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GREAT-ER

Quarterly progress report:
June - September 1997

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October 1997

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1 Summary of progress and forecast activities

1.1 PROGRESS WITHIN REPORTING PERIOD

This report presents the activities undertaken by the Institute of Hydrology during the period 1 June to 30 September 1997 as part of the GREAT-ER project. The main activities within the reporting period have been:

- The development of a summary document describing the availability of hydrological and climatological data across the European Union. This document "Hydrological and Climate data in Europe" (Croker & Young, 1997) is presented in draft as a separate document to this progress report;

- A review of the RUG discussion document on sewer flow modelling presented at the Enlarged Task Force Meeting held in Milan. This review is in response to an action arising from the last meeting;

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

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

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

- 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;

- The incorporation of the impact of artificial influences within the basin on the natural flow regime as estimated by the model. This part of the work package 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.

Subject to a potential revision of how the flows from sewage treatment plants within the catchments are characterised the hydrological model is now complete. Against the overall work schedule presented in Figure 1.1, the completion of the hydrological model has been delayed by approximately one month. This delay arose out of an unavoidable delay in receiving data on abstractions from the Environment Agency. However one benefit of this delay is that the Environment Agency were also able to source data on historical releases from impounding reservoirs within the basin. These reservoirs exert a considerable influence on the upper reaches within the basin. Using these data used in conjunction with the data on statutory compensation releases, detailed in Round & Young, 1996, meant that the influence of these reservoirs could be incorporated in the model with a greater degree of confidence than would otherwise have been possible.

The review of the sewer flow modelling proposal is presented in Chapter 2 of this report. Due to time constraints it has not been possible to fully write up the development work on the hydrological model for this progress report. Chapters 3 to 5 present a summary of this work with the emphasis on the performance of the model within the pilot study area. A full description of the development work will be prepared for the Annual Report.

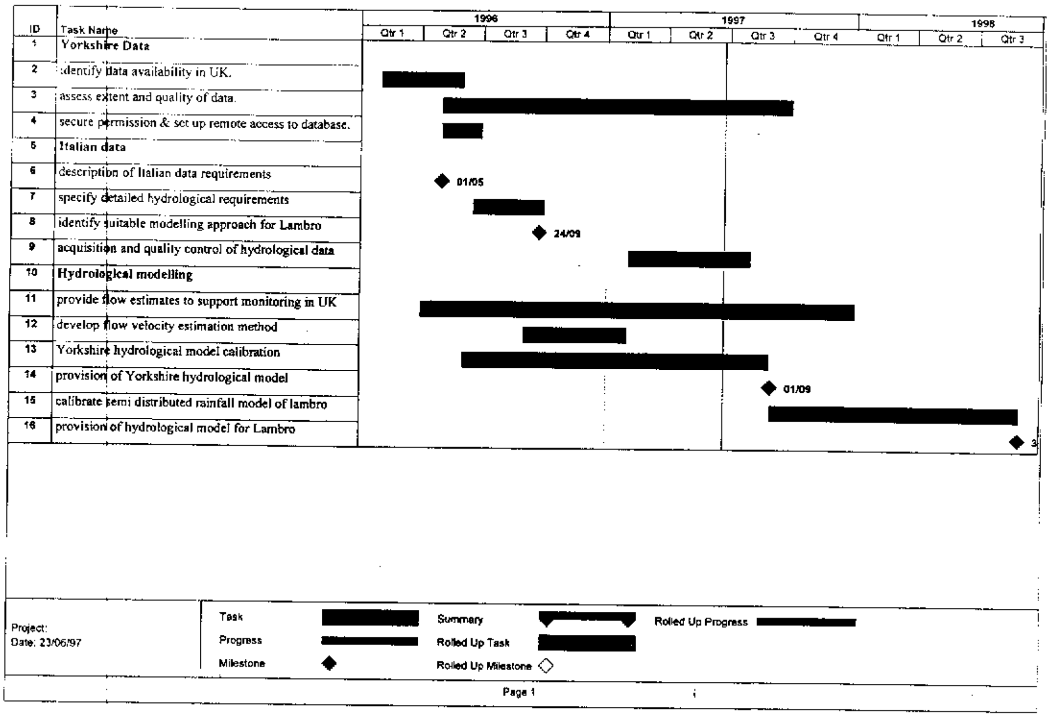

Figure 1.1 *GREAT-ER work schedule*

1.2 FORECAST ACTIVITIES FOR THE NEXT REPORTING PERIOD

During the period October 1997 - January 1998, the following issues will be addressed:

- It is anticipated that the way in which sewer flows are to be represented within the software will be finalised in conjunction with RUG, the Environment Agency and Yorkshire Water Services. This issue of quantifying the foul component of these flows for the major plants within the pilot study area were discussed at the UK sub group meeting held on the 24th September 1997. Yorkshire Water Services and the Environment Agency agreed to try and source additional data on the foul component of the measured influent average daily flows for the major treatment plants. Once these are available it is proposed that these data should be incorporated within the hydrological model;

- With the UK monitoring programme now well advanced the hydrological model will be used in conjunction with daily flow data for target gauging stations to estimate flows at the sampling sites corresponding to each sample. This activity will use the approach presented in Round & Young, 1996. It is anticipated that close liaison between Agency hydrometric staff and Institute staff will be required if this activity is to be successful;

- The quality control of the hydrological data that has been provided by the University of Milan for the Lambro River will be undertaken during this period. It is not anticipated that work on the hydrological model for the Lambro will be initiated during this period as the geographic focus of the GREAT-ER modelling activities within the Lambro basin do not appear to be clearly defined as yet. Depending on geographic extent of the modelling activities it may be necessary to collate more extensive hydrological/climatological data for the basin.

The activities on the GANNT chart relating to the Lambro modelling activities must be regarded as fluid at this point in time.

2 Sewer flows and the feasibility of a generic model

2.1 OVERVIEW OF WATER TRANSPORT WITHIN THE UNSATURATED ZONE

It is an undisputed fact that sewers are not watertight. Whether water infiltrates into or leaks from the sewer is a function of the moisture deficit in the material surrounding the sewer. Generally sewers lie within two metres of the surface and thus commonly lie within the unsaturated zone. The text book conceptualisation of the unsaturated zone is an aeration zone close to the surface followed by a capillary water zones and a groundwater zone with the boundary between the capillary zone groundwater and delineated by the water table. This is demonstrated diagrammatically in Figure 2.1

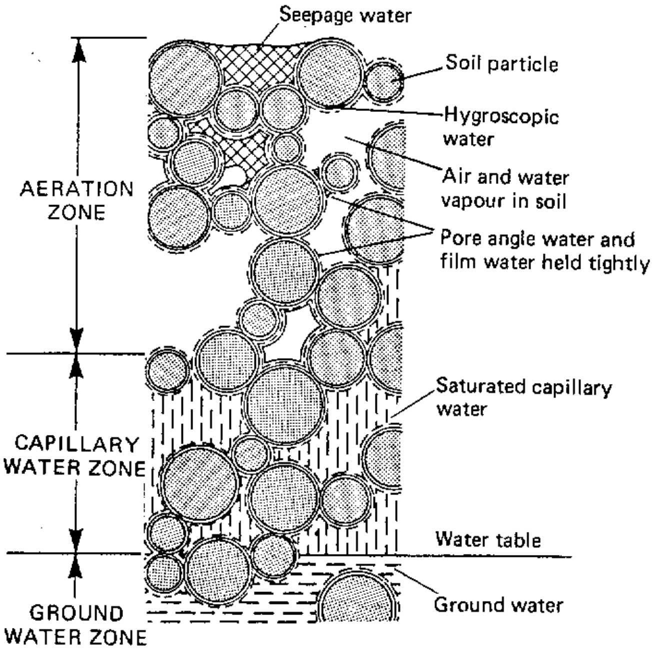

Figure 2.1 *Schematic representation of the unsaturated zone (Source: Shaw, 1983)*

The traditional way of analysing water movement in the unsaturated zone is through consideration of the energy required for movement. As kinetic energy transfers are low (movement is slow) the work (energy) required to induce movement is reduced to considering the sum of the potential energy terms of gravity, adsorptive and capillary forces. If these energy components (joules) are expressed as the energy per unit volume then the problem can be considered in terms of total potential. The equipotential surface where the total potential is equal to atmospheric pressure is denoted the water table. Water below the water table, where the potential is greater than one atmosphere, is termed groundwater. It is important to note that this delineation is based on considerations of energy and not the physical presence of a recognised aquifer unit.

The hydrological processes within the unsaturated zone are very complex and highly non-linear. Water may move both laterally and vertically dependent on the hydraulic potential, hydraulic properties of the medium and the ability of the underlying aquifer (if any) to accept water. In modelling moisture deficits the following broad issues need to be addressed:

- surface infiltration characteristics;
- evapotranspiration processes;
- topography;
- hydraulic properties of the soil;
- depth to underlying geological material ;
- permeability and storativity of underlying geological material;
- water movement in the underlying geological material (if any);
- proximity of surface water bodies and the exchanges with these bodies.

These are all very complex issues that are dependent on site specific conditions for which there are little data. In the context of sewer leakage an issue that also needs to be recognised is that sewers commonly lie in close proximity to other services, including water supply pipes. Water supply pipes also leak and thus may maintain soil moisture in the local vicinity hence modifying the infiltration/exfiltration relationships for sewers. Another important issue is that the presence of the trenches in which services run will highly influence the routing of subsurface water by providing preferential flow paths.

The logical conclusion that has to be reached is that, even if the data can be sourced, a dynamic, multi-layer/three dimensional numerical model is required to model soil moisture within the saturated zone and the near surface part of the saturated zone. This is obviously not appropriate within GREAT-ER. One question that needs to be asked is, in the context of the local, site specific nature of many of these controls, is it feasible, or scientifically valid, to develop a generic, conceptual model for sewer leakage? The remainder of this document relates to specific comments on the RUG discussion document.

2.2 COMMENTS ON THE RUG PROPOSAL FOR SEWER MODELLING

At the fourth Enlarged Task Force meeting a discussion document was circulated on modelling sewer infiltration/exfiltration and storm water inputs to sewer networks (Boeije, 1997). The Institute of Hydrology and the Environment Agency were actioned to comment on the proposals within this document. The proposed modelling approaches are primarily based on personal communications between Geert Boeije and Bob Crabtree of WRc. If it is appropriate to model sewer leakage and storm water inputs to sewers within GREAT-ER then, given the lack of relevant data, a conceptual approach is an appropriate way of tackling the issue. The question that needs to be asked is whether the model is valid. The following comments on the proposal relate to assumptions within the structure of the proposed models and should be read in conjunction with the original document.

2.2.1 Separate sewers

The formulation of the model (a normally distributed correction factor) implies that both leakage and infiltration are proportional to the flow in the sewer. When the soil surrounding the sewer is saturated transfers between the sewer and the surrounding material will be dependent on the degree of hydraulic contact (how leaky the sewer system is) and the difference in hydraulic potential. As the hydraulic potential in the sewer will remain relatively constant the variation will be controlled by the variation in hydraulic potential in the soil. When the soil is unsaturated then transfers will be proportional to the hydraulic head in the sewer only. This Darcian representation, although highly simplistic, is commonly used in conceptualising groundwater/surface water interactions.

A second issue is the correlation of any descriptors of the variability in hydraulic potential to stream flow and rainfall. The relationship between rainfall and stream flow is highly nonlinear with little direct correlation between the two. This is particularly so in high storage catchments such as groundwater dominated catchments.

It should also be appreciated that the response of groundwater levels to climatic inputs is much slower than the equivalent stream flow response. Obviously the storage within the system exerts a strong control on the response of the system. This would need to be reflected in any leakage model.

2.2.2 Combined Sewer

In modelling a combined sewer the rainwater inputs to the sewer system obviously need to be considered. It should also be recognised that many sewer systems intercept small streams, etc. Once again these interceptions are very site specific in nature.

Option 1 - Runoff from a correction factor

The assumption in the use of a second correction factor, alpha, to represent the rain water contribution implies that the runoff is proportional to the foul sewer flow. This has some logic in that there probably is a link between the magnitude of the foul component and the size of the sewer network catchment - but it is unlikely to be as straightforward as this. Additionally the structure implies that if there is a high foul component on a particular day then there is likely to be more surface runoff.

It is proposed within the document that the surface runoff coefficient be represented by a log normal distribution. This is unlikely to be the case as daily rainfall (and hence runoff) is not log normally distributed. On a large proportion of days in the year the daily rainfall is zero. There is extensive literature on stochastic daily rainfall generators; these are generally two stage processes based on the probability that it will rain today and a probabilistic estimate of how intense that rainfall will be. Obviously daily rainfall events are not independent; if it rains today there is a higher probability that it will rain tomorrow.

The proposal to describe the runoff correction factor by a log-normal distribution with the 95 percentile set to one is open to criticism. The mean is a measure of central tendency and thus is a measure of the average runoff coefficient. If the proposed approach has been understood correctly, the offset implies that for 5 % of the time the coefficient is less that 1 and thus the actual flow in the sewer is lower than the foul component. This implies that for five percent of the time the foul component is reduced as a consequence of runoff processes. The basic problem with the coefficient approach is that it implies the runoff component of sewer flow is a function of the foul component when, in reality, the origins of the two components of sewer flow are essentially independent of one another. The correlation with stream flow proposed are hypothetical and, furthermore, they are only applicable to flood flows and are likely to operate at shorter time scales that a day (15 minute data are normally used to model flood events). At low flows the stream flow is related to the depletion of catchment stores and not directly to daily (or sub-daily) rainfall distributions.

Option 2 - Runoff Model

This option is not recommended within the discussion document for use in GREAT-ER. The approach is more conceptually realistic than option 1 but, as pointed out, it would require a rainfall generator. This is feasible but would be expensive and may be beyond the scope of GREAT-ER. If this option is taken further then the spatial extent of the sewer catchment would be required. This cannot be back calculated from population and population density.

3 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, and a statistical, multi-variate model for estimating the Q95 flow statistic from the hydrological response of soil types. A major conceptual limitation to the Q95 model, which are used within the Micro LOW FLOWS software, is that 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.

Within the context of this project, incorporating the timing of low flow events across the UK has made use of existing techniques for estimating annual and monthly low flow statistics. The existing techniques are summarised in the following sections. These procedures are presented in more detail in the Quarterly Progress Report for the period February to May 1997 (Croker & Young, 1997).

3.1 ANNUAL FLOW STATISTICS

The mean and Q95 flow statistics estimated from catchment characteristics are used to determine the flow duration curve for an ungauged catchment. The overall estimation procedure is summarised in Figure 3.1. The following sections briefly summarise the individual stages in the estimation procedure.

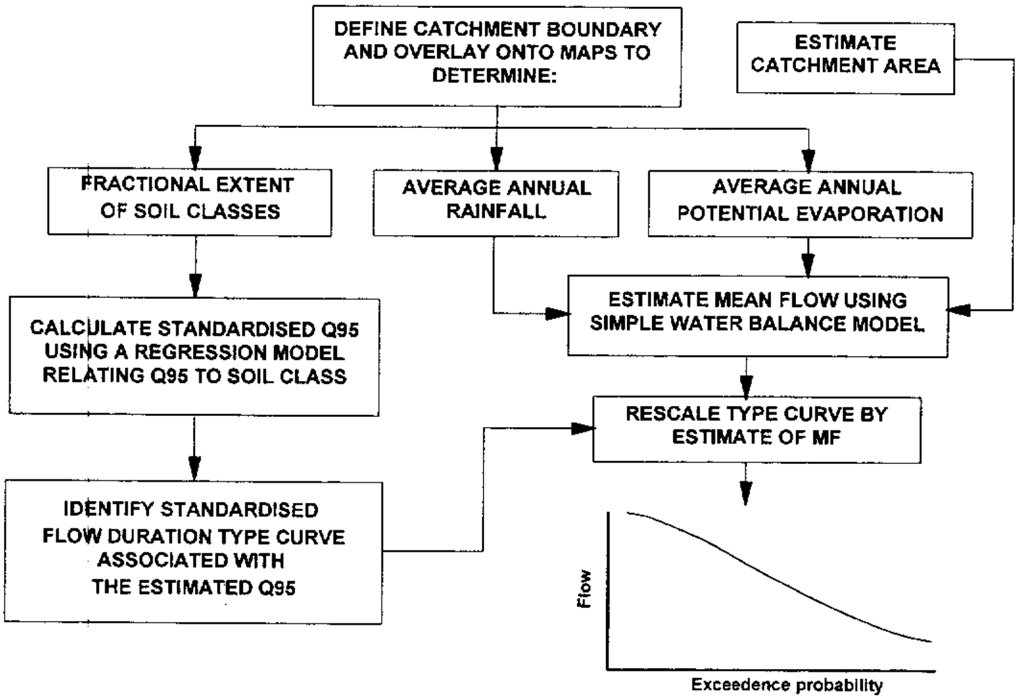

Figure 3.1 *Procedure for estimating natural long-term statistics*

3.1.1 Mean flow

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 when the rainfall is greater than 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:

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

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.

3.1.2 Low flow statistics

The Q95 (i.e. the flow equalled or exceeded for 95% of the time) flow statistic is expressed as a percentage of the long-term mean flow to minimise the control of the catchment area and variations in average annual rainfall on the magnitude of the low flow statistic. This is an essential step prior to regionalisation. The multivariate regression model relates the standardised Q95 statistic to the fractional extent of the Low Flow HOST Groups, based on the Hydrology Of Soil Types (HOST) classification (Gustard *et al*, 1992).

3.1.3 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 equalled or exceeded. In the UK, the gradient of a flow duration curve is principally controlled by the catchment hydrogeological response of which by the magnitude of the standardised Q95. is a robust indication

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 3.2.

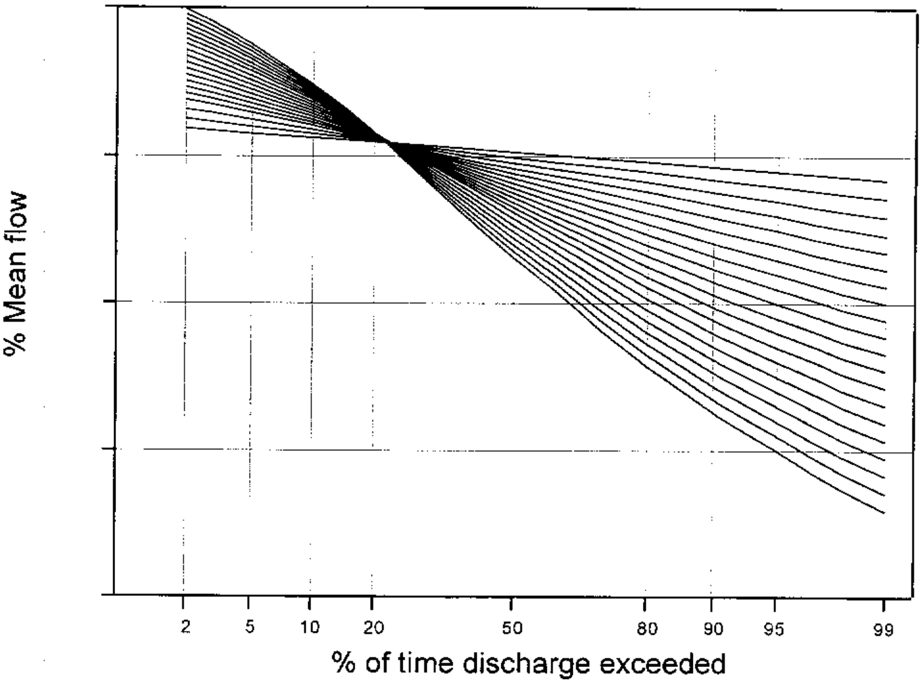

Figure 3.2 *Annual flow duration type curves*

3.2 MONTHLY STATISTICS

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) are used to identify the seasonal variations in the flow regimes. The overall estimation procedure for monthly statistics is summarised in Figure 3.3 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 flow duration curve.

3.2.1 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 MRV can be determined directly from series of maps (Bullock et al, 1994) or from a set of tables, depending on the magnitude of the long term Q95. The MRV then needs to be converted to a discharge in cumecs by scaling by the long-term mean flow.

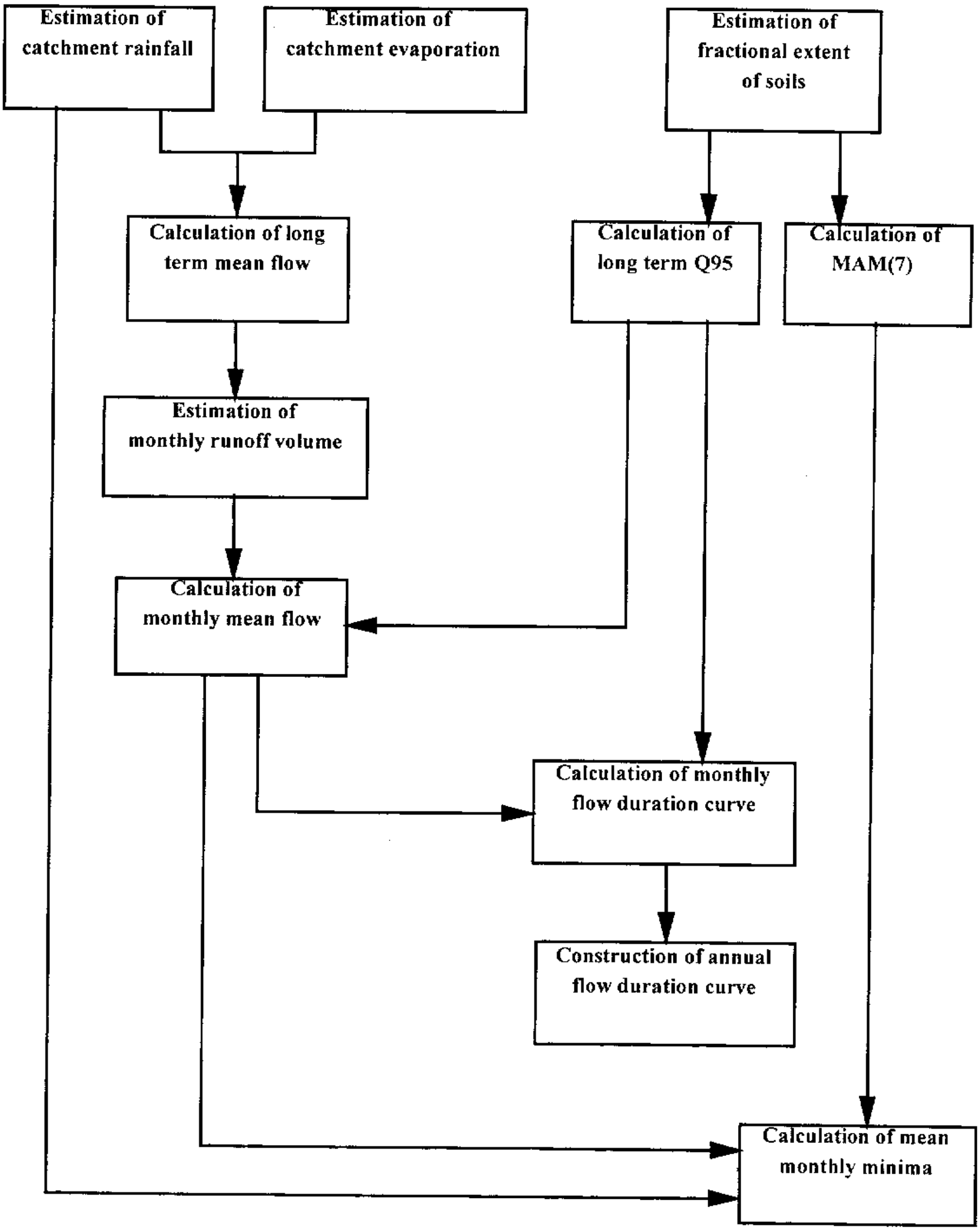

Figure 3.3 *Procedure for estimating natural monthly statistics*

3.2.2 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 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, which represents the annual type curve that most closely matches the pooled monthly flow duration curves.

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 type curves directly to avoid inconsistencies. Therefore, this can be done by making adjustments to the individual points of each curve.

4 Enhancement of the natural hydrological model for the Yorkshire pilot study area

4.1 EXISTING METHODS FOR 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. 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 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 characteristics can be determined.

As discussed previously, the Q95 model within Micro LOW FLOWS is based on the low flow groupings of the Hydrology Of Soil Types (HOST) classes into Low Flow HOST Groups (LFHG), which incorporates hydrological information from gauged catchments with the physical properties of the soil series.

A grid of Q95 was generated from the HOST database using the parameter estimates derived from the multivariate regression between Q95 and the proportional extent of LFHGs. The parameter estimates are given in Report 108. The digital database of Q95 is archived within the software at a resolution of 1 km x 1 km. In common with the rainfall and potential evaporation, the catchment average Q95 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 DISTRIBUTING THE MEAN FLOW AND Q95

An implicit assumption in the estimation of Q95 is that the temporal distribution of flows is coherent over all parts of upstream catchment. For this to be valid, then all stretches within the catchment would have to experience temporal coherence of rainfall, evaporation and catchment response. These conditions may occur in small catchments, but are unlikely to occur in larger catchments, particularly in catchments where there is a diverse mixture of impermeable and permeable geology within the catchment.

As described in the previous section, 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 disregards any variations in the response due to the hydrogeology. By considering the catchment above a stretch as consisting of a series of small 'sub-catchments', which although not necessarily contiguous in space are homogenous in hydrogeology (ie LFHG), and making use of the low flow statistics calculated at a monthly resolution, then the timing of low flows can be taken into account.

As described in Chapter 3, the annual runoff is based on a water balance where the losses are a function of the rainfall: when the rainfall is high, the actual evaporation is equal to the potential evaporation; when the rainfall is less than 850 mm, then soil moisture deficits and plant requirements mean that the actual evaporation is less than the potential evaporation. 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 significant in upland catchments that may experience high rainfall gradients across the catchment; an adjustment factor can be applied to the potential evaporation in the low rainfall areas but not in the high rainfall areas. Previously a simple average of rainfall and evaporation would have been taken across the catchment, from which the annual runoff was calculated. However, the distribution of the annual runoff has been taken one step further by calculating the runoff on a cell by cell basis.

4.3 INCORPORATING THE TIMING INTO 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. During the reporting period, 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.

4.4 VALIDATION OF THE RESULTS IN YORKSHIRE

An assessment of the performance of the distributed estimation procedure has been undertaken for locations in the Aire catchment. The difference between the Q95 generated using the existing and revised techniques are illustrated in Figures 4.2.

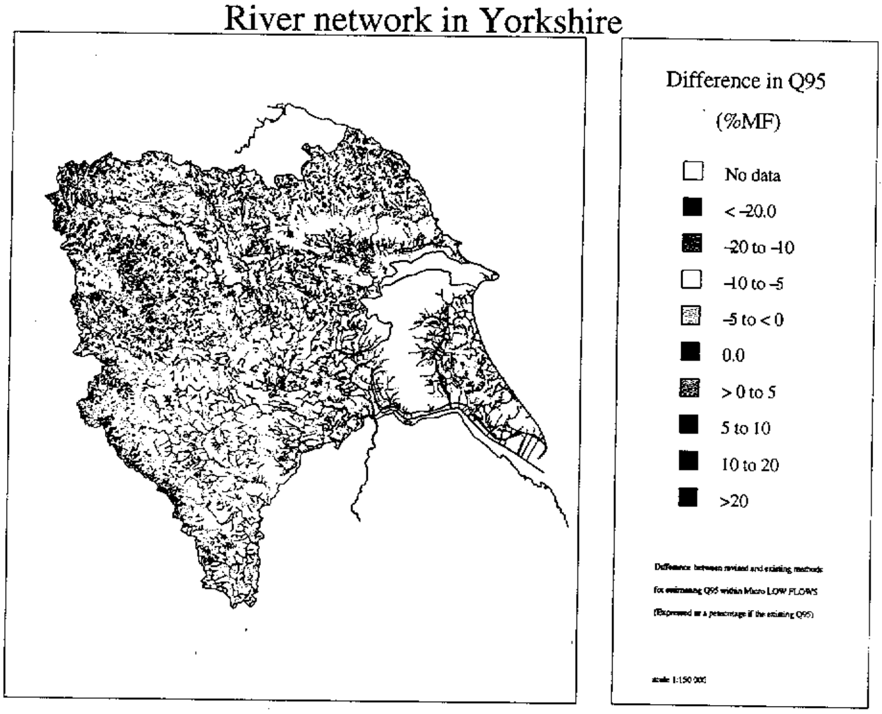

Figure 4.2 *Differences in the Q95 in Yorkshire*

From Figure 4.3, there is little variation between the Q95 estimates derived using the old and new methods in the headwater catchments. This is principally as a result of the distribution of HOST classes within the catchment remaining constant in the smaller catchments. As the catchment increases in size, then the difference between the old and new Q95 becomes more pronounced. In particular, it should be noticed that the distributed Q95 is significantly lower than the existing Q95 at Beal Weir. This reflects the variations in the geological characteristics in the larger catchments and the strong west-east rainfall gradient from the Pennines to the Vale of York.

The differences for a number of specific locations within the Aire catchment are given in Table 4.1.

Table 4.1 *Percentage difference in the Q95*

	Location	Percentage change in natural Q95
Downstream location in catchment	Beal Weir	≥ -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%

From Table 4.2, the variations with catchment size can clearly be identified. 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.

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.

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. 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.

Therefore, since the lower part of the catchment are more permeable a consequence of the mean flow model, these standardised Q95 response will be re-scaled by a smaller mean flow, thus yielding a lower Q95. The upper part of the catchment, whilst being re-scaled by a higher MF have a much lower standardised Q95. The net effect is negative in the context of the Yorkshire model. This is a direct consequence of the strong west-east rainfall gradient.

5 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) and discussed in detail with Environment Agency and National Water Archive staff at the Institute of Hydrology.

5.1 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.

5.2 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 gauging stations by applying a ratio of gauged estimate of effective runoff to the estimated effective runoff. In headwater stretches, the ratio is applied to all stretches upstream of gauging stations. Further downstream, the ratio is determined by a weighted average of the effective runoff from upstream and downstream gauges to the estimated runoff weights.

For any stretch, the locations of all gauging stations upstream are identified and also the location of the next downstream gauging station along the main stream channel is identified. Each stretch can have one associated downstream gauge, but several associated upstream gauges due to dendritic structure of the river network. From the selected gauging stations, only the 'natural' gauges are used in the adjustment, as identified in the previous section.

For each ungauged stretch, the empirical calibration factor applied to the mean flow is calculated from the upstream and downstream natural gauges that directly affect the stretch. Weights are determined by 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.

Figure 5.1 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 the distributed mean flow (ie runoff calculated on a 1km^2 grid square basis) is higher than the mean flow derived using the existing methods. The calibrated mean flow, is now very close 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

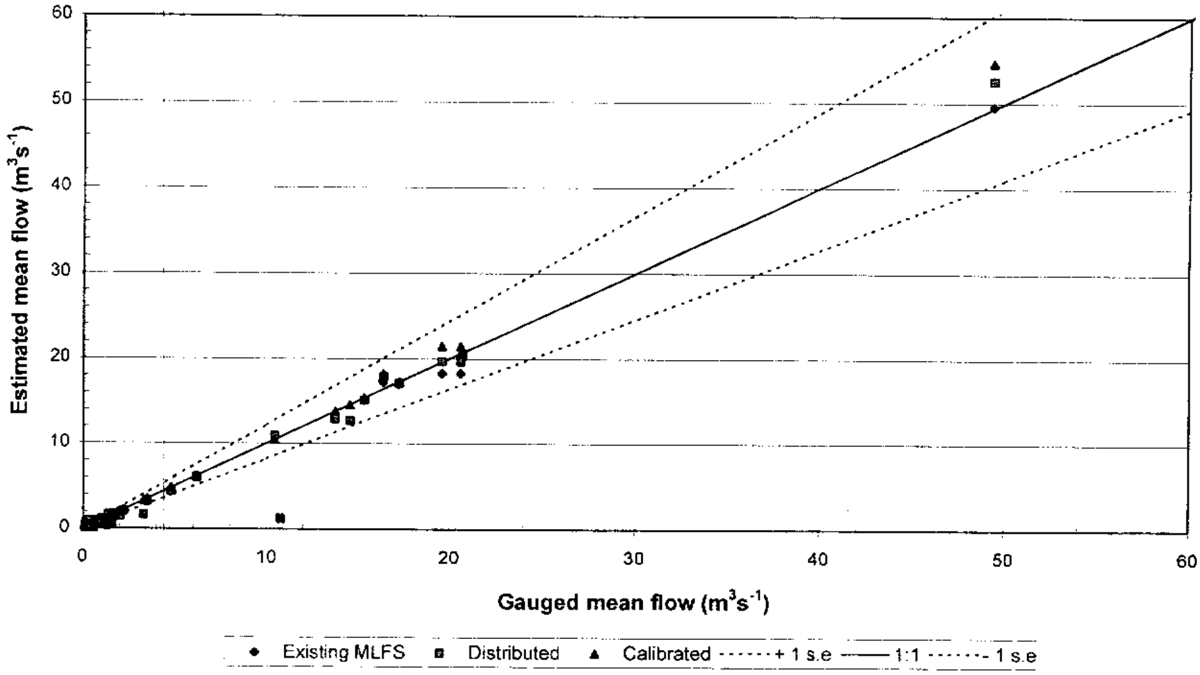

Figure 5.1 *Micro LOW FLOWS estimates of mean flow*

6 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 have been collated. The data have been loaded onto the revised Micro LOW FLOWS 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.

6.1 ARTIFICIAL INFLUENCE DATA

6.1.1 Abstraction data

Data for in excess of 3000 sites were provided by the Environment Agency for the whole of Yorkshire, with approximately 500 sites in the Aire and Calder catchments. The data, provided as spreadsheet files, contained licence details including licenced quantities, licence periods and time series of actual annual abstraction volumes for past 10 years. Using the actual abstraction volumes, an average annual abstraction rate was calculated for each purpose and site.

Within Micro LOW FLOWS, the techniques for incorporating artificial influences requires the identification of net monthly influence profiles upstream of a stretch. 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.

The distribution of abstractions within the Aire and Calder catchments are illustrated in Figure 6.1 and the number of abstractions for different purposes above gauging stations in the Aire and Calder catchments are illustrated in Figure 6.2. 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 are 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 6.3.

6.1.2 Discharge data

Information on the 50 principal discharges in the Aire, Calder & Don-Rother catchments were provided by Yorkshire Water Services. 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 (ie 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.

6.1.3 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).

Subsequent information was been made available from the Environment Agency, including detailed descriptions of the reservoir structures and the relevant Water Resource/Reservoir Acts which have specified the compensation release requirements. For selected reservoirs, additional time series information of compensation releases and overflows were provided by YWS via the Agencyfrom which average monthly release profiles from the reservoirs were determined.

It should be noted that the time series of reservoir data came in a variety of different formats and a variety of different units (not always documented). Therefore considerable effort was required to process the data to calculate monthly release profiles in cubic metres per second 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).

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.

6.2 CALIBRATION OF THE SOFTWARE

The first stage of the calibration was to ensure that the artificial influences, especially the reservoirs, were located on the correct stretch during the automatic loading procedures since potential problems can arise where the influence is located close to the confluence of two stretches.

Having loaded all the influence data, influenced estimates of mean flows across the catchment indicated that there were significant underestimates when compared with the influenced flows measured at the gauging stations. These discrepancies 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. Therefore, it could be assumed that the anomalies were as a result of anomalies in the abstraction profiles and unrepresentative discharges such as returns from cooling water abstractions..

Within the software, Micro LOW FLOWS applies an uptake factor to the annual licence to predict an abstraction rate in the absence of actual monthly data. Therefore, by considering the licensed monthly abstractions to be equal to the actual monthly abstraction profiles, the uptake factors can be optimised to improve the estimates of mean flow compared when with the gauged influenced mean flow within the catchment. 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 calibration factors are presented in Table 6.1.

Table 6.1 *Optimised uptake factors*

Abstraction Purpose	% uptake
Spray Irrigation	100
Cooling Water	4
Industrial Processes	48
Public Water Supply	60
British Waterways	0
General Agriculture	50
Private Water Supply	20
Fish Farming	2
Mine Drainage	100
Undefined	20

Table 6.1 shows that the percentage uptake for cooling water is only 4%, ie that 96 percent of the water is returned. 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.

6.3 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;

3. Optimising the characterisation of the complex artificial influences within the basin to improve the influenced mean flow estimates.

The overall impact of the enhancements are illustrated in Figures 6.5 and 6.6.

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