GREAT-ER

Quarterly progress report: February - May 1997

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Contents

1. Summary of Progress

1.1 OBJECTIVES FOR THE REPORTING PERIOD

This report presents the activities undertaken by the Institute of Hydrology during the period 1 February to 31 May 1997 as part of the GREAT-ER project. The overall work schedule for the project is presented in Figure 1.1. The specific objectives to be undertaken during the reporting period have been to:

1. Initiate tasks associated with refining the application of the hydrological model within Micro LOW FLOWS. In particular, to develop techniques for incorporating the variation in the timing of low flow events into the model and using local data to improve the reliability of the flow estimates;

2. Derive flow estimates to support monitoring studies within the selected UK pilot study catchments;

3. Acquire and undertake quality control of hydrological data required for constructing the Italian hydrological model through collaboration with the University of Milan.

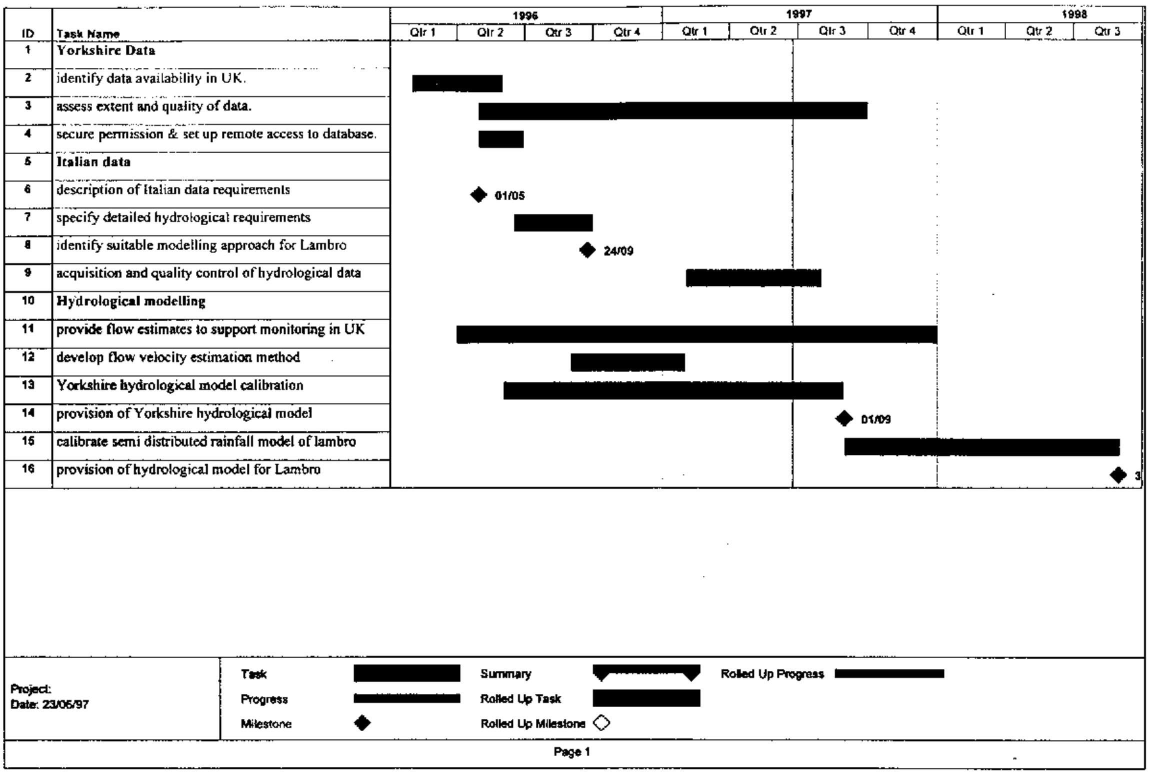

Figure 1.1 *GREAT-ER work schedule*

1.2 PROGRESS DURING THE REPORTING PERIOD

Within the reporting period, activities have 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 reliability of 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.

The specific details of progress associated with Task 1 above are discussed in Chapter 2.

No progress has been made with regard to the collation of hydrological data from Italy. It has also been agreed that the derivation of flow estimates to support the monitoring studies would be deferred until the sampling program was nearing completion.

However, overall, the work is on schedule for meeting the targets specified in the work plan.

2. Incorporating the timing of low flow events

2.1 EXISTING ESTIMATION PROCEDURES FOR ANNUAL STATISTICS

Existing models for estimating natural low flow statistics at ungauged locations are based on relatively simple conceptual models relating climate and mean runoff and statistical models that relate low flows and hydrogeology. The mean and low flow statistics can then be used to determine the flow duration curve for the ungauged catchment. The overall estimation procedure is summarised in Figure 2.1. The following sections briefly summarise the individual stages in the estimation procedure.

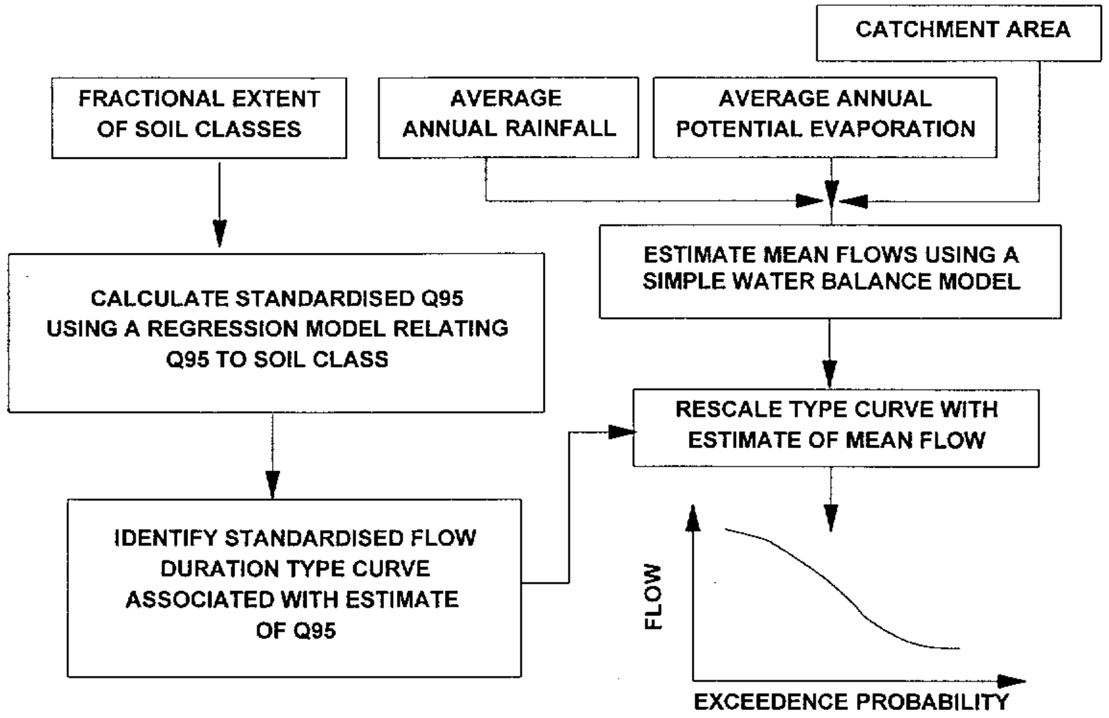

Figure 2.1 *Procedure for estimating natural long-term statistics*

2.1.1 Mean flow

The primary climatic variables used to estimate the mean flow are the standard period (1941-70) annual average rainfall (SAAR) and the annual average 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 $SAAR \geq 850mm$

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

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

In the manual estimation of the mean flow, the user would overlay the catchment boundary onto grids of rainfall and evaporation to obtain catchment average estimates of the climatic variables. Depending on the magnitude of the rainfall, a factor would be applied to the potential evaporation to derive the actual evaporation. The difference between the rainfall and actual evaporation would then need to be scaled by the catchment area to give a flow in cumecs.

2.1.2 Low flow statistic

A key low flow statistic used to characterise the low flow regime is the long term Q95 (i.e. the flow exceeded, or equalled, for 95% of the time) and, in regional analysis, is commonly expressed as a percentage of the long-term mean flow, referred to as the standardised Q95. A statistical multivariate regression model has been derived to relate the low flow statistic to the hydrological characteristics of soils within gauged catchments (Gustard *et al*, 1992). The Hydrology of Soil Types (HOST) classification (Boorman *et al*, 1992) and the derived Low Flow HOST Groups represent the hydrological characteristics of soils within the UK.

In an ungauged catchment, the manual procedure for estimating the Q95 is based on overlaying the catchment boundary onto an appropriate soil map (for example the 1:250 000 scale soil association map series published by the Soil Survey & Land Research Centre or the Macaulay Land Use Research Centre) and calculating the proportions of each soil association within the catchment. A value of Q95 for each soil association has been determined based on the HOST class assigned to the constituent soil series of each soil association (published in Gustard *et al*, 1992). Therefore, for each soil association, a weighted Q95 can be calculated based on the proportional area and the catchment Q95 is the sum of the weighted Q95 values.

2.1.3 Annual flow duration curve

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

Therefore, 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). The type curves are illustrated in Figure 2.2.

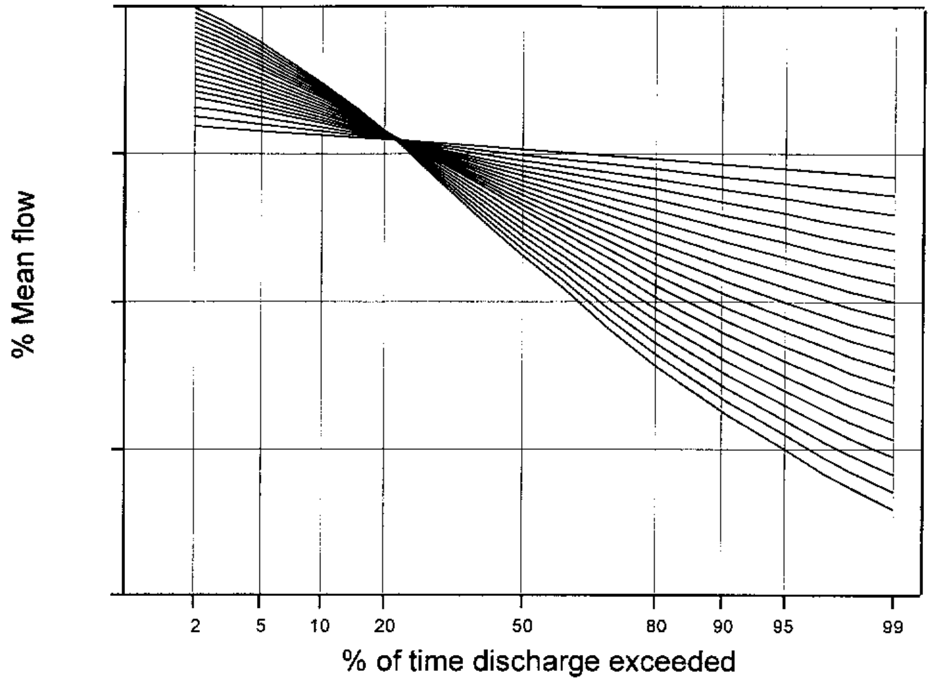

Figure 2.2 *Annual flow duration type curves*

2.1.4 Implementation of annual low flow estimation procedures within Micro LOW FLOWS

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 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. By accumulating the number of squares above a given stretch and taking the average of the individual grid square values, catchment average values of these climate and low flow characteristics can be determined.

2.2 TIMING OF LOW FLOW EVENTS

A major conceptual limitation of the existing model used within Micro LOW FLOWS is that it is assumed that the standardised Q95 flow occurs at the same point in time for all stretches within the river network, irrespective of changing catchment hydrogeology. Analysis of the timing of the minimum flow during the year for gauging stations in the UK, illustrated in Figure 2.3, confirms that this assumption is not valid (Bullock *et al*, 1994).

The direction of the arrow indicates the mean day of occurrence of the annual 7-day minima (roughly equivalent, numerically speaking, to the Q95 flow) and the length of the arrow is proportional to the standard deviation (in days). Through comparison with geological maps of the UK, Figure 2.3 illustrates that the geology is an important factor in controlling the time of year when low flow events occur. For example, catchments in the impermeable upland areas experience high winter flows and low flows in summer, compared to chalk catchments in East Anglia where there is less variation over the year and minimum flows are likely to occur in the autumn. The inter-year variability is also greater in the impermeable catchments compared with the more permeable catchments where the catchment response is damped by catchment storage.

In order to be able to incorporate these seasonal variations, due to climate and geology, it is possible to estimate low flow statistics at a monthly resolution, making use of the existing low flow estimation techniques developed by Bullock *et al* (1994), discussed in more detail in the Section 2.3. More specifically, by considering a catchment as containing a series of discrete homogeneous hydrological "sub-catchments", it is possible to reflect the different hydrological responses of different parts of the catchment. In addition, by considering the individual sub-catchments, it is possible to take into account the spatial variations in catchment rainfall. This is of particular advantage in upland catchments which may experience high rainfall gradients across the catchment.

2.3 ESTIMATING MONTHLY STATISTICS

The following Section describes the existing techniques for estimating low flow statistics at a monthly time scale, developed through an R&D project (Bullock *et al*, 1994) funded by the former UK National Rivers Authority (now amalgamated into the Environment Agency). The overall estimation procedure for monthly statistics is summarised in Figure 2.4 and the individual steps in the estimation procedures are briefly discussed in Sections 2.3.1 to 2.3.3. 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 flow duration curve.

2.3.1 Monthly mean flow

The monthly flow duration curves are normally expressed as a percentage of the monthly mean flow; therefore, the monthly mean flow is required to enable the flow duration curve to be expressed in cumecs. The mean flow for each month is determined using the long-term Q95 to identify the monthly runoff volume (MRV), which is expressed as a percentage of long term annual runoff volume (ARV). The estimated long term mean flow is required to covert the monthly runoff from a volume to a discharge in cumecs.

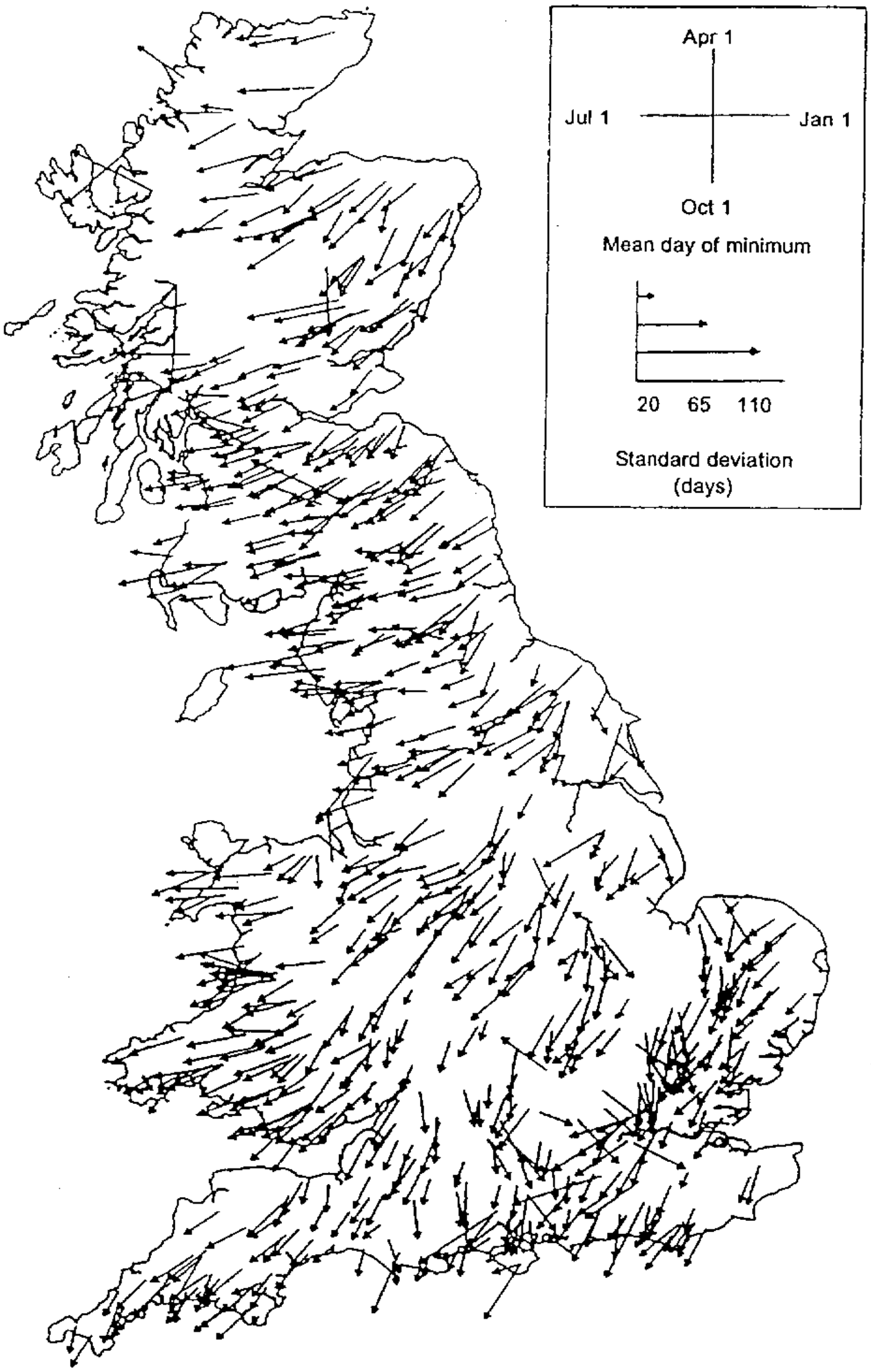

Figure 2.3 *Seasonal variations in the occurrence of annual minima (Source: Bullock et al, 1994)*

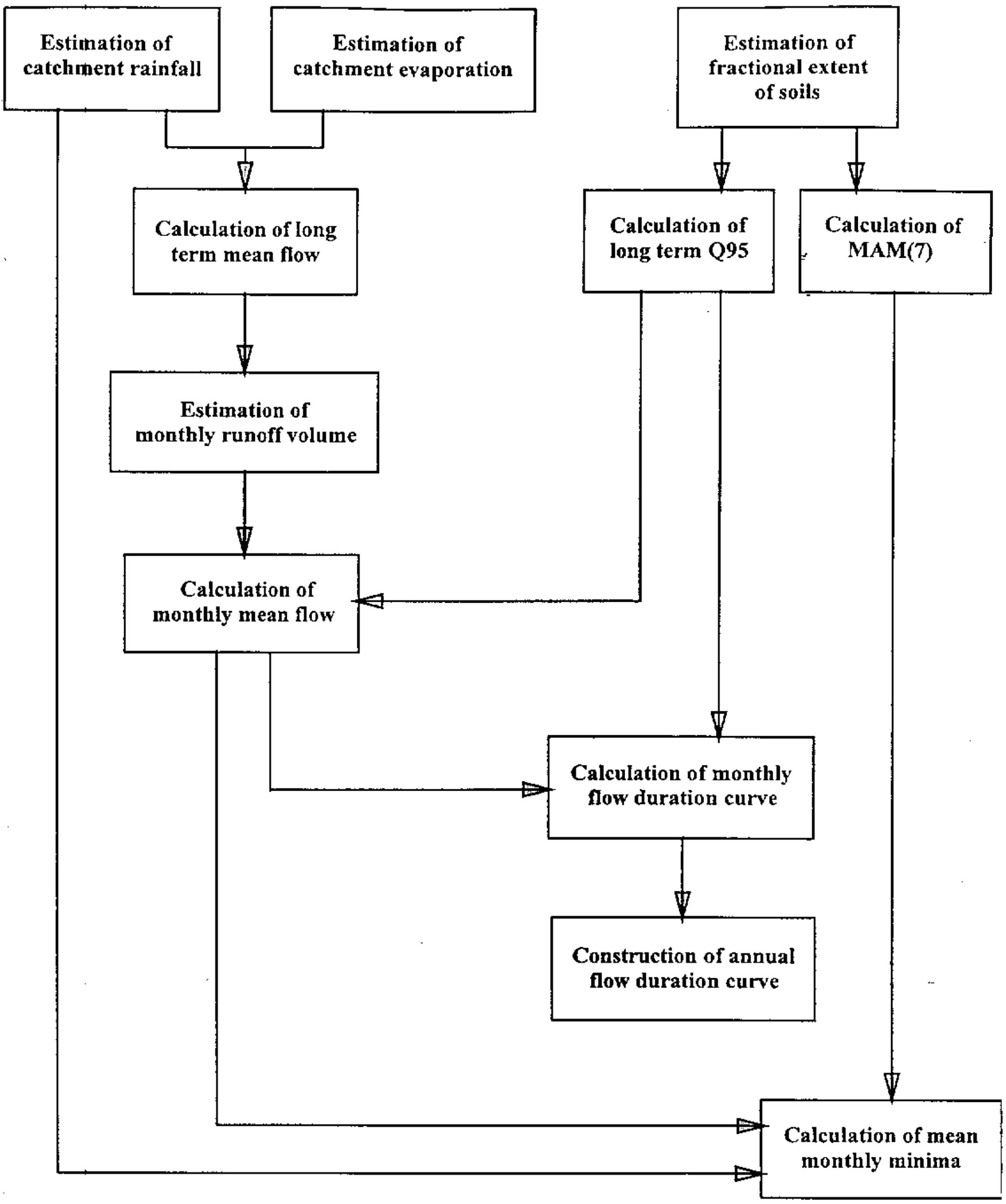

Figure 2.4 *Procedure for estimating natural monthly statistics*

The variability of the MRV is related to the magnitude of the standardised Q95; i.e. the permeability of the catchment. Catchments in Great Britain with a Q95 of less than 30% of mean flow demonstrate significant regional as well as seasonal variations in the magnitude of monthly runoff. For example, the variation of the monthly runoff volume in May compared to November is illustrated in Figure 2.5. For more permeable catchments in Great Britain (with Q95 flows greater than 30% of mean flow) the spatial variability of MRV is not significant. The seasonal variations in monthly runoff volume are represented in Table 2.1. Similarly, the monthly runoff volumes within catchments in Northern Ireland display only small regional variations. The seasonal variations for MRV in Northern Ireland are represented in Table 2.2.

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:

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

2.3.2 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 flow duration curve. 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 flow duration curve at an ungauged site. Therefore the existing type curves can be used to derive monthly flow duration curves.

In common with the annual flow duration curve, the estimation of the standardised monthly flow duration curves 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 flow duration curves.

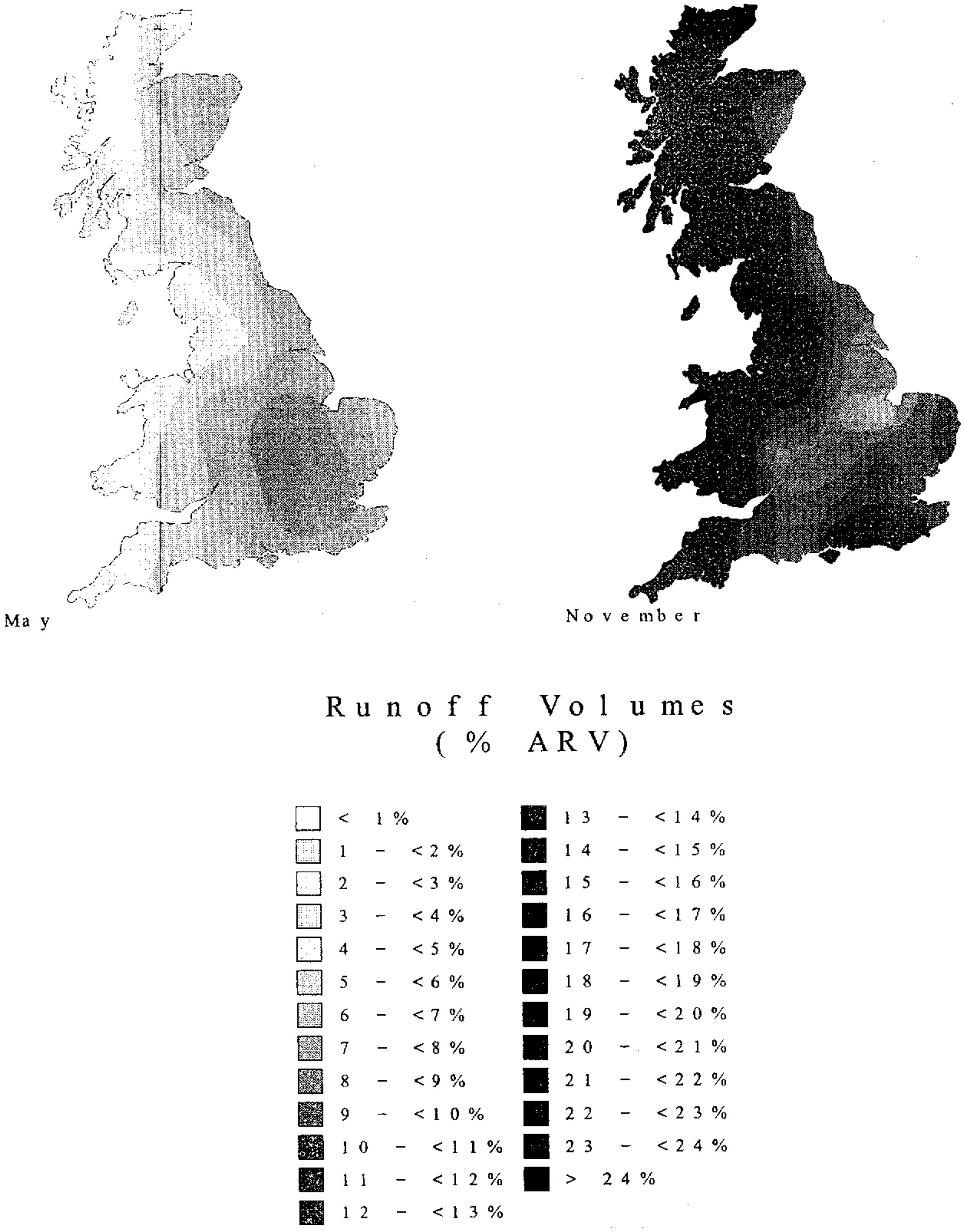

Figure 2.5 *Monthly runoff volumes (as a percentage of annual runoff volume) for May and November for catchments with a Q95 between 15-30% of the mean flow (source Bullock et al, 1994)*

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

A month is not an hydrologically significant period compared to a year, therefore the annual flow duration curve needs to be reconstructed from the 12 standardised monthly flow duration curves, using the monthly mean flow estimates to scale the flows. The monthly curves (in $m^3 s^{-1}$) are divided into 30 "daily flows" at equally distributed percentiles and each "daily flow" is assigned a flag to identify the month from which the flows are derived.

A composite flow duration curve (CURVEM) is derived by ranking the 360 values (derived from the 30 flows from each of the 12 months) from highest (rank 1) to lowest (rank 360) and then calculating a probability of exceedence (P_n) for each of the 360 flows. However, it is important that the reconstructed annual flow duration curve equals the natural annual flow duration curve, for purposes of consistency. Therefore, the natural annual flow duration curve (CURVEA) can be divided into 360 "daily flow" values at equivalent percentiles, P_n, and the two curves can be compared. The flow values from CURVEM are adjusted to equal the flow value of CURVEA if the two are different.

In order to make use of the seasonal variations in flows, the monthly flow duration curves need to be extracted from the annual curve by identifying the 30 component flows for each month using the flag.

2.4 PROGRESS WITHIN THE REPORTING PERIOD

During the reporting period, work has been undertaken to apply the hydrological model within Micro LOW FLOWS (as described in Section 2.1 to 2.3 above) in order to apply the monthly estimation procedures to discrete geological regions within a catchment. The overall procedure is summarised as follows:

1. Identify the extent of each hydrogeological region, 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;
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.

The principal tasks undertaken have been:

1. 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;
2. 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;
3. Development of algorithms to estimate fitted monthly flow duration curves for each Low Flow HOST group above a river stretch;
4. 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;
5. Development of comparison routines for assessing the differences between the existing flow duration curves for a stretch and the revised methods which incorporate the timing of low flow events.

2.5 PRELIMINARY RESULTS IN THE AIRE CATCHMENT

A preliminary assessment of the performance of the distributed estimation procedure has been undertaken for locations in the Aire catchment, illustrated in Figure 2.6. The difference in Q95, derived using the revised and existing Q95 models and expressed as a percentage of the Q95 from the existing model, is given in Table 2.4 for a number of locations within the Aire catchment.

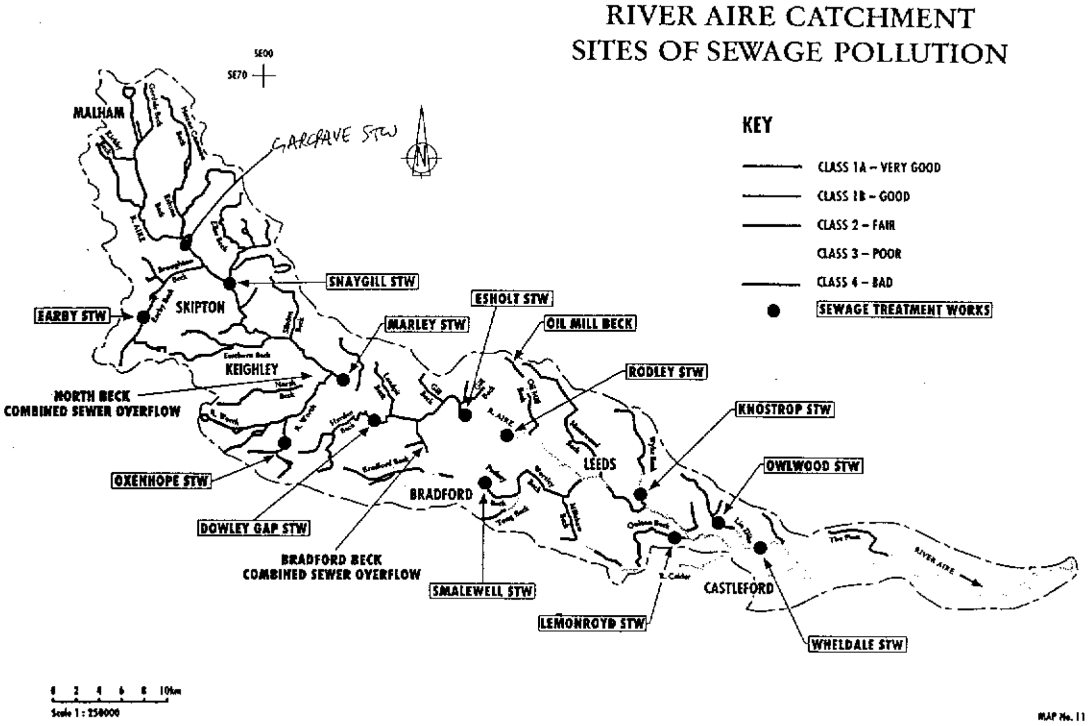

Figure 2.6 *River Aire Catchment*

Table 2.4 *Percentage difference in the Q95*

	Location	Percentage change in Q95
Downstream location in catchment	Beal Wier	≥ -7%
	Knostrop STW	≥ -7%
	Esholt STW	-6% to –7%
	Marley STW	0%
	Snaygill STW	+3% to 4%
Upstream location in catchment	Gargrave STW	+4% to 5%

It would be expected that the low flows would increase due to the increasingly diverse hydrogeology of larger catchments and hence increasing variations in the timing of low flow events. Table 2.4 indicates that negative changes in the Q95 occur at the bottom of the Aire catchment, i.e. that the revised method produces a Q95 that is less than that derived using the existing method, becoming positive towards the top of the catchment.

This is primarily as a result of the influence of distributing the mean flow model. The lower part of the catchment has a mean annual rainfall of less than 850 mm, therefore the reduction factor is applied to potential evaporation to reduce the actual evaporation. In the upper part of the catchment, the rainfall is greater than 850 mm, therefore it is assumed that the actual evaporation is equal to the potential evaporation. Using the existing techniques, the overall rainfall for the catchment is calculated to be greater than 850 mm, and no reduction factor was applied to the potential evaporation.

The inference from these results, although it has to be more widely checked, is that the mean flow model is more important than the timing of low flows.

3. Future work

3.1 INCORPORATING LOCAL HYDROMETRIC DATA AND CHARACTERISING THE IMPACTS OF ARTIFICIAL INFLUENCES ON THE FLOW REGIME

Although information on gauging stations is archived within Micro LOW FLOWS, it is the responsibility of the operational hydrologist to validate the natural flow estimates derived from the software using available local data and hydrological experience to make the best estimate of the flow regime at the ungauged site. In order to improve the software and enhance the reliability of the estimation procedures, procedures for incorporating local data into the hydrological model have been initiated during the reporting period.

The first part of the process is to ensure that the natural estimates adequately reflect the natural flows measured at nearby gauging stations in natural catchments. The second part is to calibrate the model to incorporate the artificial influence data, linking the estimated influenced flows to flows recorded at nearby gauging stations with good hydrometric records where the net impact of artificial influences is implicitly measured in the data.

3.1.1 Calibration of mean flow

Natural gauging stations will be used to calibrate the natural mean flow statistics. These gauging stations will be selected initially on the hydrometric and artificial influence grades assigned by Gustard *et al* (1992) and discussed in detail with Environment Agency and National Water Archive staff. A provisional strategy for fitting the mean flow estimates to the natural gauged statistics for catchments in the basin is being developed. This is based on applying a ratio of gauged estimate of effective runoff to the estimate of effective runoff estimated by the software.

For headwater catchments, the ratio will be applied to all stretches upstream of the gauging stations. Further down the catchment, the ratio will be determined by a weighted average of upstream gauges.

3.1.2 Calibration of the hydrological model for the impacts of artificial influences

During the previous reporting period, information on reservoirs and 50 principal discharges in the Yorkshire Water Services Region have been collated. Limited data is available for abstractions. It is anticipated that the Environment Agency will provide further abstraction data. During the next reporting period, the artificial influence data will be quality controlled and loaded onto the Micro LOW FLOWS databases.

Once the data has been loaded, the predicted and actual flow duration curves for appropriate artificially influenced gauging stations will be compared. It is anticipated that there will be differences between these curves which may be a function of the residual error in the revised natural low flow statistics, unexplained artificial influences, hydrometric errors in the gauged data and sampling errors in the gauged data. An approach for incorporating these differences in a hydrologically appropriate manner is currently being developed.

The artificially influenced catchments used to calibrate the influences will be carefully selected based on the assigned grades and in consultation with hydrometric staff. It is important that any anomalous stations should not be included

References

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.

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.