputs from the river (or aquifer). By comparison, the impact of impounding reservoirs is more complex. The reservoir provides storage for water supply purposes and the flow profile downstream of the dam is controlled by the compensation release policy of the reservoir. In many Environment Agency Regions, a number of reservoirs are linked through conjunctive use schemes.

A study of compensation flows in the UK was undertaken by Gustard *et al* (1987). This study was aimed at reviewing the existing levels of compensation flows, setting guidelines for determining flows below impounding reservoirs and establishing a national reservoir archive. The information held on the archive includes the following:

(i) The grid reference of the dam site.

(ii) The primary function of the reservoir, for example for hydropower, maintaining compensation flows, water supply or pumped storage.

(iii) The natural and total area draining into the reservoir.

(iv) The net and gross capacity of the reservoir.

(v) The natural and estimated mean flow at the reservoir outflow site or maintained flow point.

(vi) The compensation flow and the release policy, for example constant, seasonally varying or varying daily/weekly to maintain flows at some point downstream.

(vii) The natural yield of the reservoir.

In order to incorporate the impact of the reservoir into the adjustment procedures, an estimate of the typical monthly release flow in each month is required. Estimates of the release can be derived with reference to the compensation release policy if actual data are not available.

3.2 QUANTIFYING ARTIFICIAL INFLUENCES

3.2.1 Abstractions from surface water sources

In England and Wales abstractions are controlled by licences issued by the regulatory bodies. As part of the licence conditions, abstractors have a duty to provide the regulators with annual and monthly returns on the amount of water abstracted. The archiving of these data from returns is highly variable. Therefore, the information required to incorporate the impacts of abstractions into any estimation procedures may not be readily available for loading into the software. In addition, the quality of the annual data, especially for agricultural related abstractions, may not necessarily be reliable.

3.2.2 Abstractions from groundwater sources

Abstractions from groundwater sources do not have an immediate effect on the flows in the river. The impact of the abstraction will vary depending on the properties of the aquifer, such as the transmissivity and storativity, distance of the borehole from the river, the behaviour of the aquifer to the pumping regime and also on the hydraulic contact between the aquifer and the river bed.

Such complexities in trying to characterise the aquifers led to the adoption of the Theis model (Theis, 1941; Jenkins, 1970), a simple analytical model for predicting the impact of groundwater abstractions on streamflow, to assess twelve monthly stream depletion factors that could be applied to the monthly abstraction rates at a site (Bullock *et al*, 1994). There a number of major assumptions and simplifications associated with the Theis model, however the equations require a minimal amount of input data for describing the aquifer which make it suitable for implementation on a regional scale where the limiting factor is the paucity of the data.

3.2.3 Discharges

The mean monthly discharges are required to construct the monthly influence profiles for a site. The volumetric data relating to the actual discharge from sewage treatment plants is poorly monitored, therefore, in general, only a mean annual figure is provided on the discharge consent. In the absence of actual data, the mean monthly discharge can be represented by the design dry weather flow. This value is the design criteria for the works and represents only a crude guide to the true population, per capita water use, industrial effluent flows to sewer and mains leakage within the area served by the works. It also does not take into account storm discharges, although these are not an issue when assessing the volumetric impact on low flows.

3.2.4 Impounding reservoirs

The method for incorporating the impact of impounding reservoirs is equivalent to replacing the natural river flows and artificial influences upstream of the dam site by the monthly reservoir release profiles. The release profiles should combine compensation flows, reservoir spill, augmentation releases or freshets where appropriate.

Gustard *et al* (1987) found that there was no single method for setting compensation flows, and for many reservoirs, the operating authorities set compensation releases based on local factors and operating policies. Actual data for monthly reservoir releases and reservoir spill are not widely available in the UK. However, a simple approximation of monthly releases could be derived using the compensation flow given in the reservoir archive, distributed according to the compensation release policy.

3.3 CONSTRUCTING NET MONTHLY INFLUENCE PROFILES

The monthly influence profile at a site is the net balance, for any given month, of all upstream abstractions (subtractive influence), discharges (additive influence) and reservoir releases. In a catchment with only abstractions and discharges, a negative influence profile indicates that abstractions are dominant within a catchment. A positive influence profile indicates that discharges exceed abstractions within the catchment. In a catchment containing only abstractions (ABS) and discharges (DIS) the influence profile (IP) can be simplified to:

$IP_k = DIS_k - ABS_k$

where k = months 1 to 12

and DIS_k is indexed by

$$\sum_{i=1}^{n} \mathrm{SCAMTH}(i,k)$$

or

$$\sum_{i=1}^{n} \mathrm{SCPMTH}(i,k)$$

where SCAMTH(i,k) = actual monthly discharges for month (k) at site (i)
SCPMTH(i,k) = predicted monthly discharges for month (k) at site (i)

and ABS_k

$$\sum_{i=1}^{n} \mathrm{SACTMTH}(i,k)$$

or

$$\sum_{i=1}^{n} \mathrm{SPREPMTH}(i,k)$$

where SACTMTH(i,k) = actual monthly abstraction for month (k) at site (i)
SPREMTH(i,k) = predicted monthly abstraction for month (k) at site (i)

In a catchment containing an impounding reservoir, then the impact of all abstractions, discharges and reservoirs located upstream of the impoundment need to be discounted. The natural flow contributions from the catchment upstream of the reservoir should also be excluded and the monthly release profiles replace the natural flow at the site.

In practice, an appropriate catchment boundary can be defined which excludes the part of the catchment upstream of the reservoir and the catchment characteristics are, therefore, calculated for the portion of the (natural) catchment that occurs below the dam site.

Within Micro LOW FLOWS, this approach is not workable since the catchment boundaries are defined automatically. Therefore, an accounting solution, which discounts the contribution to flow from the catchment upstream of the dam site, is applied to implement the impact of the reservoir for downstream locations. This is described in Bullock *et al* (1994).

4. Implementation of the hydrological models within Micro LOW FLOWS

Micro LOW FLOWS provides a rapid and consistent method for estimating low flow and catchment characteristics at gauged and ungauged locations in the UK. The current version of the software implements the methods described in the IH Report 108 and the NRA R&D Note 274, as described in Chapters 2 and 3. Within the software the catchment characteristics, the mean and Q95 flows and FDCs can be generated automatically.

4.1 ESTIMATING CATCHMENT CHARACTERISTICS

Within the Micro LOW FLOWS software, a digital river network for hydrometric regions within the UK is archived, based on the 1:50 000 scale Ordnance Survey maps. Using the river network, catchment characteristics are automatically calculated through the generation of a synthetic boundary for the catchment above every stretch. The synthetic catchment area is determined by the number of grid cells, with a resolution of 0.5 km x 0.5 km, above each stretch. The grid cells are assigned to each stretch based on a shortest distance algorithm and constrained by digitised coastlines, hydrometric and catchment boundaries.

Digital databases of SAAR and PE are archived within the software as well as a grid of standardised Q95 derived using the HOST classification. All catchment characteristic grids are held at a resolution of 1 km x 1 km. For every cell assigned to each river stretch, a value of SAAR, PE and Q95 is known. Catchment average values of these climate and low flow characteristics can be determined by accumulating the number of squares above a given stretch and taking the average of the individual grid square values.

4.2 INCORPORATING ARTIFICIAL INFLUENCES

The software incorporates geographically referenced databases of gauging stations, licensed abstractions, consented discharges, impounding reservoirs and spot gauging information. Within the existing framework of Micro LOW FLOWS, the information relating to gauging stations and spot current meter readings are held for information only. The abstraction, discharge and reservoir information is used to make adjustments to the natural flow estimates.

The key step in the implementation of the adjustments is the construction of monthly influence profiles for twelve months based on the net impact of water use upstream of a location. The techniques available for quantifying the artificial influences were described in Chapter 3. Micro LOW FLOWS is able to:

1. Identify all occurrences of individual artificial influences upstream of a location. These influence features are attached to individual river stretches, therefore, when a stretch is selected, the number of stretches upstream of the point are known, and hence the details of the upstream influences can be identified.

2. Quantify the monthly abstractions, discharges and reservoir releases for each artificial influence based on the information archived. The databases have facilities to archive actual and predicted data, which can be edited as required.

3. Accumulation of individual upstream impacts to create a net monthly influence, applying the reservoir algorithms where appropriate.

4.3 ADJUSTING NATURAL LOW FLOW STATISTICS

Once the natural low flow statistics have been derived (Chapter 2) and the upstream artificial influence profiles generated (Chapter 3), then adjustments can be made to the natural monthly low flow statistics. The influenced monthly statistics can then be aggregated to provide estimates of the influenced annual statistics.

4.3.1 Mean flow

The net monthly influence profiles, reflecting the cumulative impact of all influences upstream of the site, are applied to the corresponding estimated values of natural monthly mean flows to calculate twelve values of artificially influenced monthly mean flows. Below the reservoir site, the basic adjustment algorithm is given by:

$$INF_kMF_{DS} = NAT_kMF_{DS} - NAT_kMF_{RS} + RR_k$$

where: NAT_kMF_{RS} = the natural monthly mean flow at the reservoir site (RS) for month (k)
INF_kMF_{DS} = the influenced monthly mean flow at the design site (DS) for month (k)
RR_k = the monthly reservoir release for month (k)

If the catchment contains abstractions and discharges between the dam and the design site, then the overall artificial influence algorithm for monthly mean flow becomes:

$$INF_kMF_{DS} = (NAT_kMF_{DS} - NAT_kMF_{RS}) + RR_k + (DIS_{kDS} - DIS_{kUI}) - (ABS_{kDS} - ABS_{kUI})$$

where: DIS_{kDS} = the sum of all discharges above the design site
DIS_{kUI} = the sum of those discharges upstream of the impoundment (UI)
ABS_{kDS} = the sum of all abstractions above the design site
DIS_{kUI} = the sum of those abstractions upstream of the impoundment

The artificially influence annual mean flow is then calculated as the weighted mean of the twelve values of INF_kMF_{DS} (where $k = 1$ to 12).

4.3.2 Flow duration curve

The estimation of 12 monthly FDCs, scaled by the natural monthly mean flow and fitted to the annual FDC, is a pre-requisite for estimating the impact of the artificial influence profile on the annual FDC.

The estimated natural monthly FDCs are each represented by 30 'daily' flows at equal probability intervals. It is assumed that the influence is constant within the month, therefore the net monthly influence profiles are applied to each 'daily' flow value within the corresponding month.

The principles for adjusting the FDCs are the same as for the monthly mean flow. i.e. that below the reservoir site:

$$INF_kFDC_{DS} = NAT_kFDC_{DS} - NAT_kFDC_{RS} + RR_k$$

where NAT_kFDC_{RS} = the natural FDC at reservoir site (RS) for month k
NAT_kFDC_{DS} = the natural FDC at the design site (DS) for month k
RR_k = the monthly reservoir release for month k

For abstractions and discharges downstream of the impoundment, the overall artificial influence algorithm for the monthly flow duration curve in month (k) is given by:

$$INF_kFDC_{DS} = (NAT_kFDC_{DS} - NAT_kFDC_{RS}) + RR_k + (DIS_{kDS} - DIS_{kUI}) - (ABS_{kDS} - ABS_{kUI})$$

Having adjusted the monthly FDCs for the impact of the influences, the 360 individual adjusted flow values are ranked in order of magnitude and an exceedance probability (P_n) assigned to each flow, based on the rank. The influenced annual FDC is therefore the resultant distribution derived by plotting the flows against the corresponding probability.

5. Enhancement of the natural hydrological model for the Yorkshire pilot study area

Within Micro LOW FLOWS, the low flow response of a catchment is determined from the average of all Q95 cells above the selected stretch. Therefore, this ignores any variations in the timing of low flows. The differences in the timing of low flows, as represented by the mean day of occurrence of the Q95 are discussed in the GRET-ER Working Note No. 6. The analysis showed that at a daily resolution a large difference in the Base Flow Index (BFI) was needed before the mean day of occurrence of the Q95 became significantly different. This was due to the large standard error observed around the mean day of occurrence.

However, Bullock *et al* (1994) demonstrated that on a monthly time scale variations did occur between different hydrogeological units. Therefore, a catchment above a stretch can be assumed to consist of a series of small 'sub-catchments', where each sub-catchment is determined by a discrete hydrological unit (i.e. Low Flow HOST Group). Within the estimation procedure, it is not necessary for these sub-catchments to be contiguous in space. Therefore, the low flow statistics can be calculated at a monthly resolution for each sub-catchment and the timing of low flows can be taken into account.

As described in Chapter 2, the annual runoff is based on a water balance where the actual evaporation is a function of the catchment rainfall. Therefore, a further benefit of considering the individual sub-catchments, is that it is possible to take into account the spatial variations in catchment rainfall and evaporation. This benefit is particularly important in upland catchments where the rainfall gradients across the catchment are significant; an adjustment factor can be applied to the potential evaporation in the low rainfall areas only. Within the procedures developed for Micro LOW FLOWS the distribution of the annual runoff has been taken one step further by calculating the runoff at a $1km^2$ resolution using this principle.

5.1 PILOT STUDY CATCHMENTS IN YORKSHIRE

The GREAT-ER pilot study is focussing on the subcatchments within the Yorkshire rivers. The enhanced hydrological model is being developed for the whole basin, although the incorporation of the artificial influences is restricted to the case study catchments. These case study catchments, the Calder, Aire, Went and Rother are described below.

5.1.1 River Calder

The River Calder flows from the Pennine Moors eastwards to its confluence with the River Aire at Castleford, a distance of 109 km (NRA, 1995) and draining a total area of 957 km^2. The catchment is heavily industrialised, including textile manufacturers, chemical plants and dye works. The parts of the catchment have been a traditional mining areas. Therefore, water from reservoirs, lakes and rivers is used to support these industries and also for public water supply. Some groundwater abstractions are made, which also provide for industrial purposes, although some parts of the Millstone Grit are exploited to provide some water for public water supply. Within the catchment, 39 impounding reservoirs and 23 sewage treatment works support a population of 790, 000. A further 4 reservoirs provide water for the canals.

5.1.2 River Aire

The headwaters of the River Aire drain from the carboniferous limestone on the edge of the Pennines, through Skipton, Keighly and the Leeds/Bradford conurbation, to its confluence with the River Ouse near Goole, an overall distance of 148 km. The area of the Aire sub-catchment is 1100 km^2, excluding the Calder catchment (NRA, 1993). In common with the Calder catchment, water is abstracted from reservoirs and rivers for public water supply and industrial use. Within the catchment there are 18 impounding reservoirs used for public water supply and one for supporting the Leeds/Liverpool Canal.

In contrast to the Calder catchment, the Aire is not self sufficient in the water resources available to support the population. A significant amount of water is transferred into the catchment from the Wharfe, Ouse and Derwent for public water supply. Domestic and trade effluent are discharged into the Aire and its tributaries. The overall impact of the transfer of potable water and discharging of treated effluent from 40 plants is that the flow in the river is significantly higher than the natural flows would have been.

In addition to the domestic and industrial population, abstractions within the Aire catchment support two large power stations, fish farms and industrial cooling processes. The impact of these abstractions are very much reduced, since a large percentage of the cooling water is returned to the river.

Abstractions from the Carboniferous limestone are predominantly used for industrial purposes. Water for public water supply is taken from the Sherwood Sandstone aquifers near Selby, Goole, Askern and Pontefract.

5.1.3 Don/Rother/Dearne system

The Upper Don is important for fisheries, recreation and conservation. Below Doncaster, the Lower Don is also becoming important for fisheries, although the continued development of fisheries is dependant upon improvements in the water quality. Tidal influences of the Humber Estuary reach as far as Doncaster and the river is very responsive to rainfall events as a result of steep-sided valleys in upper parts of the catchment, therefore much of the Lower Don is dominated by tidal and fluvial flood defences. The principal tributaries of the Don are the River Rother and the River Dearne in the Upper part of the catchment and the River Went in the Lower Don catchment.

There are a total of 19 reservoirs in the catchment, which are used for public water supply and also water for industry and agriculture. However, the Don catchment flows through densely populated and industrialised areas, therefore the overall water quality is poor due to the effluent discharges. A major problem is caused by the minewater discharges

5.2 INCORPORATING TIMING IN THE SOFTWARE

The overall procedure for incorporating the seasonal variations is summarised as follows:

1. Identify the extent of each hydrogeologically homogenous region as represented by the Low Flow HOST Group, in the catchment;

2. Consider each area of a single Low Flow HOST Group as a sub-catchment and estimate the monthly and annual mean flow and flow duration curves. The monthly curves are fitted to the annual curves for the sub-catchment to ensure mass is conserved between the monthly and annual flow duration curves;

3. Sum the monthly flow duration curves across the sub-catchments for each month, i.e. to produce a set of January curves, February curves etc, retaining a flag to indicate the month and sub-catchment;

4. Combine the monthly flow duration curves for the whole catchment to yield an annual curve for the whole catchment.

In order to incorporate the impact of timing, it has been necessary to make modifications to the software. These modifications have included:

1. Distribution of the mean flow model at a 1km^2 grid resolution;

2. Expansion of the database facilities within Micro LOW FLOWS to hold the fractional extent of Low Flow HOST Groups above every river stretch within the Yorkshire network;

3. Development of tree-walking algorithms to identify the fractional extent of Low Flow HOST Groups above each river stretch and associated fractional average values of the 24 monthly runoff grids, SAAR and PE grids;

4. Development of algorithms to estimate fitted monthly flow duration curves for each Low Flow HOST group above a river stretch;

5. Development of algorithms for summing monthly flow duration curves across Low Flow HOST Groups and subsequent recombination of composite monthly flow duration curves to yield an annual flow duration curve above each river stretch;

6. Development of comparison routines for assessing the differences between the existing flow duration curves for a stretch and the revised methods that incorporate the timing of low flow events.

5.3 ASSESSMENT OF THE RESULTS IN YORKSHIRE

The performance of the distributed estimation procedure has been assessed for locations in the Aire catchment. The distinct hydrogeological regions within the Yorkshire pilot study region used to determine the sub-catchments are illustrated in Figure 5.1. The chalk region of the Yorkshire Wolds (Low Flow HOST Group 1), the mudstones (Low Flow HOST Group 6), the glacial clay, sands and gravel deposits (Low Flow HOST Group 7) and the millstone grit of the Pennines (Low Flow HOST Group 10) are clearly identifiable.

In the Aire and Calder catchments, the urban conurbations dominate in the lower parts of the catchments, while the Millstone Grit of the upper Calder and limestone of the upper Aire are clearly visible. Figures 5.2 and 5.3 illustrate the distribution of mean flow and Q95, which reflect these geological characteristics.

The differences in mean flow and Q95, derived from the revised estimation procedure with the existing technique, are presented for the catchment above Beal Weir in Figures 5.4 and 5.5. The differences for specific locations within the Aire catchment are given in Table 5.1.

Table 5.1 *Percentage difference in the MF and Q95*

Location	Percentage change in natural MF	Percentage change in natural Q95
Beal Weir	1-2 %	-12 to -13 %
Knostrop STW	0 %	-1 to 0 %
Esholt STW	0-1 %	-4 to -5 %
Marley STW	0 %	-1 to 0 %
Snaygill STW	0 %	2 to 3 %
Gargrave STW	0 %	3 to 4 %

Comparing the mean flow and Q95 estimates on a stretch by stretch basis illustrates that differences between the two approaches becomes more significant as the variability of the hydrogeology within a catchment increases. In particular, from Figure 5.5 and Table 5.1 it can be seen that the distributed Q95 is significantly lower than the existing Q95 in the lower parts of the catchment but the differences become positive towards the top of the catchment.

The headwaters of the Aire rise on limestone moorlands around Malham. Further down the catchment, millstone grit becomes common between Skipton and Bradford. Coal Measures, consisting of shales, grits and coal seams dominate in the lower part of the catchment. The bottom of the catchment is made up of soft sandstone overlain by glacial and alluvial material. Therefore, the standardised Q95 will be higher in the more permeable lower parts of the catchment.

In addition, there is a significant rainfall gradient across the catchment such that in the upper part of the catchment, the mean annual rainfall is close to 1100mm compared to a mean annual rainfall of 600-650mm in lower part of the catchment the mean. Therefore, as a result of using the distributed model, the reduction factor is only applied to potential evaporation in the lower parts of the catchment where the annual rainfall is less than the threshold of 850mm.

Therefore, compared to the existing method, the overall impact on the flow estimates will be that the Q95, when expressed in cumecs, will be reduced in the lower parts of the catchment where the higher standardised Q95 response in this area is re-scaled by a smaller mean flow. The net effect over the whole of the Yorkshire region is for a negative change in Q95 in the lower catchment. The differences in Q95 reflect both the variations in the geological characteristics of the larger catchment and also the strong west-east rainfall gradient from the Pennines to the Vale of York.

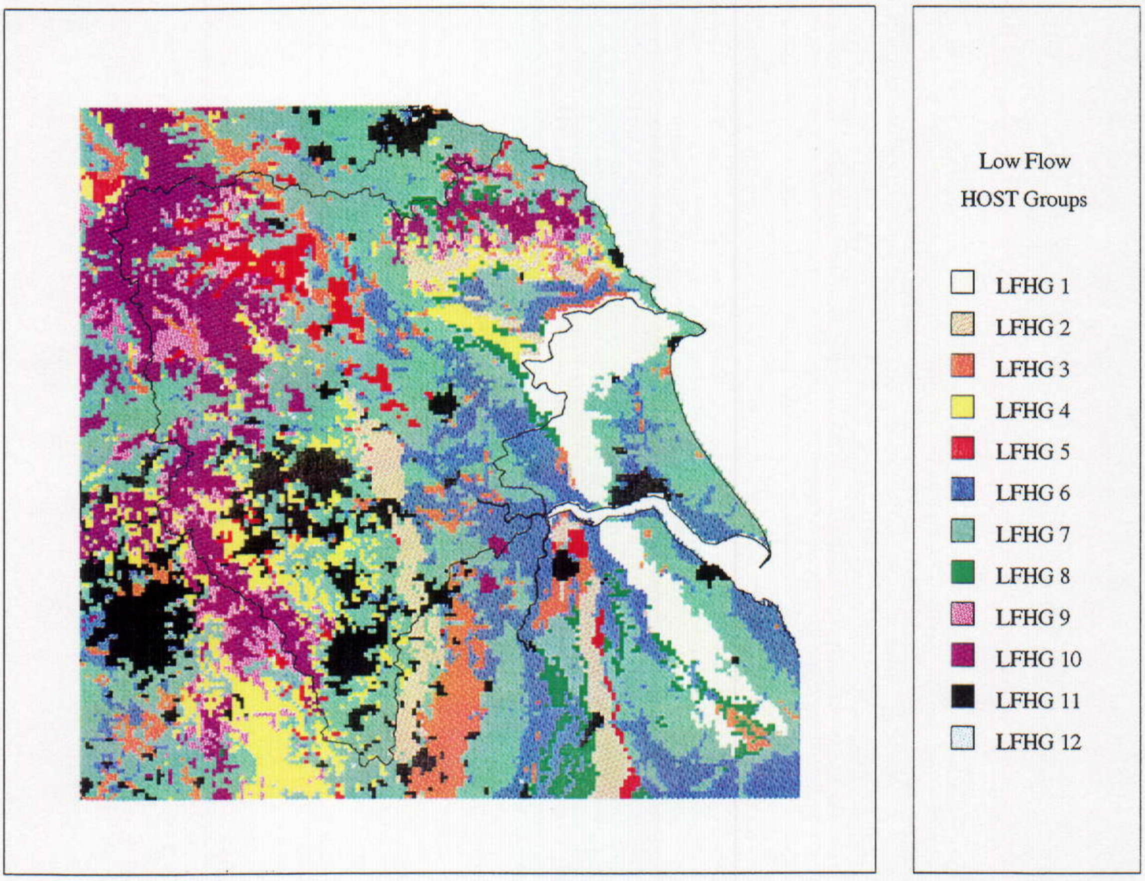

Figure 5.1 *Distribution of Low Flow HOST Groups in Yorkshire*

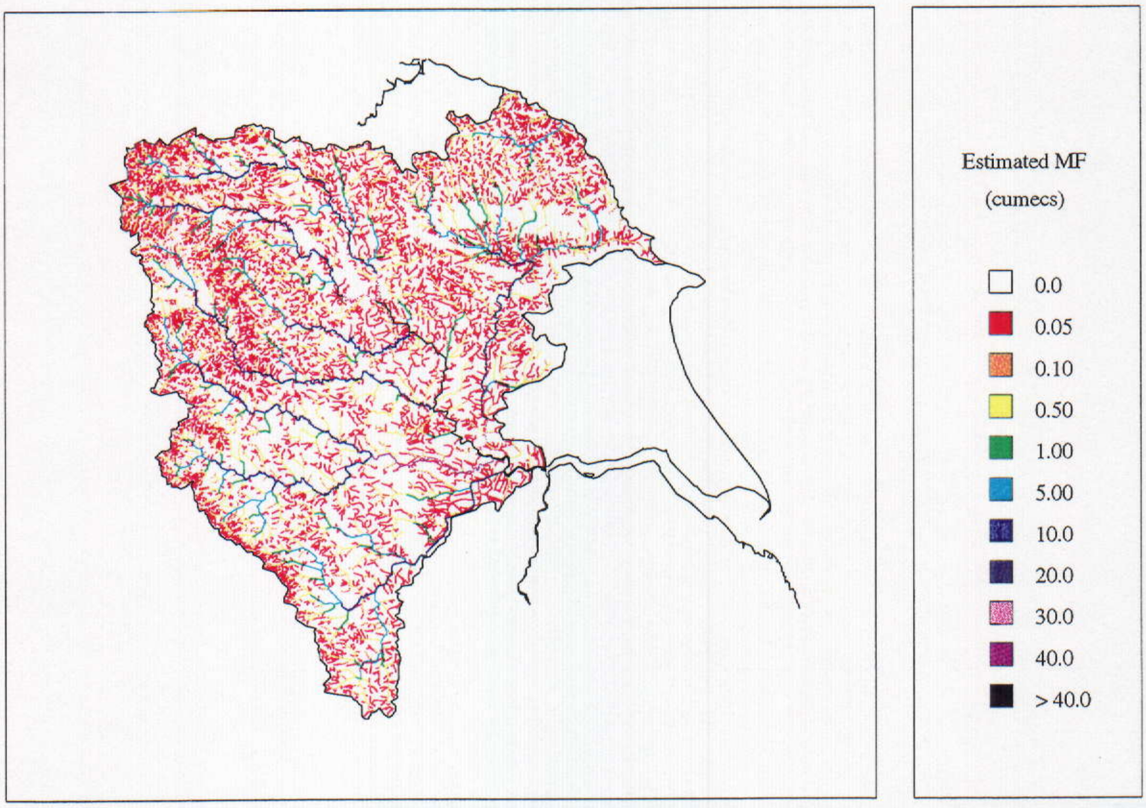

Figure 5.2 *Distribution of mean flow in Yorkshire*

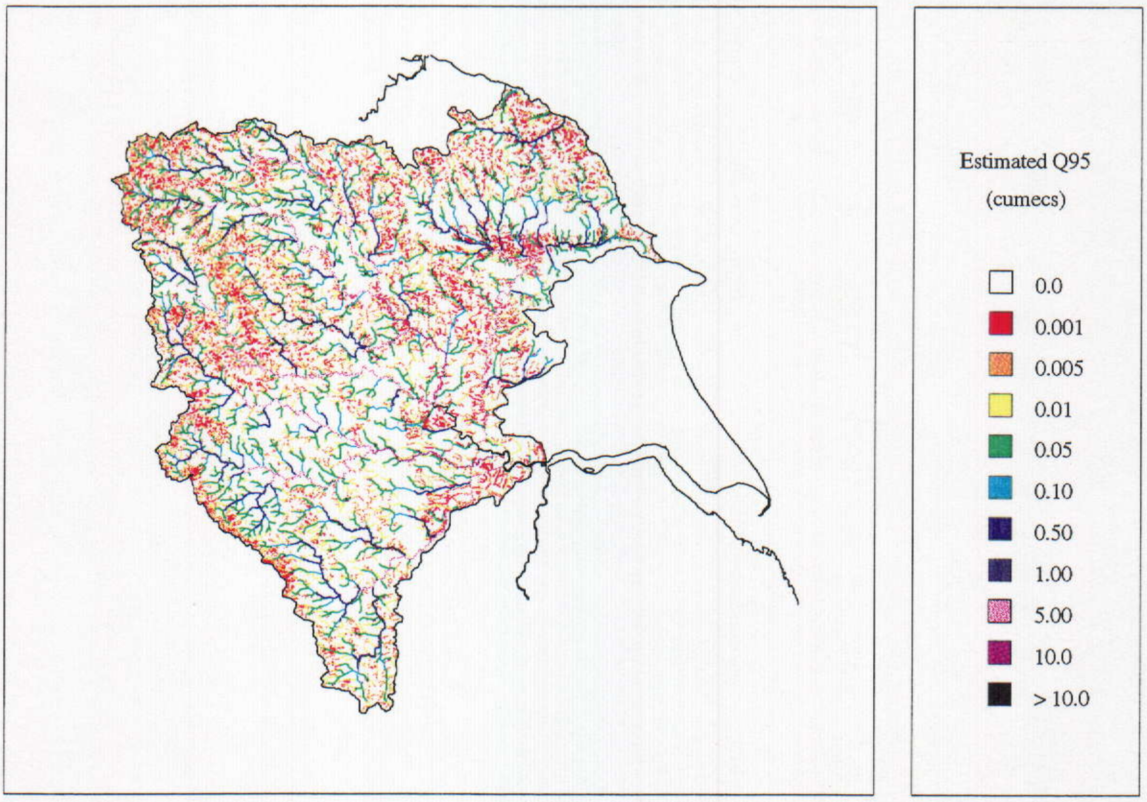

Figure 5.3 *Distribution of Q95 in Yorkshire*

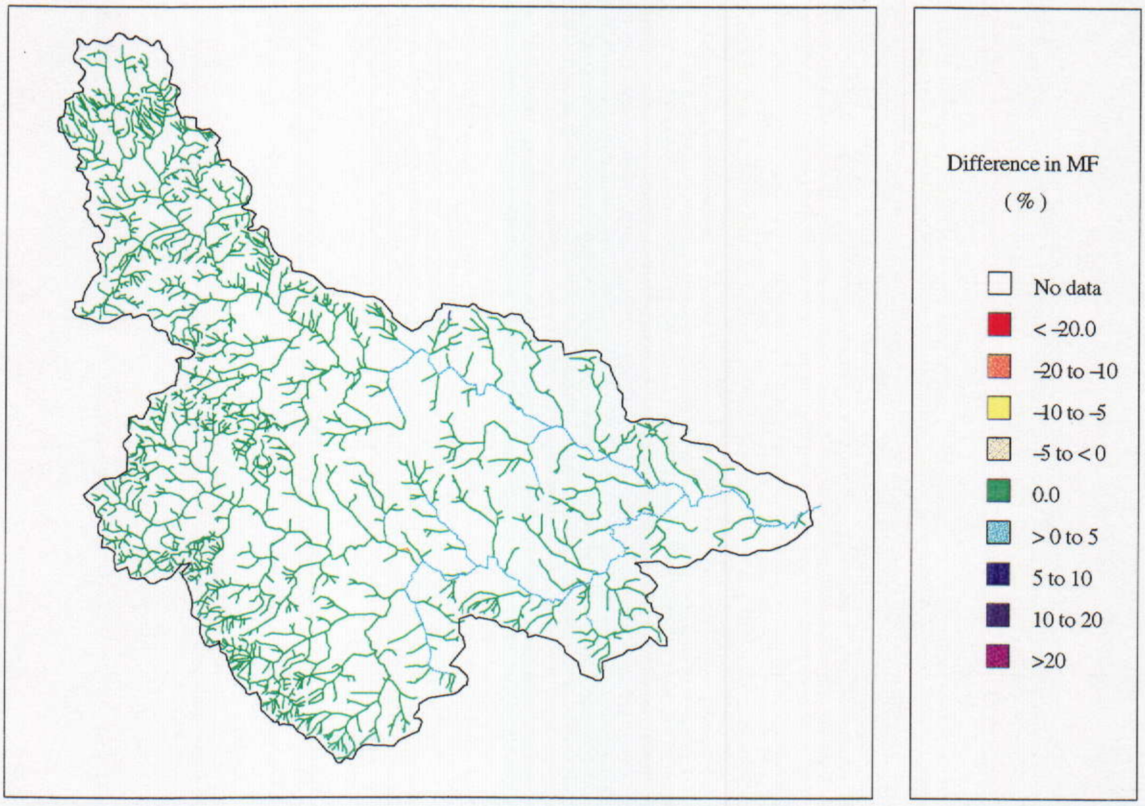

Figure 5.4 *Differences in the MF in the Aire catchment above Beal Weir*

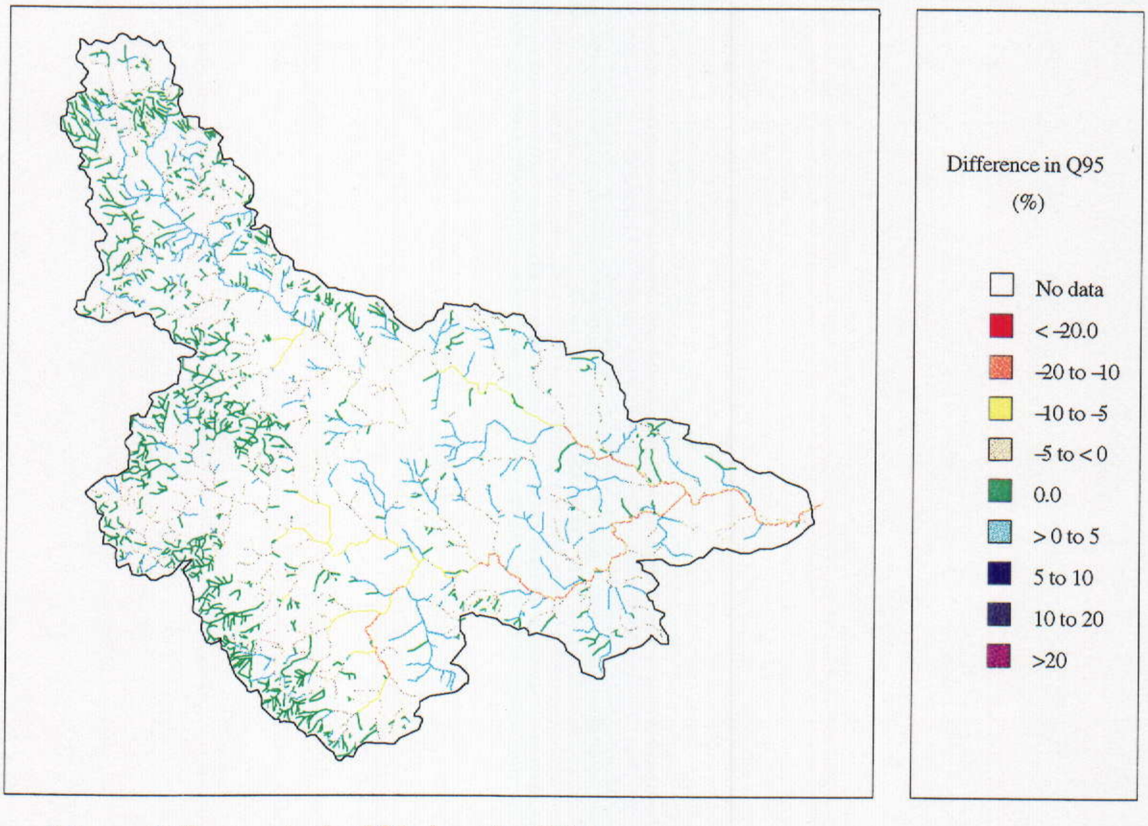

Figure 5.5 *Differences in the Q95 above Beal Weir*

6. Incorporation of local data from natural catchments within the Yorkshire region

Within the existing Micro LOW FLOWS V2.1 software, hydrometric and artificial influences are located by grid reference and attached to the digital river network by stretch. This provides an invaluable geographic reference system when the locations are highlighted on the river network. Measured flow statistics are held for the gauging stations whilst associated with each artificial influence are details of the abstraction, discharges or reservoir releases.

Whereas the artificial influence data is used within the software to adjust the natural low flow statistics, there is no equivalent algorithm to take into account the measured flow data. In the past, it has been the responsibility of the operational hydrologist to validate the natural low flow statistics using local data and hydrological experience. Therefore, techniques have been developed for incorporating gauged flow statistics into the estimation procedures in order to improve the performance of the mean flow model.

Only natural gauging stations are used to calibrate the natural mean flow statistics. Influenced stations with good hydrometric records are used to calibrate the influenced statistics, discussed in the next Chapter. The gauging stations have been selected initially on the hydrometric and artificial influence grades assigned by Gustard *et al* (1992).

6.1 QUALITY ASSESSMENT OF GAUGING STATIONS

Grades A to C have been assigned to gauging stations for both hydrometric quality and degree of artificial influence. Grade A represents high quality flow measurements, with little or no deterioration caused by siltation or weed growth and a gauged Q95 which is less than 20% different from the natural runoff estimated through naturalisation by decomposition. For a gauging station to be suitable for inclusion in the calibration, a grade of BB or better needs to be assigned. These stations are referred to as being "usable". Stations that are classified as AA are considered to be "pristine".

Within Hydrometric Area 27, there are a total of 86 catchments for which gauged flow data is available of which 24 are pristine, 46 are usable (and include the pristine stations) and 25 have good quality records, but contain significant artificial influences (graded AC). The usable stations are used in the calibration of the mean flow and the AC graded stations are incorporated in the second phase of the calibration of mean flow, where comparison of the influenced mean flows will be required. Table 6.1 lists the usable gauging stations which are available for inclusion in the calibration procedure.

Further investigation of the gauging station data identified catchments where the gauged runoff was not consistent with the catchment characteristics, illustrated in Figures 6.1 and 6.2. It was noted that the topographic boundaries for stations 27032, 27033, 27038 and 27047 were not coincident with the groundwater divide. This is also assumed to be the case for stations 27009 and 27071. For stations 27015 and 27041, flood flows from the headwater stretches were being diverted from the catchment. Other stations with anomalies were found to have hydrometric processing errors or insufficient length of record to provide reliable results. As a result, these anomalous stations were excluded from the model calibration.

Table 6.1 *Usable gauging stations available in the Yorkshire region*

Station	River	Location	Grade	Start year	End year
27002	Wharfe	Flint Mill Weir	BB	1980	1995
27007	Ure	Westwick Lock	AA	1958	1995
27008	Swale	Leckby Grange	BA	1955	1984
27009	Ouse	Skelton	BA	1982	1995
27010	Hodge Beck	Bransdale	BA	1936	1979
27015	Derwent	Stamford Bridge	AA	1961	1975
27023	Dearne	Barnsley Weir	AB	1960	1995
27024	Swale	Richmond	AA	1961	1980
27027	Wharfe	Ilkley	AA	1961	1975
27032	Hebden Beck	Hebden	AA	1966	1988
27033	Sea Cut	Scarborough	AB	1969	1995
27034	Ure	Kilgram Bridge	AA	1967	1995
27035	Aire	Kildwick Bridge	AB	1968	1995
27038	Costa Beck	Gatehouses	AA	1970	1995
27040	Doe Lea	Staveley	AB	1970	1995
27041	Derwent	Buttercrambe	AA	1973	1995
27042	Dove	Kirkby Mills	AB	1972	1995
27043	Wharfe	Addingham	AA	1974	1995
27044	Blackfoss Beck	Sandhills Bridge	AB	1974	1995
27047	Snaizeholme Beck	Low Houses	BA	1972	1995
27049	Rye	Ness	AA	1974	1995
27050	Esk	Sleights	AA	1970	1995
27051	Crimple	Burn Bridge	AA	1972	1995
27052	Whitting	Sheepbridge	AB	1976	1995
27054	Hodge Beck	Cherry Farm	AA	1974	1995
27055	Rye	Broadway Foot	AA	1974	1995
27056	Pickering Beck	Ings Bridge	AA	1974	1995
27057	Seven	Normansby	AA	1974	1995
27058	Riccal	Crook House Farm	AA	1974	1995
27059	Laver	Ripon	AB	1977	1995
27064	Went	Walden Stubbs	AA	1979	1995
27066	Blackburn Brook	Ashlowes	AB	1984	1995
27067	Sheaf	Highfield Road	AA	1984	1995
27069	Wiske	Kirby Wiske	AB	1984	1988
27070	Eller Beck	Skipton	AB	1986	1995
27071	Swale	Crakehill	AA	1980	1995
27072	Worth	Keighley	AA	1984	1995
27073	Brompton Beck	Snaignton Ings	AB	1984	1995
27075	Bedale Beck	Leeming	AA	1986	1995
27076	Bielby Beck	Thornton lock	AB	1986	1995
27077	Bradford Beck	Shipley	AB	1986	1995
27081	Oulton Beck	Farrer Lane	AB	1986	1995
27082	Cundall Beck	Bat Bridge	AB	1987	1995
27083	Foss	Huntingdon	AB	1987	1995
27084	Eastburn Beck	Crosshills	BA	1988	1995
27085	Cod Beck	Dalton	AB	1989	1992
27086	Skell	Alma Weir	AB	1984	1995

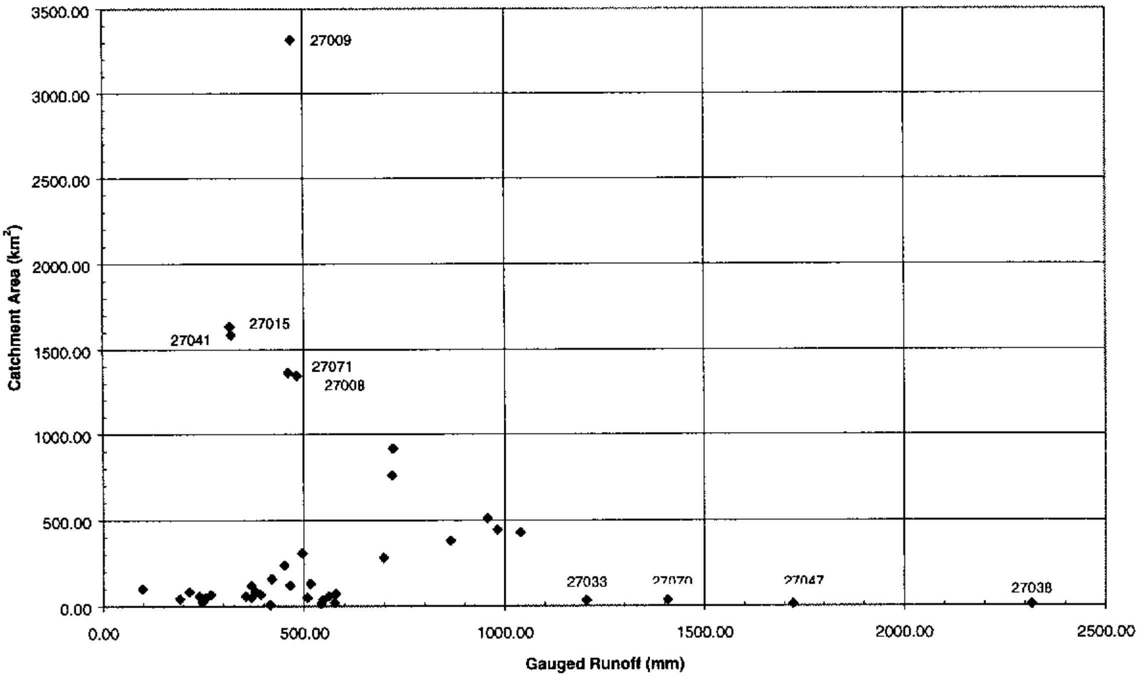

Figure 6.1 *Gauged effective runoff against catchment area*

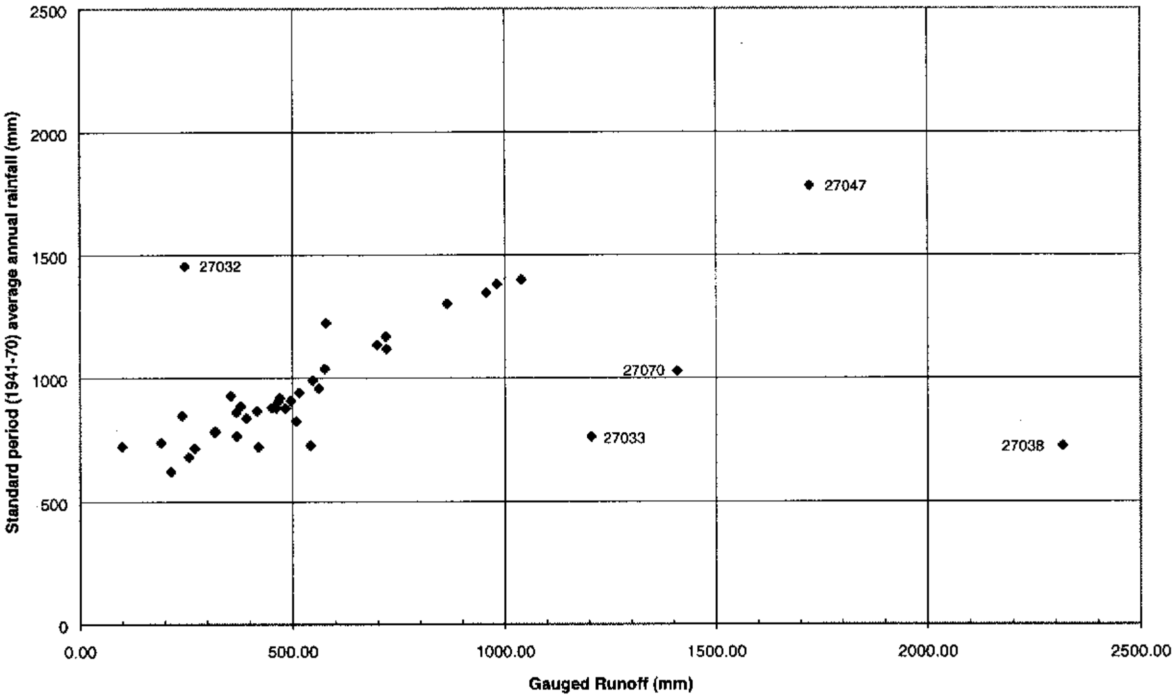

Figure 6.2 *Effective runoff against Standard period (1941 – 70) Average Annual Rainfall*

6.2 CALIBRATION OF MEAN FLOW

The enhancement to the natural mean flow estimates derived by the software is based on fitting the estimated mean flow to the mean flow measured at nearby natural gauging stations. For any stretch, the locations of all gauging stations upstream of the stretch and the next downstream gauging station along the main stream channel can be identified. The branching structure of the river network means that each stretch can have one associated downstream gauge, but several associated upstream gauges, illustrated in Figure 6.3.

In headwater stretches (e.g. at Site 1), the natural estimates of mean flow for all stretches upstream of gauging stations are fitted using a simple error correction factor derived from the downstream gauge (Gauge b). Further downstream (e.g. at Site 2), the correction factor is determined by weighting the errors associated with all upstream and downstream gauges (Gauges a, b and c). For stretches downstream of the lowest gauging station in the system (e.g. Gauge c), the errors associated with the gauging station are applied to the natural mean flow estimates (at Site 3). Only natural gauging stations are used to determine the correction and weighting factors.

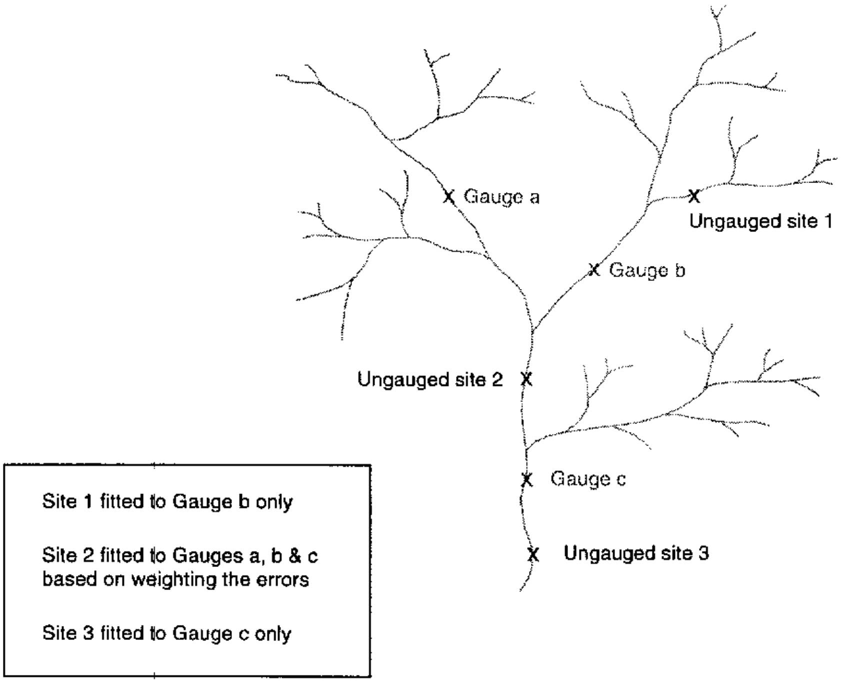

Figure 6.3 *Identification of upstream and downstream gauging stations*

Therefore, for each ungauged stretch (i), the correction factor (CF) is calculated from the upstream and downstream natural gauges that directly affect the stretch using:

$$CF(i) = \frac{MF_{gauge(i)}}{MF_{est\_g(i)}} - 1$$

where:

$MF_{est\_g(i)}$ = mean flow estimated at gauging station (i)
$MF_{gauge(i)}$ = mean flow measured at gauging station (i)

This factor will be zero if the measured and estimated values are the same, negative if the measured mean flow is less than the estimated mean flow for the stretch and positive if the measured mean flow is greater than the estimated mean flow for the site.

Assuming (n) natural gauging stations affecting the ungauged site (e.g. at Site 2), then a weighting factor must be applied to each correction factor based on the similarity of the estimated mean flow at the gauged location to that at the ungauged location. A greater weight is applied to gauging stations where the estimated mean flow is similar to that of the ungauged site. Therefore, for stretches where the estimated mean flow at the site is less than the estimated mean flow at gauging station (i.e. the gauge is downstream of the estimate site), the weighting factor (WF) is determined by:

$$\mathrm{WF(i)} = \frac{\mathrm{MF_{est\_s(i)}}}{\mathrm{MF_{est\_g(i)}}} \qquad \mathrm{WF(i)} \leq 1$$

and for stretches where the estimated mean flow at the gauging station is less that estimated mean flow at the site (i.e. the gauge is upstream of the estimate site), the weighting factor is determined by:

$$\mathrm{WF(i)} = \frac{\mathrm{MF_{est\_g(i)}}}{\mathrm{MF_{est\_s(i)}}} \qquad \mathrm{WF(i)} \geq 1$$

where

$\mathrm{MF_{est\_g(i)}}$ = mean flow estimated at gauging station (i)
$\mathrm{MF_{gauge(i)}}$ = mean flow measured at gauging station (i)
$\mathrm{Mf_{est\_s(i)}}$ = mean flow estimated at the site (i)

Therefore, for all stretches above the most downstream gauging station, the overall correction factor for the site (s) is calculated by:

$$\mathrm{CF_s} = \frac{\sum_{i=1}^{n}(\mathrm{WF(i)\ x\ CF(i)})}{\sum_{i=1}^{n}\mathrm{WF(i)}}$$

and the calibrated mean flow for the site ($\mathrm{MF_{cal\_s}}$) is given by:

$$\mathrm{MF_{cal\_s}} = \mathrm{MF_{est\_s}}\ \mathrm{x}\ (1+\mathrm{CF_s})$$

If the site is downstream of the lowest gauging station in the system (e.g. at Site 3), then the calibrated mean flows is given by:

$$\mathrm{MF_{cal\_s}} = \mathrm{MF_{est\_s}} + (\mathrm{MF_{gauge}} - \mathrm{MF_{est\_g}})$$

Figure 6.4 illustrates the mean flow for the usable gauging stations in Yorkshire estimated within Micro LOW FLOWS using the different methods. It can be seen that there is very little difference between the distributed mean flow (i.e. runoff calculated on a $1\mathrm{km}^2$ grid square basis) and the mean flow derived using the existing method. The majority of these estimates are within the confidence limits of the models (i.e. factorial standard error of 1.22). The calibrated mean flows are now equal to the observed natural mean flow values. The improvements in the estimation procedure using the calibration technique are particularly noticeable in the small catchments, where previously the limitations caused by the grid resolution have been a problem.

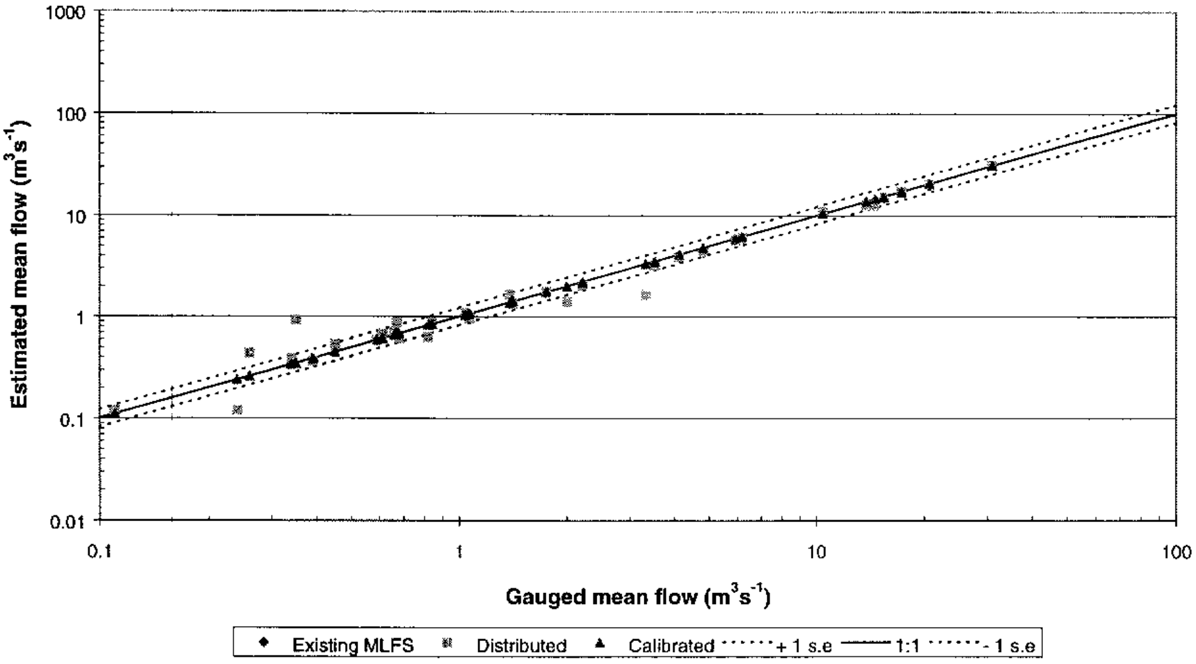

Figure 6.4 *Micro LOW FLOWS estimates of mean flow*

7. Incorporation of the impacts of artificial influences within the Aire and Calder catchments

Artificial influence data for calibrating the hydrological model have been provided by the Environment Agency and Yorkshire Water Services. Information on abstractions, reservoirs and 50 principal sewage treatment plant discharges operated by Yorkshire Water Services has been collated. The data have been loaded onto the databases within the enhanced Micro LOW FLOWS software and techniques have been developed to calibrate the software, based on optimising the characterisation of abstractions through comparison of influenced estimates of mean flow with the gauged flows from nearby influenced gauging stations.

7.1 ARTIFICIAL INFLUENCE DATA

7.1.1 Abstraction data

The Environment Agency provided data for in excess of 3000 sites for the whole of Yorkshire, with approximately 500 sites in the Aire and Calder catchments. The data contained licence details including licensed quantities, licence periods and time series of actual annual abstraction volumes for the past 10 years. Using the actual abstraction volumes, an average annual abstraction rate was calculated for each purpose and site. The distribution of abstractions within the Aire and Calder catchments is illustrated in Figure 7.1.

Within Micro LOW FLOWS, the techniques for incorporating artificial influences requires the identification of net monthly influence profiles upstream of a stretch (refer to Chapter 3). Therefore the annual abstraction rate was distributed over twelve months according to the seasonal period specified on the licence. Where no seasonal period was specified, the distribution was based on existing knowledge of typical profiles for different abstraction purposes.

Within the Aire and Calder catchments Figure 7.2 presents the percentage of total abstractions above each gauging station for different purposes above gauging stations. This demonstrates that in the Calder catchments, industrial purposes represent the greatest percentage of the total number of abstractions. By comparison, the greatest percentage of abstraction purposes in the Aire catchment is for public water supply. However, the total licensed abstraction for each purpose upstream of the gauging stations in both the Aire and Calder sub-catchments indicates that the greatest proportion of the abstracted volume for cooling water, with public water supply representing the second. This is illustrated for the Calder catchment in Figure 7.3.

7.1.2 Discharge data

Information on the 50 principal discharges in the Aire, Calder & Don-Rother catchments were provided by Yorkshire Water Services. The locations of the treatment plants in the Aire/Calder catchment above Beal Weir are illustrated in Figure 7.4.

The discharge consents provided figures for the dry weather flow (DWF), average daily flow (ADF) and Flow to Full Treatment (FFT). Although the ADF (in cumecs) may be assumed to represent the actual discharge, the measurement will include some component of runoff from the catchment (i.e. through infiltration, streams diverted to sewers and surface runoff into the combined sewers) which are already taken into account within the natural flow estimation procedure. It was therefore felt that, unless a better estimate of the foul component of the measured discharge could be provided, the design DWF would still be used to represent the monthly discharge profile to minimise 'double accounting'. Generally, the DWF figure was slightly lower than the ADF for plants.

No information has been provided for discharge consents from other, less important, wastewater treatment plants in the Aire and Calder catchments. Additionally, no information has been loaded to represent discharges from non YWS consents. The total consented dry weather flow from the supplied consents above gauging stations in the Aire & Calder catchments are presented in Figure 7.5

7.1.3 Reservoir release profiles

The extent of available information for the impounding reservoirs in the Yorkshire Region was previously identified and summarised in the GREAT-ER four month progress report for the period February 1996 to May 1996 (Institute of Hydrology, 1996). Information had been obtained from the following sources:

(i) A study of compensation flows in the UK, Report 99. Institute of Hydrology, 1987

Reservoirs with a capacity greater than 500Ml or a catchment area greater than 5km^2 were listed and included information on the amount of compensation release and/or the release policy from the reservoirs. Where multiple reservoirs were linked in a system of supply only and compensation reservoirs, the lowest reservoir (usually compensation only) was taken to represent the whole system.

(ii) Reservoirs Act 1975: Register of Dams. Building Research Establishment, 1994

All dams in the UK that were believed to have been covered by the Reservoir Act 1975 were listed. However, the database includes numerous service reservoirs and works that are not be relevant to the requirements of this study, and have been excluded.

(iii) Catchment Management Plans. National Rivers Authority.

Subsequent information was made available from the Environment Agency, including detailed descriptions of the reservoir structures and the relevant Water Resource/Reservoir Acts that specified the compensation release requirements. For selected reservoirs, additional time series information of compensation releases and overflows were provided by Yorkshire Water Services via the Agency. From this data average monthly release profiles from the reservoirs were determined. It should be noted that the time series of reservoir data were provided in a variety of different formats and corresponded to data given in different units (not always documented). Therefore considerable effort was required by the Institute of Hydrology to process the data in order to be able to calculate monthly release profiles in cumecs and to cross reference the profiles with figures provided in the printed material (either the notes provided by the Agency or the IH Reservoir Archive).

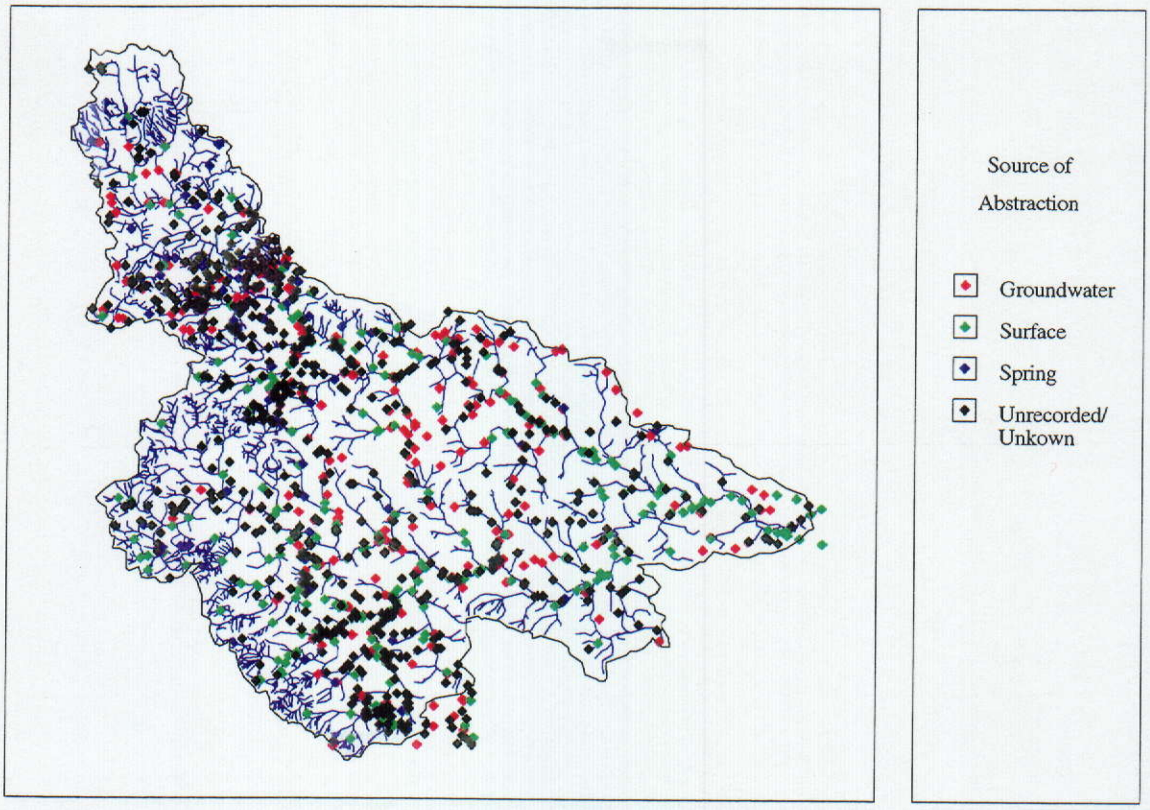

Figure 7.1 *Abstraction sites above gauging stations in the Aire and Calder catchments*

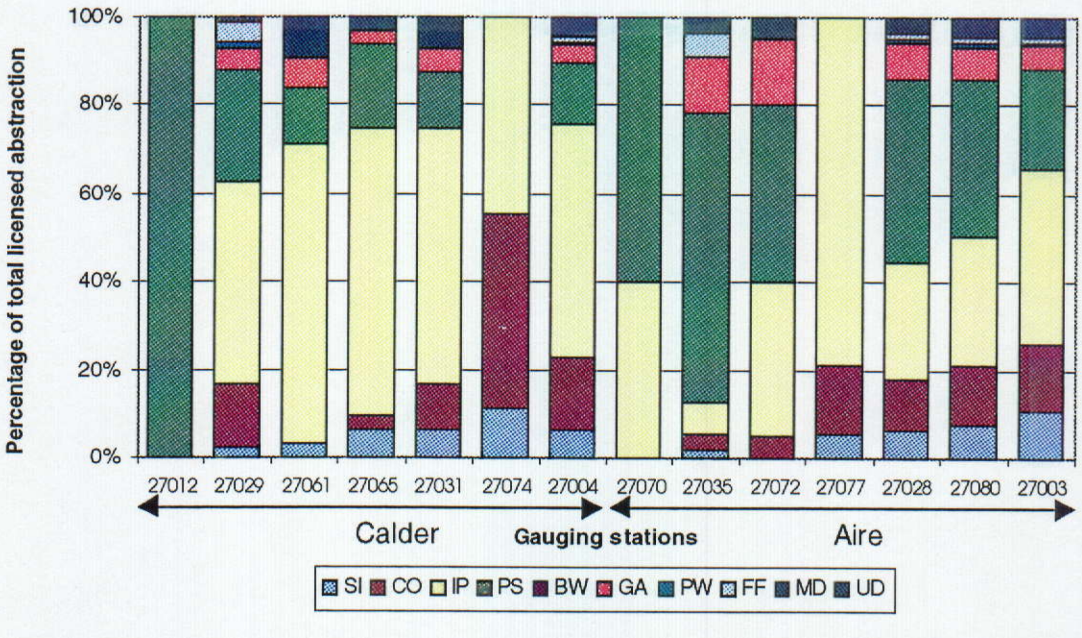

Figure 7.2 *Abstraction purposes above gauging stations in the Aire and Calder catchments*

Note: SI = Spray Irrigation; CO = Cooling Water; IP = Industrial Processes; PS = Public Water Supply; BW = British Waterways; GA = General Agriculture; PW = Private Water Supply; FF = Fish Farming; MD = Mine Drainage; UD = Undefined

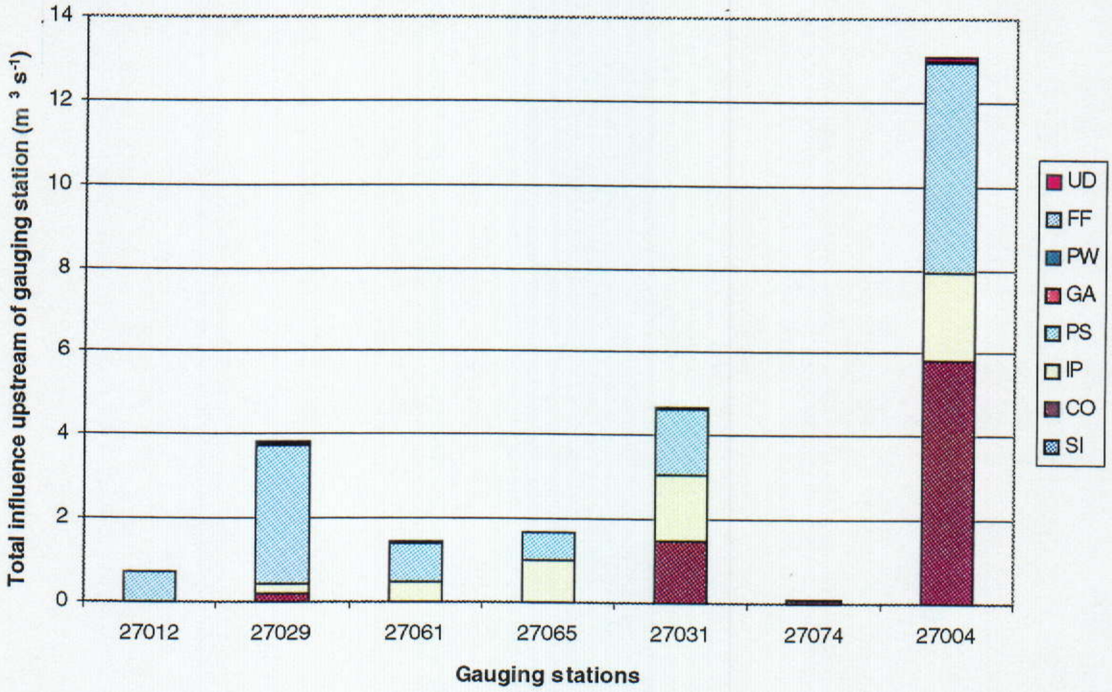

Figure 7.3 *Total abstractions upstream of gauging stations in the Calder catchment*

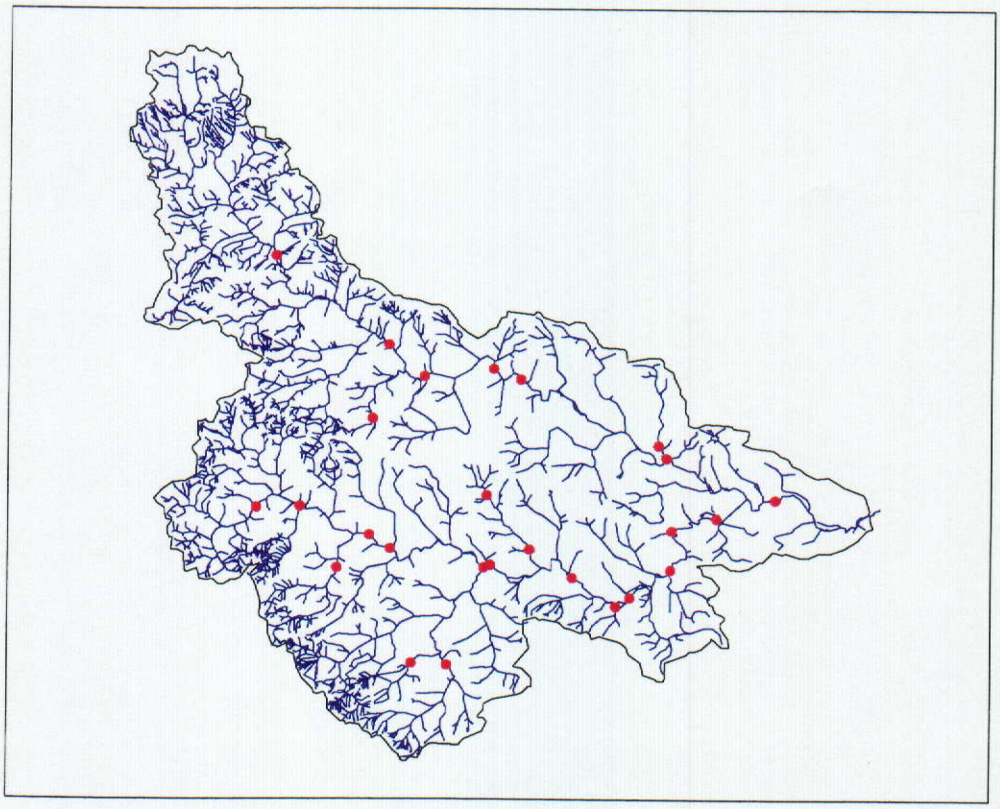

Figure 7.4 *Discharge sites within the Aire and Calder catchments*

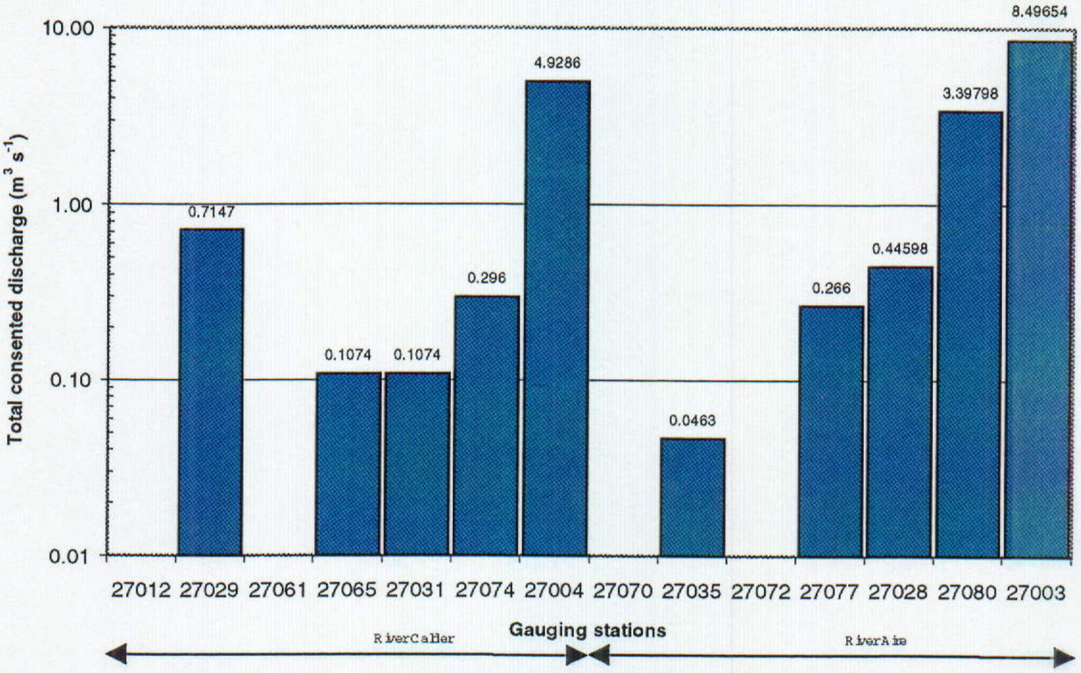

Figure 7.5 *Total consented dry weather flow in the Aire and Calder catchments*

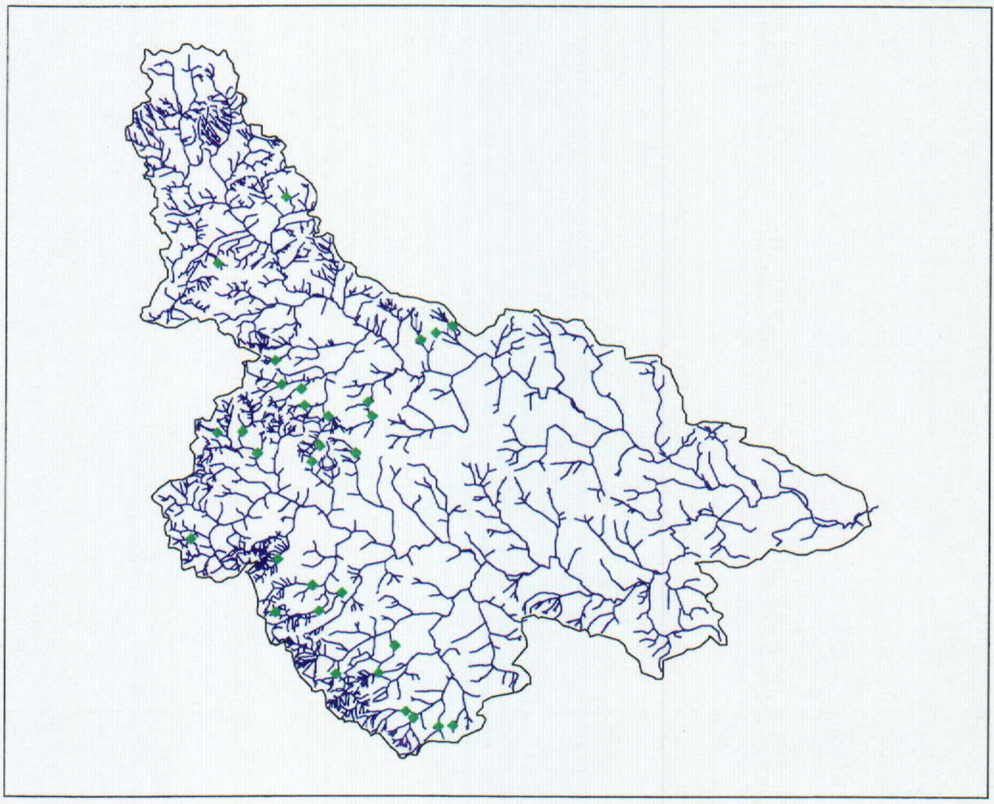

Figure 7.6 *Compensation reservoirs in the Aire and Calder catchments*

Within the major river catchments, many of the reservoirs are linked together in conjunctive use schemes and reservoir systems. Within these systems, the upper reservoirs are often used for supply and the lower reservoir used for releasing compensation flows. Therefore, in these situations, only the downstream reservoir has been referenced within the software. The distribution of the compensation reservoirs in the Aire and Calder catchments is illustrated in Figure 7.6.

7.2 ARTIFICIALLY INFLUENCED CATCHMENTS USED IN THE CALIBRATION

As discussed in Chapter 6, the gauging stations on the National River Flow Archive were given a grade to classify the hydrometric quality and degree of artificial influence. The techniques for calibrating the natural mean flow model using the natural gauging stations with good hydrometric records were also discussed in Chapter 6.

Having obtained the best estimates of the natural flow, the software can be calibrated against the artificially influenced gauging stations. It is important that the flow records from the artificially influenced catchments do not contain any anomalous data, therefore only stations graded AC or BC are suitable for inclusion. The usable gauging stations in Yorkshire are listed in Table 7.1.

Table 7.1 Influenced gauging stations

Station	River	Location	Grade	Start year	End year
27003	Aire	Beal Weir	BC	1958	1995
27006	Don	Hadfields Weir	AC	1965	1995
27011	Washburn	Lindley Wodd Res	AC	1953	1995
27012	Hebden Water	High Greenwood	AC	1954	1995
27013	Ewden Beck	More Hall Res	AC	1954	1995
27016	Little Don	Underbank Res	AC	1956	1995
27017	Loxley	Damflask Reservoir	AC	1956	1995
27019	Booth Dean Clough	Booth Wood Mill	AC	1956	1995
27021	Don	Doncaster	AC	1959	1995
27025	Rother	Woodhouse Mill	AC	1961	1995
27026	Rother	Whittington	AC	1963	1995
27028	Aire	Armley	BC	1972	1995
27029	Calder	Elland	AC	1961	1995
27030	Dearne	Adwick	AC	1963	1995
27031	Colne	Colnebridge	AC	1964	1995
27039	Holme	Digley Res	AC	1967	1995
27048	Derwent	West Ayton	AC	1972	1995
27053	Nidd	Birstwith	AC	1975	1995
27061	Colne	Longroyd Bridge	AC	1978	1995
27062	Nidd	Skip Bridge	AC	1979	1995
27063	Dibb	Grimwith Reservoir	AC	1980	1995
27065	Holme	Queens Mill	AC	1979	1995
27068	Ryburn	Ripponden	AC	1984	1995
27074	Spen Beck	Northorpe	AC	1984	1995
27080	Aire	Fleet Weir	AC	1986	1995

7.3 CALIBRATION OF THE SOFTWARE

Following the collation and initial processing of all the relevant artificial influence and gauging station data (as discussed in the previous Sections), the data were loaded onto the Micro LOW FLOWS databases. The next step in the calibration procedure was to ensure that the artificial influences, especially the reservoirs, were located on the correct stretches during the automatic loading procedures. This is important because errors can occur in the influenced estimates if the influences are assigned to the wrong stretch. This is particularly significant close to the confluence of two rivers.

Having loaded all the influence data, the influenced mean flows were estimated across the catchment. The influenced mean flow estimates at gauging station locations were significantly lower than the influenced mean flows estimated from the gauging flows. The influenced mean flow estimates were often negative. Investigation of the raw data identified a number of anomalies, especially in the abstraction licence data and reservoir data. All revoked or lapsed abstraction licenses had initially been included on the databases, therefore these licenses were removed. In addition, it was noted that some abstraction licenses were assigned to river stretches below reservoirs, based on the grid reference of the license, but inspection of the raw data identified that these abstractions were from the nearby reservoirs. Therefore, it was necessary to relocate these abstractions. Overall, due to the quality of the annual return and reservoir release data, repeated attempts were required to load the data in order to ensure that the influences were correctly located and that any anomalies were corrected or not included in the databases.

Once the quality control of the data had been completed, the remaining differences between the gauged and estimated influenced statistics were assumed to represent unquantified influences within the catchment. Therefore, a procedure was developed to make optimum use of the existing influences within a complex system. It was assumed that the consented discharges and reservoir release profiles had been characterised satisfactorily from the data provided. Thus the inconsistencies were considered to be a result of anomalies in the abstraction profiles, such as unrecorded returns from cooling water and fish farming abstractions, and unrepresented discharges.

The procedure that was adopted was to minimise the sum of the squared differences between the estimated influenced mean flows and the gauged (influenced) mean flows over the whole catchment, using experience relating to the consumptive nature of abstraction types. The optimised return factors are presented in Table 7.2.

Table 7.2 *Optimised return factors*

Abstraction Purpose	Percentage of abstracted water returned to the system
Spray Irrigation	0
Cooling Water	96
Industrial Processes	0
Public Water Supply	0
British Waterways	-
General Agriculture	0
Private Water Supply	0
Fish Farming	98
Mine Drainage	0
Undefined	80

Table 7.2 shows that 96 percent of the water abstracted for cooling water is returned to the river. Similarly, fish farming can be considered as a non-consumptive purpose, with only 2% of the abstracted volume being lost. By comparison, it is assumed that all of the spray irrigation licences are taking their full entitlement and the use is entirely consumptive. The final calibrated results for the Aire/Calder catchments are illustrated in Figures 7.7 and 7.8. A summary of the overall results are presented in Tables 7.3 and 7.4 in which the bias in the mean flow estimates expresses the estimated mean flow as a percentage of the gauged mean flow. This is then converted to an absolute error.

Table 7.3 *Final calibrated natural and influenced estimates of mean flow at gauging stations*

Gauging station	Gauged MF (m^3s^{-1})	Calibrated MF (m^3s^{-1})	Influenced MF (m^3s^{-1})	Error in bias of mean flow (%)
Natural				
27070	1.590	0.641	0.589	-59.69
27035	6.190	6.193	6.145	0.05
27072	1.380	1.378	0.919	-0.14
27077	0.670	0.672	0.924	0.30
Mean				0.07 *
Influenced				
27012	0.700	1.065	0.681	-2.71
27029	8.620	8.908	7.781	-9.73
27061	1.470	2.072	1.254	-14.69
27065	2.190	2.496	1.383	-36.85
27031	4.420	5.562	3.588	-18.82
27074	0.800	0.537	0.832	4.00
27028	15.100	12.484	11.969	-20.74
27004	17.810	17.658	18.626	4.58
27080	17.200	14.076	16.254	-5.50
27003	35.580	32.845	35.916	0.94
Mean				-9.95

Note * mean excluding station 27070

From Table 7.3 it can be seen that, with the exception of gauging station 27070, the error in the natural calibrated mean flow is almost zero. This is what would be expected, since the mean flow is fitted to the nearby natural gauging stations. Gauging station 27070 was identified previously in Chapter 5 as being an outlier, since the runoff was not consistent with the catchment area. Therefore, the results for this gauging station should be ignored

In the influenced catchments, the mean error in the bias between the influenced estimates and measured values is –10%, i.e. the overall model is consistently under-predicting the mean flow at 64% of catchments. This would imply that there are still errors associated with the characterisation of the artificial influence data. The information provided in Table 7.3 can be used as a guide to identify the catchments in which the major problems occur, notably 27065 and 27028 where the error in bias is greater than 20%. Therefore, additional investigations will need to be undertaken to improve the results further.

Taking the Aire and Calder catchments as a whole, 64% of the stations have an estimated mean flow within ±5% of the gauged mean flow (whether natural or influenced) and 70% are within ±10% of the gauged mean flow.

By comparison, the benefits of the enhancements on the Q95 are not as significant In both the natural and influenced catchments the estimated Q95 flows are significantly different to the gauged flows. Across the whole Aire/Calder catchment, only 15% of catchments have Q95 flows within ±5% of the measured flows and 36% of stations are within ±15%. The mean error in Q95 is 7%, indicating that the low flows are over-predicted.

Table 7.4 *Final calibrated natural and influenced estimates of mean flow at gauging stations*

Gauging station	Gauged Q95 (m^3s^{-1})	Calibrated Q95 (m^3s^{-1})	Influenced Q95 (m^3s^{-1})	Error in bias of Q95 (%)
Natural				
27070	0.090	0.063	0.065	-30.00
27035	0.480	0.716	0.710	49.17
27072	0.260	0.168	0.283	-35.39
27077	0.160	0.177	0.429	10.63
Mean				8.14 *
Influenced				
27012	0.230	0.078	0.231	0.44
27029	1.800	1.288	2.490	38.33
27061	0.290	0.358	0.268	-7.59
27065	0.450	0.472	0.245	-45.56
27031	0.630	0.070	0.706	12.06
27074	0.320	0.122	0.417	30.31
27028	3.420	1.762	2.248	-34.27
27004				
27080	4.750	2.172	5.334	12.30
27003	8.350	5.551	13.445	61.02
Mean				7.45

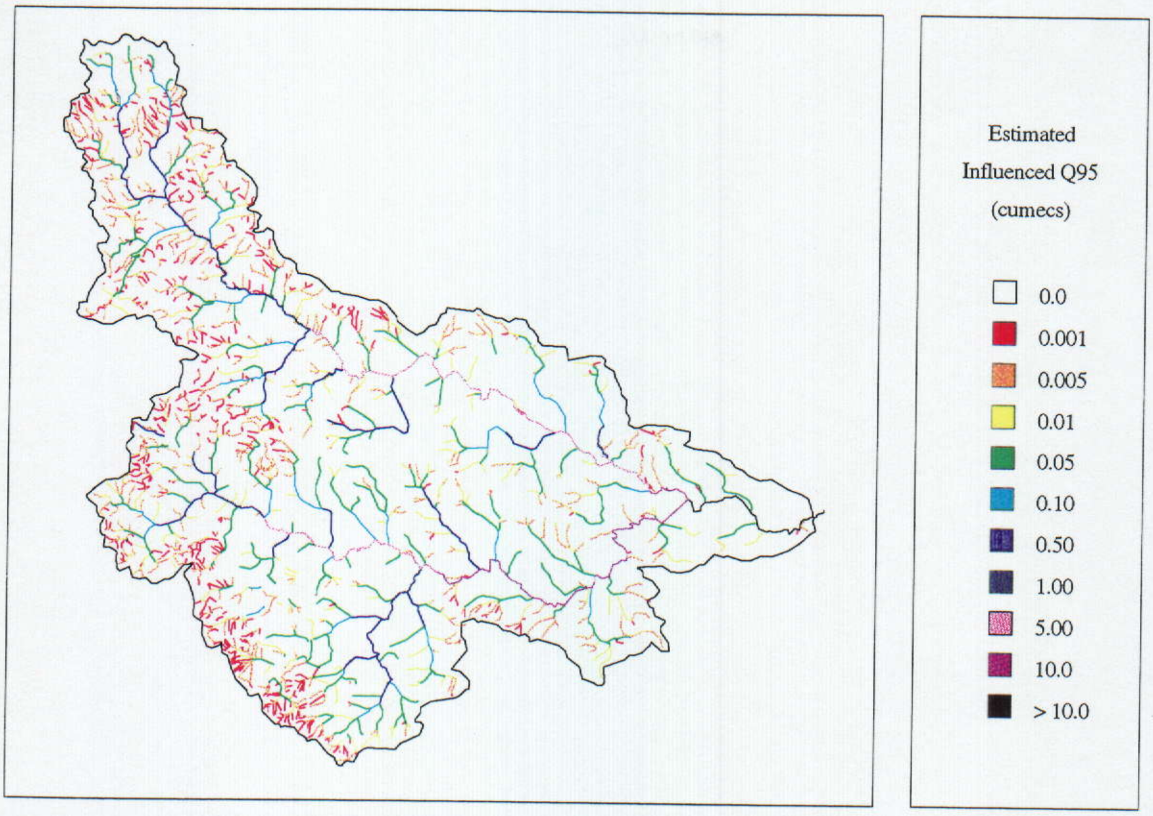

Figure 7.7 *Final estimates of influenced mean flow*

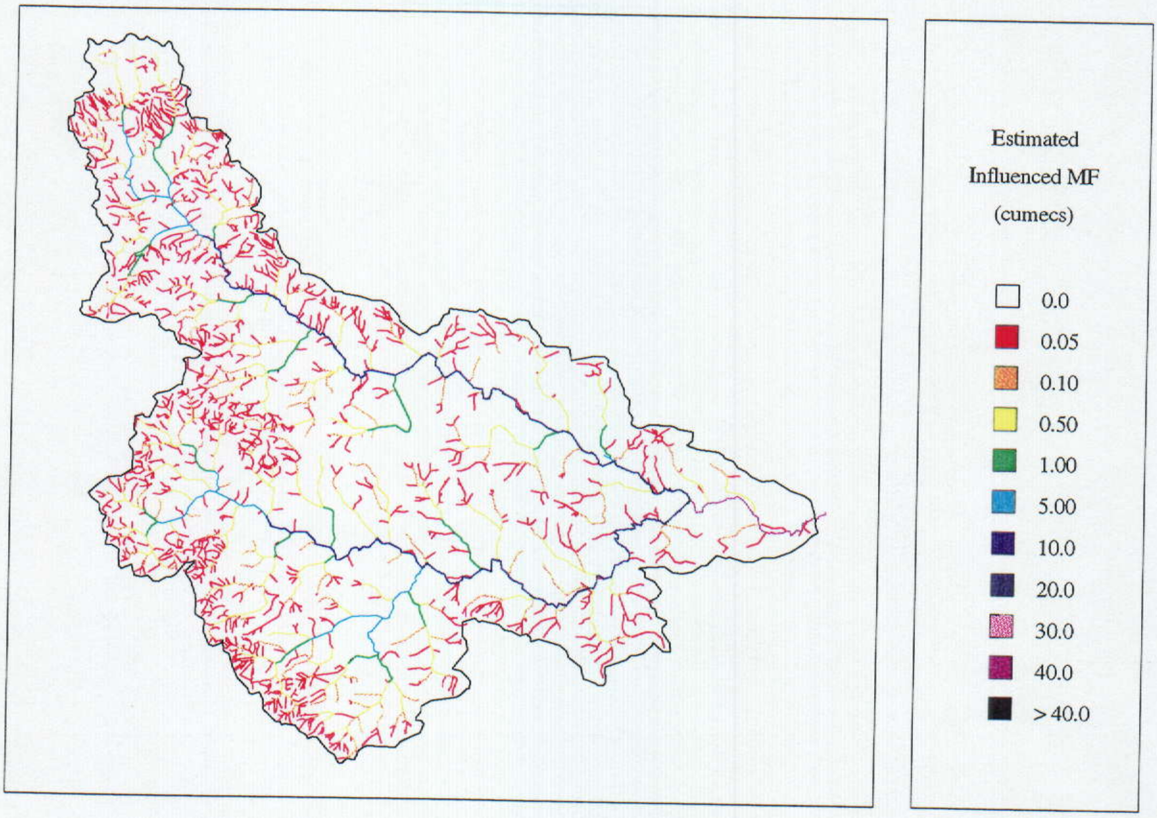

Figure 7.8 *Final estimates of influenced Q95*

8. Overview and conclusions

8.1 THE FINAL CALIBRATED SOFTWARE

During the reporting period, enhancements have been made to the Micro LOW FLOWS software, such that the final software is able to improve the estimates of both natural and influenced mean flow and Q95. These enhancements include:

Q95

1. Incorporating the variation in the timing of low flow events at a monthly resolution through distributing the standardised Q95 model, estimates of Q95 have been improved;

Mean flow

1. Distributing the mean flow model on a cell by cell basis for 1km^2 resolution grid to improve the estimates of natural mean flow;

2. Incorporating measured mean flow values from natural catchments within the basin into the estimation procedures;

3. Development of procedures for optimising the characterisation of the complex artificial influences within the basin to improve the influenced flow estimates.

8.2 CONCLUSIONS

The enhancements made to the software, both in terms of the estimation procedures and the functionality of the software, provide more reliable estimates of the natural and artificially influenced flow statistics for both mean and Q95 flows in ungauged sites.

The results from distributing the standardised Q95 model indicate that the differences in the low flow statistics (expressed in cumecs) estimated using the existing and revised approach become more significant as the size of the catchment increases. This can be attributed to an increase in the variability of the hydrogeology within a catchment and, more significantly, to the presence of substantial rainfall gradients across the catchments. In the natural headwater catchments of the Upper Aire sub-catchment the mean bias in the estimated and measured Q95 is 8%.

Incorporating the mean flow derived from flow data from nearby natural gauging stations provided enhancements to the natural mean flow estimates further, such that, in the natural headwater catchments the errors are almost zero. However, the benefits in the Q95 estimation procedure are less dramatic, such that, although the mean error is 8%, the errors at the individual gauging stations are greater than 30%.

The final improvements in the estimated flow statistics have been achieved by optimising the characterisation of the artificial influences, incorporating the mean flow values derived at gauging stations measuring significantly influenced flows.

For all gauging upstream of Beal Weir, the mean error in the influenced mean flow statistics is -10%, indicating that the estimated statistics are lower than the gauged statistics, while the Q95 is 7% greater than the gauged flow statistic. However, 70% of catchments above Beal Weir are within ±10% of the gauged mean flow and 64% of the stations have an estimated mean flow within ±5% of the gauged mean flow (whether natural or influenced). In contrast, only 15% of catchments have Q95 flows within ±5% of the measured flows and 36% of stations are within ±15%.

However, it should be emphasised that the success in achieving results within 10% of the gauged values for 45% of catchments (i.e. combining errors for both mean flow and Q95) belies the relative simplicity of the approach adopted, the complexity of the system and the variable quality of the data. A significant amount of work has been involved in calibrating the software, with particular emphasis on characterising the artificial influences. A number of key issues needed to be addressed during the loading of the artificial influence data:

(i) The first issue was in obtaining actual values of abstraction licences, discharge consents and reservoir releases. As discussed in the previous Chapter, a large amount of data was available, but it was not in an easily accessible format. In countries other than the UK, the availability of data may be severely limited;

(ii) The available data files required a substantial amount of reformatting to extract the appropriate information required by Micro LOW FLOWS and to create new data files suitable for loading onto the databases within the software. Different nomenclature in regions other than the UK may also pose potential problems.

(iii) The loading of the data required several iterations to ensure that the influences were in the correct locations and that anomalies were corrected or excluded. Visual inspection of the locations of the influences was used to identify influences attached to the wrong stretches. However, identifying discrepancies between the stretch estimates and the measured values from gauging stations on the same stretch required a number of small programs to be written. The programs detected catchments in which large errors were present, but manual cross-referencing with the raw data files was required to ascertain reasons for these errors. In many cases, the discrepancies were traced to abstractions linked to reservoirs or revoked abstraction licences. The automatic loading procedures are not able to take into account the complex influence interactions found in many catchments, for example conjunctive use schemes, reservoir control rules. Therefore it is important to carefully cross-reference the data files by hand to ensure that there is no double accounting of influences and make informed judgements as to how to deal with these influences.

(iv) Within the pilot study in the Yorkshire Region, data for a total of 3000 abstraction licences, 50 principal discharge consents and 32 reservoirs were provided. This information represented a substantial data input for a relatively small area and required a significant amount of processing before the data was usable. Therefore, this should be seen as a very important issue when the system is to be used for other regions in Europe.

References

Anonymous. Grimwith: solving the Bradford problem. Water Bulletin, 73, 12-13.

Boorman, D.B. & Hollis, J.M. 1990. Hydrology of Soil Types. A hydrologically based classification of the soils of England and Wales. MAFF Conference of river and coastal engineers, Loughborough University.

Building Research Establishment (1992). Reservoirs Act 1975: Register of Dams.

Bullock, A., Gustard, A., Irving, K.M. & Young, A.R. 1994. Low flow estimation in artificially influenced catchments. National Rivers Authority R&D Report No. 257.

Gustard, A. et al (1987). A study of compensation flows in the UK. Institute of Hydrology, Report 99.

Gustard, A., Bullock, A. & Dixon, J.M. 1992. Low flow estimation in the United Kingdom. Institute of Hydrology Report No. 108.

Hetherington, G. Methods for determination of safe yield and compensation water from storage reservoirs. General Report 2.

Jenkins, C.T. 1970. Comparison of rate and volume of stream depletion by wells. Techniques of water resources investigations of the USGS. Book 4. Hydrologist analysis and interpretation. US Govt printing Officer. Washington D.C.

Marsh, T., et al .1991. The 1988-1990 Yorkshire drought - A hydrological review. Institute of Hydrology & British Geological Survey.

McDonald, A. & Naden, P. 1987. Colour in upland sources: variations in small intake catchments. Water Services, 1987, 91, 1093, 121-123.

National Rivers Authority. 1993. River Calder Catchment Management Plan Consultation Report. Northumbria and Yorkshire Region.

National Rivers Authority. 1993. River Aire Catchment Management Plan. Northumbria and Yorkshire Region.

National Rivers Authority. Rivers Swale, Ure and Ouse Catchment Management Plan. Extracts from the Consultation. Report. Northumbria and Yorkshire Region.

Tattersall, K.H. 1980. Resource management of an industrial river system. J. IWES 34, 5, 453-473.

Theis, C.V. 1941. The effects of a well on the flow of a nearby stream. EOS Trans. AGU Vol 22. pp 734-738

Wilkins, M. 1992. The pride of Yorkshire. Water Bulletin, 509, 10-11.

Wilkins, M. 1993. Fishy goings on in Yorkshire. Water Bulletin, 575, 10-11.