

BRITISH HYDROLOGICAL SOCIETY

Analytical techniques for the development and operations planning of water resource and supply systems

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Modelling Water Storage and Transfer in the Anglian Region

Steve Cook[1], Nigel Fawthrop[1] & Glenn Watts[1]

Abstract

For the NRA's national and regional water resources strategies it was necessary to calculate the yields associated with potential enhancements of the Anglian Region's strategic surface water supply systems. Four existing computer models were adapted and linked to deal with options such as additional reservoirs or transfer of water from the Trent. The use of existing models had the advantage of consistency with earlier work but it did mean that slightly different methods were used for modelling each system. The results provided suitable accuracy for the purposes of the water resources strategies but for more complex or more detailed studies it may be necessary to develop new models.

Introduction

The National Rivers Authority has been working on national and regional water resources strategies for the last two years. The aim of these is to ensure that legitimate needs for water are met in a way which is environmentally sustainable; this means that water resource development should not cause long term deterioration in the water environment and preferably should contribute to the net improvement. The national strategy was published in March 1994 (NRA 1994a), and the Anglian regional strategy was launched in September 1994 (NRA 1994b). For both of these it was necessary to evaluate the yields of existing surface water storage and transfer systems and to investigate ways to enhance the availability of water in the Anglian Region. This paper describes the methods used to calculate the yields of these systems under a variety of development options.

Surface water resource systems of the Anglian Region

There are many reservoirs and transfer schemes in the Anglian Region. Only surface water systems of strategic importance are considered in this paper.

As shown in Figure 1, the major components of the existing system are:

- Trent - Witham - Ancholme Scheme (TWA)
- Rutland Water
- Grafham Water
- Ely Ouse - Essex Transfer Scheme (EOE)

Trent - Witham - Ancholme Scheme

The TWA scheme is used primarily to augment flows in the River Ancholme to meet demands of all kinds in South Humberside. Flows in the River Ancholme are regulated by a transfer of water from the lower River Witham at Short Ferry to the upper Ancholme at Toft Newton. The transfer can also be used to reduce saline intrusion in the Ancholme. In low flow periods the Witham can be augmented by a transfer from the Trent at Torksey through the Fossdyke Canal. TWA transfers are controlled by the NRA.

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Rutland Water

Rutland Water is a pumped storage reservoir in the valley of the upper Gwash in Leicestershire. It has a total volume of 137 million cubic metres. Rutland is filled from the Nene at Wansford and the Welland at Tinwell. Both of these abstractions are controlled by "hands off" flows (also known as "minimum residual flows"). Rutland is owned and operated by Anglian Water and is used to supply water to Peterborough and the Northampton area.

Grafham Water

Grafham is also a pumped storage reservoir. It is situated in a side valley near to the Bedford Ouse in Cambridgeshire, and has a total volume of 56 million cubic metres. Water is pumped from the Bedford Ouse at Offord; the abstraction is controlled by a hands off flow above which 75% of flow may be taken. Grafham is owned and operated by Anglian Water and supplies water to Northampton and Bedford; Three Valleys Water Company are also entitled to use water from Grafham. Rutland and Grafham (together with Pitsford, an 18 million cubic metre reservoir near Northampton) form Anglian Water's RUTHAMFORD conjunctive use system.

Ely Ouse - Essex Transfer Scheme

This scheme transfers water from the Ely Ouse to three of the Essex rivers. The transfer starts at the tidal limit of the Ely Ouse at Denver; water is passed upstream through a flood relief channel (the Cut-Off Channel) and then transferred through a tunnel and pipeline to the upper Stour at Kirtling Green. Some 15 km downstream at Wixoe an abstraction transfers some of the water through a pipeline to Great Sampford on the Pant (the name given to the upper reaches of the Blackwater). It is also possible to release water at Cornish Hall End on the Colne, but this facility is used very rarely. The main purpose of the transfers is to provide additional water to the reservoir intakes on the Stour (for Abberton) and the Blackwater (for Hanningfield), although the transfer is operated occasionally to alleviate water quality problems. The Ely Ouse - Essex transfer is operated by the NRA but Abberton and Hanningfield reservoirs belong to Essex and Suffolk Water Company.

Development options

Several development options have been considered in the Anglian regional strategy. These include:

- Reducing the hands off flow at Denver (making more water available for transfer to Essex)
- Constructing a new reservoir in the Ely Ouse - Essex transfer system (storing winter water and therefore improving the yield)
- Re-routing Chelmsford effluent to upstream of the Hanningfield intake
- Importing water from the Trent through the Trent - Witham - Ancholme scheme to Rutland, Grafham and Denver
- Transferring water to Thames Region by extending the Ely Ouse - Essex system

These options have been considered individually and conjunctively, and are shown schematically in Figure 2.

Method of assessing system yields

The strategies required calculation of the baseline yields of the existing systems and the increase in yield (termed the marginal yield) of each option. The method used is known as "behavioural analysis"; this involves simulating the operation of the system using a daily time step over the historic period (1932-92) to determine how much water could have been taken into supply. Existing resource simulation models were adapted for the strategy work. Four separate models were available :

- Trent - Witham - Ancholme
- Rutland
- Grafham
- Ely Ouse - Essex

Each of these had been developed at different times and for different purposes. All of the models are coded in FORTRAN 77 and run on IBM PCs. All of the models were either developed entirely in house or in conjunction with Anglian Water; the NRA has access to the code for all of them.

Trent - Witham - Ancholme model

This model performs a daily simulation of the TWA scheme. Water balances are calculated at strategic nodes in the system. Demands in the Ancholme and Witham are satisfied first using local water; if this is not available transfers from the Trent are used. The model was originally intended to calculate the transfer required from the Trent to satisfy specified demands and does not calculate the yield of the system.

Rutland yield model

The yield of Rutland (and Grafham) is calculated using the Operating Strategies method of Assessing Yield (OSAY) (Clarke *et al, 1980*). This method involves the derivation of control rules for the introduction of water conservation measures, the simulation of these rules over the historic period and the comparison of the resulting frequencies of introduction of the conservation measures with target levels of service.

Yield is defined as the volume of water that can be taken from the reservoir such that it does not empty over the historic period of record and restrictions on supply do not have to be imposed more often than the target frequency. It is calculated iteratively using a search procedure which simulates reservoir behaviour over the historic period at different demands and with different control curves, seeking a demand at which restrictions are applied the specified number of times.

The OSAY program requires as input potential reservoir inflow sequences as monthly totals. These are prepared using a FORTRAN program from daily historic flow records which are naturalised and then de-naturalised for future conditions. The available inflow sequence is calculated taking into account pumping restrictions and hands off flows. The available inflow sequence reflects only water availability and licence conditions and is the total volume of water available to the reservoir.

OSAY calculates the yield of the system but does not determine how much water would have to be abstracted to sustain this yield. For calculation of the impact of this yield on downstream flows a further program is used; this simulates daily operation of the reservoir at a defined yield.

Grafham yield model

The Grafham programs perform in exactly the same way as those used for Rutland, although different operating procedures and system configurations mean that different FORTRAN programs are used. It should be noted that the yields of Rutland and Grafham are calculated separately; there is currently no conjunctive yield model for the RUTHAMFORD system.

Ely Ouse - Essex system model

The basic water resources and associated water supply systems of the Ely Ouse - Essex system are represented in a daily simulation model of two parallel systems representing the Stour - Abberton system and the Blackwater - Chelmer - Hanningfield system. Operation is simulated on a daily time step for the period of historic flow data. The yield of the system is defined as the maximum uniform demand which could be met over the historic data period without failure. Failure occurs when one of the supply reservoirs in the system empties. This is calculated by running the model with different demands until the demand which the system can just sustain is found. Simulation times can be significant, especially if long river flow records are available. The Ely Ouse - Essex system is complex and the model reflects this complexity with many options for reservoir operation and pump capacities defined in an input file.

Linking the component models

For options involving transfers from the Trent to Essex or to Rutland and Grafham it was necessary to establish a way of linking the component models. The method used was to output information from each model in files that could be read by the next model. This required very little modification of the existing models and has the advantage that each model can still be used separately, ensuring that consistency of results can be checked. The development was facilitated by having access to the codes for each model and an understanding of model operation. A linking program was written to ensure that only the correct files could be used in each component model. The basic procedure for operation is:

1. Run the Trent - Witham - Ancholme model to determine how much Trent water is needed to meet Ancholme and Witham demands and how much is available for transfer further south.

2. There are two options for transfer: direct to Denver (for Essex) or via Rutland and Grafham to Denver.

   A *Direct to Denver.* The available water from the Witham is added to the water available from the Ely Ouse and the EOE model run in the usual way.

   B *Transfer via Rutland and Grafham.* The exact mode of operation depends on which system has first priority for water. Transferred water is made available to each system in turn according to priority; remaining transferred water is available to the next system. Each component model is operated in the usual way.

3 Actual volumes of water required from the Trent and the other rivers involved are calculated, together with information about the time transfers are in use. This information can be used to determine the cost of each option and was required for the national resource strategy.

Modifications to the computer code were minimised but it was necessary to adapt the EOE model to incorporate additional reservoirs. Changes to the models were facilitated by having access to the codes and sufficient `in house' programming skills to make the modifications and test them thoroughly. Each run of the complete suite of models takes about 30 minutes but this includes significant user input. The EOE model has the longest simulation time at about 10 minutes on a 486 25 MHz PC.

Results

Initially some 60 different combinations of options were investigated for two different periods. The first simulations covered the period 1972 to 1992 because flows were available for all of the rivers for this period. Subsequently this was extended to 1932 to 1992 as extended flow records became available for the Trent and the Witham. The longer period was adopted as a standard for results quoted in both the national and regional strategies. As options were refined additional scenarios were modelled, and significant effort was devoted to establishing (by trial and error) control rules for use in the Ely Ouse - Essex system when additional reservoirs were incorporated. In total the results of around 300 simulations were provided for the strategies, although in their final versions only around twenty options are covered. Results were provided to:

- NRA Anglian Region Water Resources Planners, for input to the regional strategy
- Consultants employed to manage development of the national strategy
- NRA national RESPLAN modelling (Page, 1994)
- NRA Thames Region, for input to regional resource simulation models
- Consultants employed to evaluate the environmental impact of development options.

Output was tailored to meet individual requirements and included:

- Baseline yield
- Marginal yields
- Time series of pumping durations and the volumes pumped
- Time series of simulated reservoir storage
- Time series of simulated river flows at many locations.

It is not possible to discuss all of these results in detail. An example of a time series of simulated river flows is given in Figure 3. This was used in the analysis of the environmental impact of the different options. Two further examples will be used to demonstrate in more detail the way that results were used.

Example 1 : Additional reservoir in the Ely Ouse Essex system (no transfers from the Trent)

Two locations for an additional reservoir in the Ely Ouse - Essex system have been identified. Great Bradley, at the top of the Stour, was established as a possible site in the 1970's. In 1992 Essex and Suffolk Water Company identified an alternative site in the Fens near Ely; this is known as the `Fenland' site. Simulations demonstrated that reservoirs of the same size could produce the same yield at either location.

Figure 4 shows the additional yield available from different sizes of Great Bradley reservoir for different pump sizes in the Ely Ouse - Essex transfer system. No increase in intake capacities for the Essex reservoirs is involved and Great Bradley is used to supply water to Abberton and Hanningfield (no water enters supply directly from Great Bradley).

It can be seen that increased reservoir size increases the marginal yield of the system. Increasing the size of the pumps in the transfer from small (current) capacity to medium capacity adds significantly to the marginal yield of the system. However, a further increase in pump size adds little to the yield, especially with the smallest and largest reservoir sizes considered.

With a small Great Bradley the extra pump capacity is wasted because there is insufficient storage for the additional water. With a large Great Bradley marginal yield is controlled by other factors such as intake capacity for the Essex reservoirs and the water available at Denver; additional pump size in the Ely Ouse - Essex transfer has little impact on the yield.

Example 2 : Transfers from the Trent to Essex

This example deals with transfers of Trent water directly from the Witham to Denver, without providing water to Rutland or Grafham. These simulations have been carried out both without an additional reservoir in the Ely Ouse - Essex system and with a Great Bradley reservoir of different sizes, and with two different Witham to Denver transfer capacities (Figure 5). In all of the options shown, the intakes for the Essex reservoirs have been increased to make use of the extra water available.

Making water available from the Trent to Essex enhances the yield of the Ely Ouse - Essex system. Even without any additional storage the yield is increased by about 75 tcmd (Ml/d) with a 200 tcmd pipeline capacity and 120 tcmd with a 400 tcmd pipeline capacity. This includes the effect of increased Essex intake capacities, worth about 5 tcmd with the small pipeline and 40 tcmd with the large pipeline.

Great Bradley Reservoir adds to the enhanced yield. The largest Great Bradley with a 400 tcmd transfer capacity adds almost 400 tcmd to the yield of the Ely Ouse - Essex system; this is 200 tcmd more than adding Great Bradley without the transfer.

Issues affecting the results

While it has been possible to calculate the yields of the major strategic surface water systems of the Anglian Region, many assumptions have had to be made. Issues of importance include:

Model differences

The models used define and calculate yield in different ways; the approach used for Rutland and Grafham defines levels of services while that used for the EOE system calculates the yield sustainable through the worst historic drought. Interim results from the NRA's recent R & D on reservoir yield (Wallace Evans, 1994) suggest that a levels of service approach may be most appropriate. The application of a levels of service approach to a system as complex as the Ely Ouse - Essex transfers may be difficult, especially where additional transfer and reservoir options are considered. Adoption of the different approaches means that yield results are not directly comparable, although the marginal yields are likely to be affected less by the differences than the total yields. Using existing models has ensured consistency with earlier work.

Length of record

All records used cover the period 1932 to 1992. This incorporates the worst drought known in the Ely Ouse - Essex system, in 1933 to 1934. However, interim results from the reservoir yield R & D suggest that yield should be calculated from records from 1920 onwards, except in the case of systems with a relatively high yield when data from 1880 onwards should be used. With the larger Great Bradleys the yield is a high proportion of daily flow, suggesting that this long period is necessary for the calculations. It is not clear exactly how such long records should be derived; the earliest gauged records in the Anglian Region start in the 1920's.

Availability of flow records

Even for the period from 1932 onwards, gauged flows were not available for all of the relevant rivers. Bedford Ouse, Ely Ouse and Essex river flows are available from the 1930's, but Nene flow gauging started in 1940 and Welland and Witham flows were not recorded until the early 1970's. Where necessary, records were extended using rainfall/run-off modelling. For the purpose of yield calculation it has been shown that inaccuracies in the calculated flows would not affect yields significantly (Watts, 1993) but this is a potential source of error, especially if the environmental impact of development is to be investigated. Even where flows are available from the 1930's it has not always been possible to naturalise these. The Essex river flows have been naturalised using the best available information (Binnie & Partners, 1993). No attempt has been made at naturalising Denver flows because of the unknown impact of Fenland water losses through sub-irrigation and evaporation. As a result, gauged Denver flows have been used in the modelling; this must have an impact on the yield although it is thought to be small (Watts, 1994).

Sensitivity to control rules

In the case of Ely Ouse - Essex transfers, control rules are built into the simulation model to determine the operation of the system. These have not been optimised although an attempt has been made to use rules which provide good levels of yield. This is particularly important in the case of simulations including extra storage at Great Bradley or the Fenland site. The operation of the additional reservoir also makes a difference to the yield of the total system; all of the results presented here assume no water is taken into supply directly from the new reservoir but passes to Abberton or Hanningfield. The definition of the failure of the Essex reservoirs also has an impact on the yield; simulations presented here assume that failure occurs not when Great Bradley is empty but when either Abberton or Hanningfield contains no water.

These issues do not invalidate the results of the simulations but they help to indicate the problems associated with modelling the yield of complex strategic water resource systems.

Costs of modelling work

All of the yield analysis for the Anglian Region's strategic surface water systems was carried out `in house'. In total the work took about 290 person days with 3 members of staff providing all of the input. This time includes program development to allow the models to be linked and to incorporate additional storage, the simulations themselves, comprehensive reports and analyses of the importance of uncertainty in the input data. It does not include the original development of the models. The work was distributed over about 18 months. The total cost (calculated from salary plus on costs) was approximately £ 49,000. One of the reasons for the spread of the work over such an extended period was that completion of one set of results led to requests for other scenarios to be investigated.

At no time was a complete specification for the project presented; requests evolved as more information became available and the national and regional strategies took shape. The results from very few of the 300 or so simulations appear in the final strategies but they all helped to shape the final documents. There are also many supporting documents which help to identify the accuracy of the work and should make it easier to replicate the results if necessary. On the whole, £ 49,000 for the volume of work carried out seems to represent reasonable value for money. It would be easy to save this amount by using these results to identify which development options do not require further (expensive) studies. The costs of designing, constructing and commissioning a reservoir are measured in hundreds of millions of pounds; preliminary studies such as that described here play a vital role in ensuring that subsequent effort is directed in an appropriate direction.

Discussion

Many simulations have been carried out to assess the value of different development options in the Anglian Region. The approach taken has good and bad aspects.

Advantages:

- A large volume of work was delivered on time and always with short deadlines
- The flexibility of the approach meant that additional questions could be addressed quickly and easily.
- Access to FORTRAN code (and programming skill) meant that new issues could be addressed readily.
- The work was consistent with previous work by the Anglian Water Authority.
- Close collaboration with the water companies (Anglian Water and Essex and Suffolk Water Company) during model development has resulted in a consistency of approach and provided many mutual benefits.
- The work achieved adequate precision for its purpose.
- Carrying out this work within the NRA ensured an understanding of the issues and assisted with staff development; the skills acquired are available for other regional work.

- The work demonstrated reasonable value for money.
- Ownership and understanding of the models meant that it was possible to transfer the EOE model to Essex and Suffolk Water Company allowing them to perform additional analyses.
- It will be possible to carry out further analysis whenever it is required, even at short notice.

Disadvantages :

- The models were not integrated seamlessly, which meant that care had to be taken to ensure that the correct files were passed between the component models.
- The models use relatively old techniques and do not include optimisation of control rules. However, they do incorporate behavioural analysis which is the nationally accepted approach. FORTRAN code does not seem to be a disadvantage because it is reasonably flexible; however some of the old models are not well structured.
- The component models are not well packaged, which means that computing expertise is required to run them and to look at the results.
- Use of existing models means that they do not calculate yield in exactly the same way.
- Conjunctive use of the RUTHAMFORD system is not simulated.
- Some components such as augmentation from groundwater are not incorporated in the models (it would be possible to add these).
- The results are sensitive to operating assumptions (this would be the case with other models).
- Input data (especially flows) is less accurate than is desirable (this would also be aproblem with any other model).
- The methods used are not consistent with those of other regions.

Conclusions

The approach described has proved to be a successful way to examine the yield of different surface water system configurations for the Anglian Region. However, it is not without its problems. The lack of consistency between the methods adds some uncertainty to the results, although marginal yields are probably comparable. Linking four separate models in this way had the advantage of consistency with earlier work but the simulations carried out stretched the method to its limits; for any more complex configuration than those described it would certainly be desirable to develop a new Ely Ouse - Essex system model, and it would be useful if a completely integrated model of all four systems were to be developed. However, the cost involved in this may not be justified against the possibly marginal increase in accuracy and the relatively small amount of time to be saved.

Even if such a model were developed there would still be uncertainties associated with factors such as the use of a limited period of flow record (in this case 1932 to 1992) and with different definitions of yield. The accuracy of the existing models and data appears to be acceptable for the national and regional strategies, and the ability to investigate different options at short notice has been a definite advantage of the approach taken.

Acknowledgements

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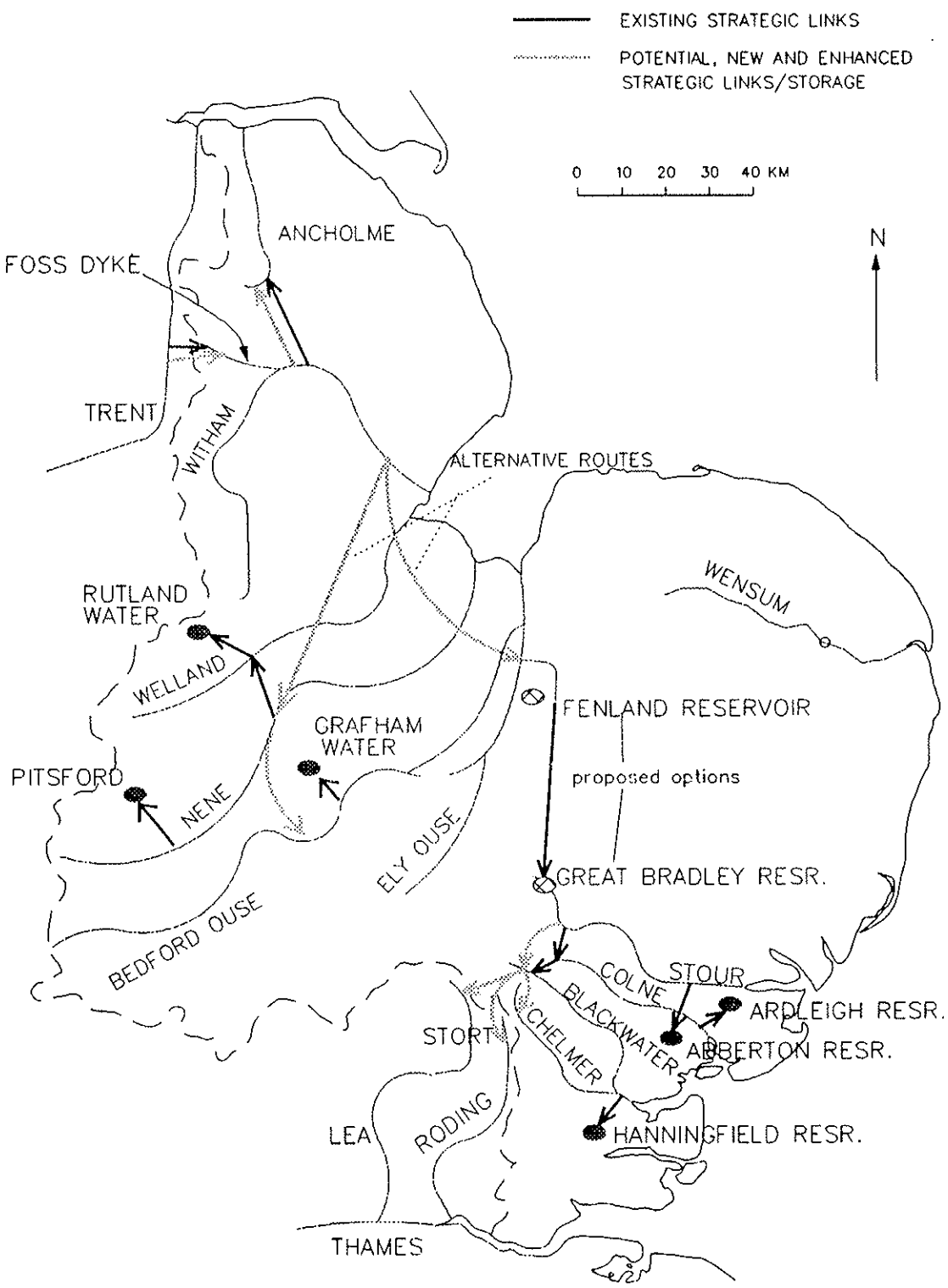


Figure 1 : Major surface water systems of the Anglian Region

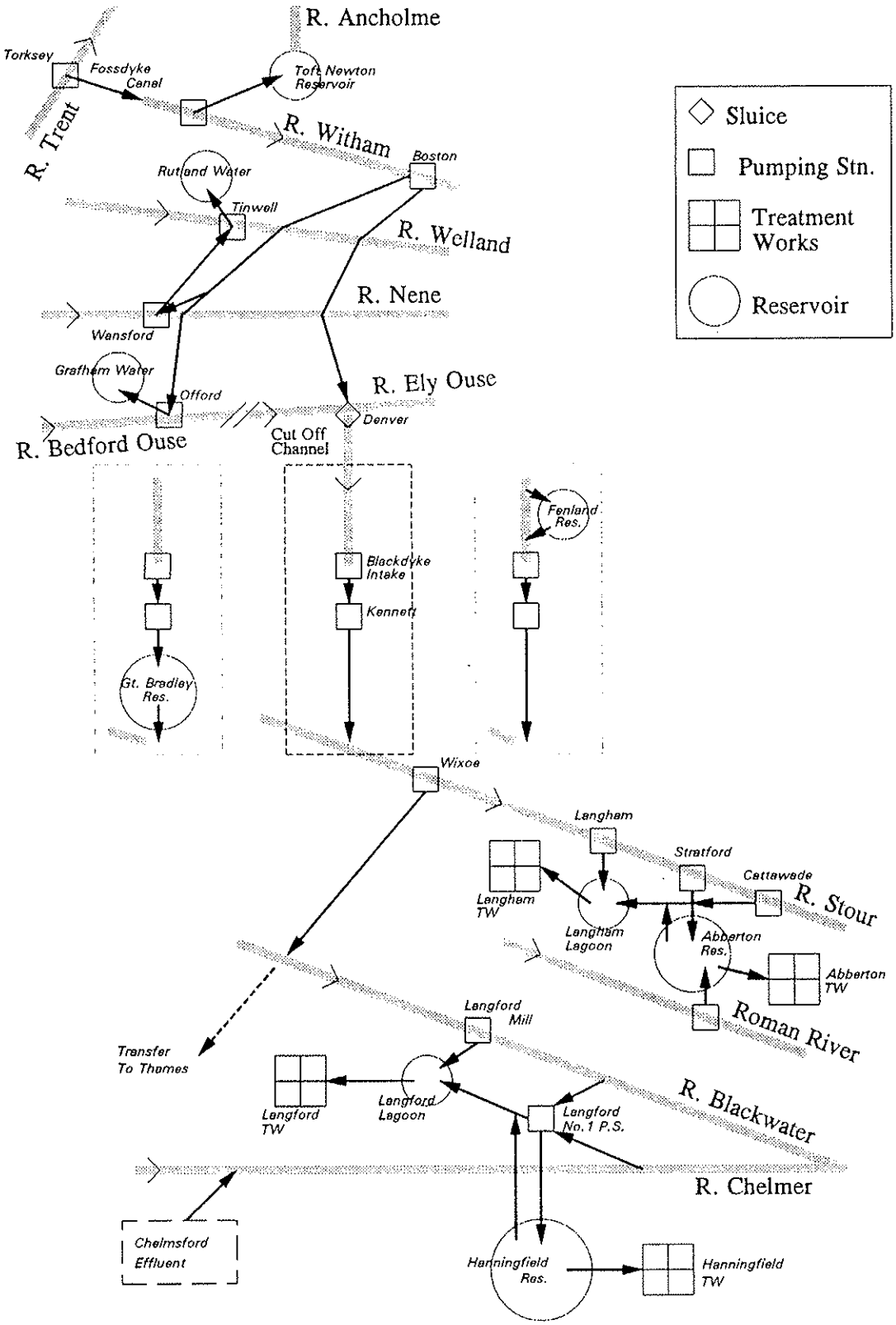


Figure 2 : Schematic diagram of Anglian Region development options

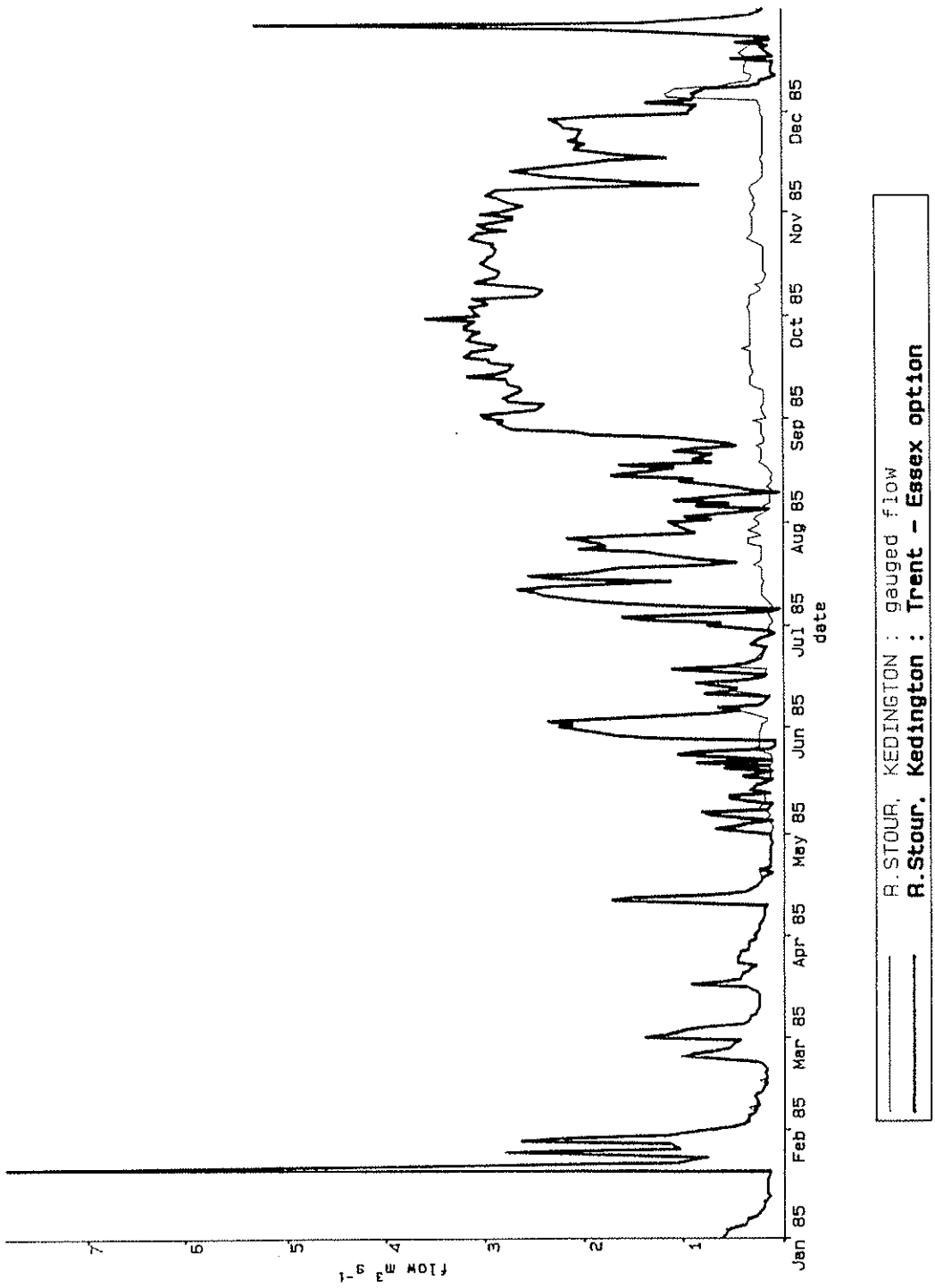


Figure 3 : Hydrograph showing the impact of reservoir development on river flow

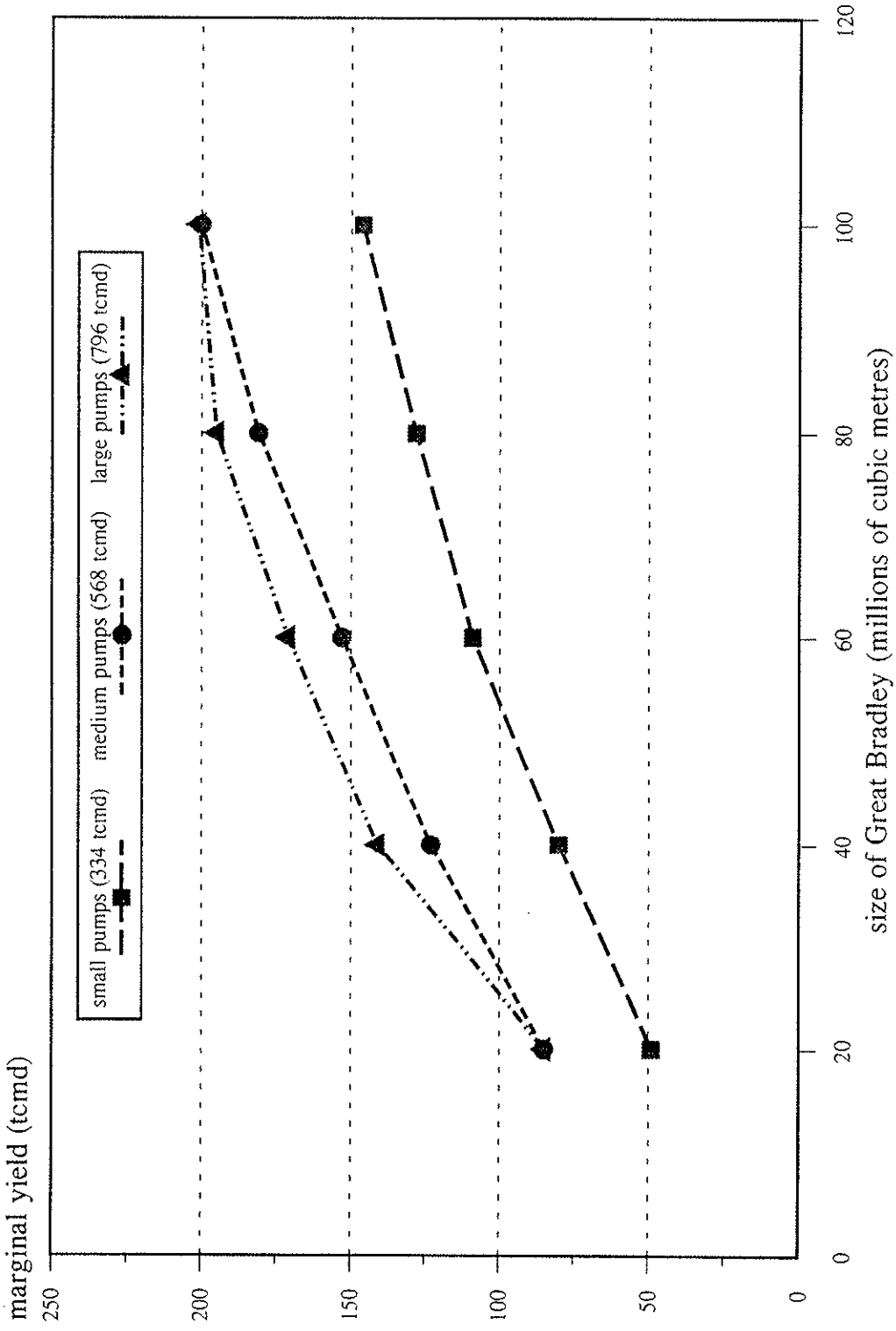


Figure 4 : Additional yield available from different sizes of Great Bradley

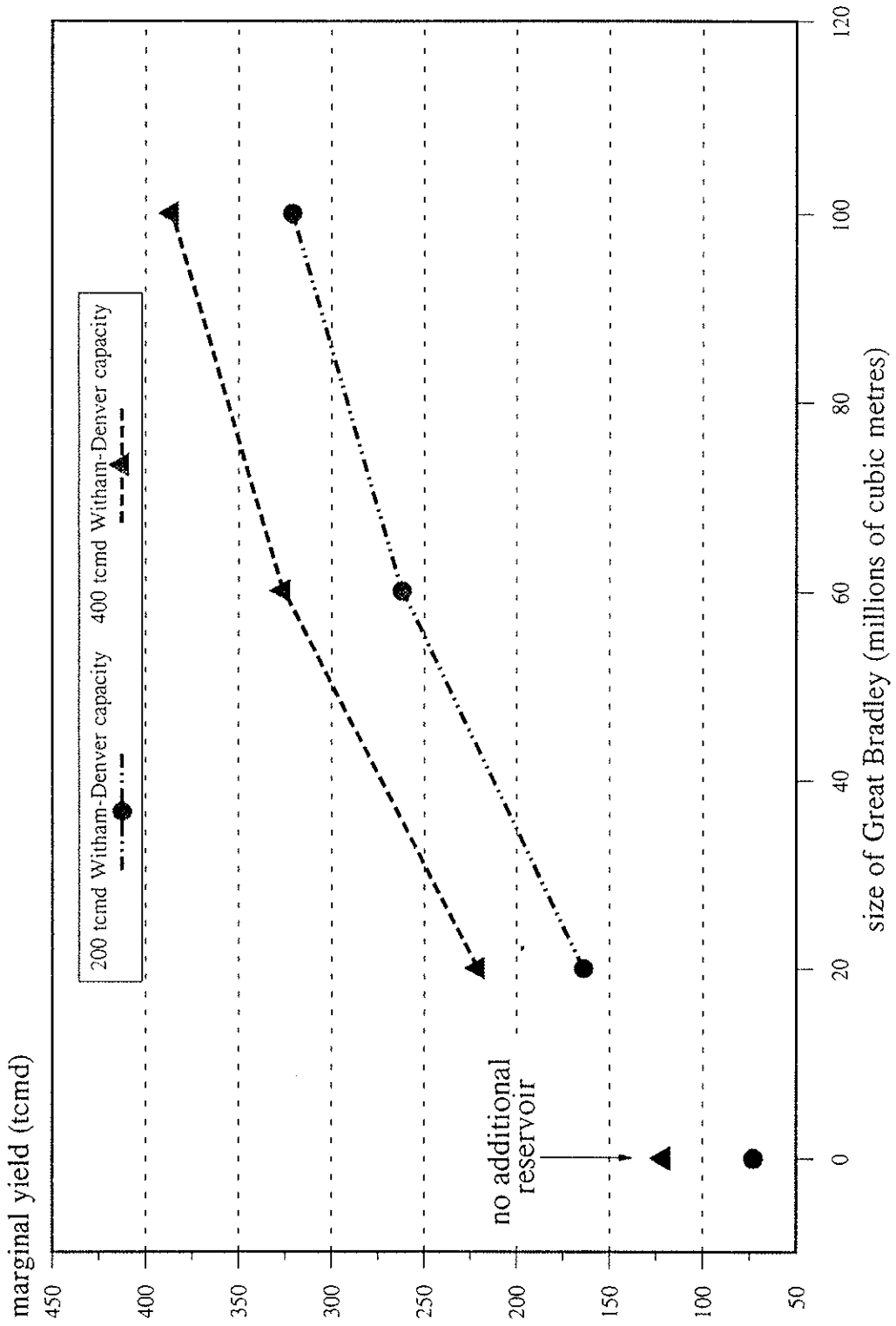


Figure 5 : Additional yield with different sizes of Great Bradley supported by Trent transfers

Modelling the Possible Re-Deployment of Lake Vyrnwy

Hilary Smithers[1] & Timothy Wyatt[2]

ABSTRACT

The paper describes modelling work undertaken to investigate the operational implications associated with a number of scenarios for re-deploying Lake Vyrnwy. A brief description is given of the methodology and the computer program used, together with a summary of the results obtained. Suggestions are made regarding ways of improving utilization of Lake Vyrnwy as a water resource, and aspects which should be considered in subsequent analyses. An appraisal is included of the modelling performed and computer program employed.

INTRODUCTION

Lake Vyrnwy is located in North Wales and was formed by building a masonry dam on Afon Vyrnwy, a tributary of the River Severn. Construction of the dam, together with the associated aqueducts and treatment works, were financed by Liverpool Corporation. On its completion in 1892, the lake formed the largest artificial reservoir in Europe. The scheme was designed to meet the growing demands for water in Liverpool and its environs.

The reservoir is now owned and operated by Severn Trent Water plc (STW), with the abstraction licence being held by North West Water plc (NWW). In addition to providing direct supplies the reservoir is used to regulate flows in the River Severn by making releases from a 5,800 Ml 'Water Bank'. Thus Vyrnwy represents a major source of water in terms of both NWW's Southern Command Zone (SCZ) and the River Severn system (Figure 1).

In March 1992, the National Rivers Authority (NRA) published a discussion document on the current and projected balance between water resources and demands in England and Wales, and identified a number of options for meeting future demands (NRA, 1992). Among the possible strategic options was to increase the regulating function of Lake Vyrnwy and hence abstractable flows from the River Severn.

Following discussions with NRA - North West Region (NRA-NW) and NWW, Power & Water Systems Consultants (PWSC) were invited to assist in investigating the likely effects of such re-deployment. Specifically, analyses were to be undertaken :

a) to estimate the magnitude of the direct supplies which would be available to NWW from Lake Vyrnwy if regulation releases were to be increased, and the likely variations that would be associated with such supplies;

b) to estimate the value of Lake Vyrnwy supplies within the present and future SCZ system of NWW;

c) to estimate the marginal costs of operating NWW's Northern Command Zone (NCZ) system and identify its maximum yield, so as to establish the costs and availability of transfers needed to meet any supply shortfalls in the SCZ system.

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[2] Power & Water Systems Consultants Ltd.

Due to the initial lack of time series data for historic and proposed patterns of regulation releases from Lake Vyrnwy, the preliminary evaluations assumed a constant daily compensation release, and constant regulation releases during the months of March - October inclusive (PWSC, 1993). Following receipt of the requisite release sequences, the operation of Lake Vyrnwy was re-analysed (PWSC,1994).

The following sections describe the way in which independent operation of Lake Vyrnwy has been analysed. Work associated with modelling and optimising operation of the SCZ and NCZ systems has been described elsewhere (Ringham, Walker & Wyatt, 1994), together with details of parallel studies undertaken by NRA-NW and NWW to identify ways in which reduced direct supplies from Lake Vyrnwy might be replaced. Alternatives considered included increasing current levels of abstraction from the River Dee and the development of new resources within NWW's supply area. The associated capital investments were estimated and these, together with results of the modelling work, provided data for use in the NRA's evaluation of alternative development strategies for meeting national demands up to the year 2021 (Page, 1994).

EXISTING OPERATION OF LAKE VYRNWY

Lake Vyrnwy is currently operated in accordance with a set of written procedures (Severn Trent Water Authority, 1985). Direct supplies are abstracted via a draw-off tower and taken approximately 30 km to the Oswestry Treatment Works through four cast iron and steel pipelines. Only three of these lines are currently operated and the effective transfer capacity to the treatment works is therefore reduced to some 200 Ml/d. Between Oswestry and the terminal storage reservoir at Prescot, a distance of about 80 km, the Vyrnwy Aqueduct is composed of three pipelines. The gravity capacity is currently estimated to be 173 Ml/d, with maximum throughput rising to 253 Ml/d if two of the lines are boosted at Bickerton pumping station.

The normal compensation release from Lake Vyrnwy is 45 Ml/d. However this is reduced to 25 Ml/d if flow at the Cownwy Gauge is above 20 Ml/d and the reservoir is drawn down by more than 0.5 m. The original Lake Vyrnwy compensation requirements provided for some 725 Ml/month to be released for downstream flow augmentation between the beginning of March and the end of October. Under the Lake Vyrnwy Compensation Variation of 1978, this requirement was modified such that regulation releases would in future be made from a 5,800 Ml 'Water Bank'.

On the 1st day of each month from March through October, 725 Ml is 'added' to the Water Bank. Water stored in the Bank is then available for release at the discretion of STW. Subject to certain restrictions, unused contents of the Water Bank may be carried over from one year to another. The pattern of releases, and the degree to which the Water Bank is exploited, vary considerably from year to year.

A flood drawdown line operates between the 15th of September and the 1st of March. If the contents of Lake Vyrnwy are above this line then, subject to certain downstream flow conditions, discharges are made to reduce the volume of water stored to that target. On any day the total daily compensation, regulation and flood drawdown release is limited to 405 Ml.

RE-DEPLOYMENT ALTERNATIVES ANALYSED

Five re-deployment scenarios were investigated, expressed in terms of the minimum direct supply (MDS) that would be available to NWW. These are shown in Table 1, together with the constant March-October regulation releases and associated (theoretical) Water Bank capacities.

Minimum Direct Supply (MDS) Rate Ml/d	Regulation Release March-October Ml/d	Associated Water Bank Capacity Ml
198.37 [1]	23.75	5,818
173.00 [2]	56.12 [3]	13,750
120.00 [4]	123.85 [3]	30,344
60.00 [5]	200.43 [3]	49,106
0.00	277.46 [3]	67,977[6]

1 Existing conditions; minimum direct supply rate consistent with maintaining a minimum storage of 6,500 Ml and determined within the study.

2 Maximum gravity supply rate through the Vyrnwy Aqueduct.

3 The maximum regulation releases consistent with maintaining the corresponding minimum direct supply rate and a minimum storage of 6,500 Ml; determined within the study.

4 Rate investigated on the assumption that maximum abstraction rate from the River Dee at Huntington increased by 80 Ml/d.

5 Minimum practical throughput assumed for the Vyrnwy Aqueduct and Oswestry Treatment Works, based on need to meet local demands.

6 At this rate the corresponding 'Water Bank' volume would exceed the net storage capacity of Lake Vyrnwy and regulating releases would need to be met partially from inflows.

Table 1 : Maximum constant regulation releases and associated Water Bank capacities for alternative re-deployment scenarios.

DATA EMPLOYED

The maximum and minimum (dead) storages for Lake Vyrnwy were taken to be 59,666 and 4,520 Ml respectively, giving an active storage volume of 55,146 Ml. The maximum throughput of the Vyrnwy Aqueduct was fixed at 200 Ml/d. Daily inflow records were used covering the period from 1st January 1932 to 31st December 1987. This period includes the most severe historic low flow sequence which occurred in 1933/34. For all runs it was assumed that the reservoir was full at the start of the simulation period. Given the high inflows recorded during the winter of 1932/33, alternative assumptions would not materially affect the results obtained.

OVERALL METHODOLOGY

Mathematical modelling within the study was carried out using PWSC's generalised Modular Optimisation/Simulation Program (MOSPA). This program has five fully integrated functional modules :

- A Simulation Module for evaluating the performance of water resource systems over given hydrological series according to defined operating policies;

- A Data Preparation Module, which creates data sets for the long-term operating policy optimization procedure by simulating system performance for a defined set of alternative operating regimes;

- A Long-Term Policy Optimization Module for deriving stationary operating policies which specify the regimes to be adopted during a multi-year sequence so that variable costs are minimized and reliability constraints satisfied;

- A Medium-Term Policy Optimization Module for deriving policies which, for a given hydrological forecast, minimize operating costs over a twelve month period while satisfying specified reliability constraints;

- A Yield Determination Module which identifies the maximum (seasonally varying) demand that could be supplied by the system while meeting defined reliability criteria.

When optimising operating policies Dynamic Programming algorithms and simulation are used iteratively to provide policies which take account of statutory, physical and hydrological constraints on system operation. Using the same simulation model the performance of optimised policies can be directly compared with current practice or proposed alternatives. The philosophy and development of MOSPA, and its application to NWW's NCZ system have been described previously (Walker & Wyatt, 1989), (Wyatt et al., 1993).

A MOSPA simulation model of NWW's SCZ system was constructed in 1990 and used to investigate the operational performance of existing and projected system configurations (PWSC, 1990). The representation of Lake Vyrnwy used in the SCZ model formed the basis for studying independent operation of the reservoir assuming constant regulation releases. However, in order to simulate the effects of varying regulation demands and accurately model Water Bank operation, a more sophisticated model of the reservoir was constructed (Figure 2).

The existing operational procedures involve keeping account of the daily contents of the Water Bank. Thus, within the model, the total active reservoir storage is divided into two components; the Water Bank and the Direct Supply Storage (Figure 2). It can be noted that while flood releases and spills are calculated with reference to the total reservoir contents, any retention levels used to maximize direct supplies must operate on the volume of water held in Direct Supply Storage.

Within the model, the quantity of water taken as direct supply is determined, on a daily basis, by the contents of the reservoir relative to a data-defined set of monthly retention levels. If the contents are below the retention level value the direct supply rate is limited to the specified minimum; if above, additional supplies are taken such that the total does not exceed the available transfer capacity.

ANALYSIS ASSUMING CONSTANT REGULATION RELEASES

A yield determination run of the MOSPA program was made to determine the maximum constant supply rate that could have been maintained over the 1932-1987 sequence, such that the contents of Lake Vyrnwy never fell below 6,500 Ml. The minimum storage value was selected to provide compatibility with previous studies of the SCZ system and, subject to this constraint, the maximum constant direct supply rate was shown to be 198.37 Ml/d.

To determine the maximum constant regulation releases that could be maintained while complying with minimum direct supply rates of 173, 120, 60 and 0 Ml/d, successive simulation runs were made varying this release until the requisite minimum storage was obtained. The resulting values are given in Table 1.

To estimate the total direct supplies that would be available to NWW, monthly retention levels were optimised for each case. The objective of the optimization was to minimize the output from the dummy 'Backup' source (Figure 2) over the simulated period (and hence maximize the total direct supply from Lake Vyrnwy), while satisfying the specified regulation release requirements, minimum reservoir storage constraint and imposed System Demand (Figure 2). The optimizations were performed using the facilities incorporated in MOSPA for deriving long-term system operating policies, the final simulations indicating the direct supplies that would have been available to NWW over the historic inflow sequence. The average direct supply values obtained are plotted in Figure 3.

ANALYSIS WITH TIME SERIES OF REGULATION RELEASES

Time series of daily compensation and regulation releases were provided by the National Rivers Authority - Seven Trent Region (NRA-ST) in the form of 5-day (pentad) values over the period from 1/ 1/1932 to 31/12/1990. The sequences were produced by a computer program used to model the River Severn system and calculate the release requirements necessary to maintain different target flows at Bewdley. They were obtained by simulating operation of Lake Vyrnwy with the sets of retention levels derived assuming constant release rates, and minimum direct supplies of 198, 173, 120 and 60 Ml/d (PWSC, 1993).

The average daily value of the time series of compensation releases was found to be some 42 Ml/d compared with the 45 Ml/d assumed in the previous analyses. Figure 4 indicates the annual magnitudes and variations associated with each of the time series, and the average, and maximum values for the years 1932 to 1987 are given in Table 2. It can be noted that the year in which the maximum is required varies between the release time series.

Minimum Direct Supply (MDS) Rate Ml/d	Maximum Annual Regulation Release Ml	(year)	Minimum Water Bank Capacity Ml	Average Annual Regulation Release Ml
195.9	5,815	(1959)	5,815	1,459
173.0	12,235	(1959)	8,950	3,493
120.0	23,290	(1964)	12,995	7,936
60.0	40,825	(1949)	19,062	14,467

Table 2 : Annual average and maximum regulation releases and minimum Water Bank capacities for re-deployment scenarios

Simulation runs with the time series provided for a MDS of 198.37 Ml/d showed that the system was unable to maintain this supply rate without infringing the minimum reservoir content of 6,500 Ml. Accordingly a MOSPA Yield Determination run was performed and this resulted in a new minimum direct supply value, consistent with the time series provided, of 195.9 Ml/d. Simulation runs carried out for the minimum direct supply rates of 60, 120 and 173 Ml/d also showed that the system was unable to support such releases while satisfying the specified minimum direct supply rates and/or the minimum storage criteria.

The cause of these 'failures' was eventually traced to inconsistencies within the time series provided, it being discovered that they contained releases outside of the specified months of March-October and, in certain cases, implied Water Bank contents in excess of the net storage capacity of the lake. Accordingly it was necessary to establish, for each release series, the minimum Water Bank capacity compatible with meeting the specified minimum direct supply rates and reservoir content. The resulting minimum Water Bank sizes are shown in Table 2.

Long-term operating policy optimisation runs were then undertaken to derive the sets of monthly reservoir retention levels which would maximise the total direct supplies from Lake Vyrnwy for each regulation release time series and Water Bank capacity combination. The average additional and average total direct supply values obtained are plotted in Figure 3.

STUDY CONCLUSIONS AND RECOMMENDATIONS

Estimation of Direct Supply Availabilities

Figure 3 shows the average direct supply rates obtained when assuming constant regulation releases and time series values. It can be seen that the use of the time series results in substantially higher values, the difference for a MDS of 60 Ml/d being in the order of 20%. The reasons for such differences are that the maximum time series regulation release requirements do not, in general, coincide with the period of minimum inflows to Lake Vyrnwy i.e. 1932 - 1934. This lack of coincidence has been exploited both when minimising Water Bank capacities, and optimising the retention levels used to maximize the total direct supplies.

Figure 3 also demonstrates the benefits of such operating policy optimisation, even with relatively unsophisticated rules of the retention level type. For example, although lowering the minimum direct supply rate from 195.9 to 120 Ml/d represents a reduction of some 38%, the **average** supply is reduced by only 5%. It should be noted, however, that seasonal and annual variations in the direct supplies available become more and more pronounced as the minimum direct supply rate is reduced.

Utilization of Lake Vyrnwy as a Water Resource

FIGURE 5(a) illustrates the way in which inflows to Lake Vyrnwy are currently utilized. Based on averaged simulation results for the period from 1/1/1932 - 31/12/1987, and the time series of regulation releases and the set of retention levels associated with maintaining a minimum direct supply rate of 195.9 Ml/d, total direct supplies account for 54% of inflow. Flood releases and spill represent for some 34% of the total, with the remaining 12% meeting compensation and regulation requirements.

FIGURE 5(b) shows the way in which inflows to Lake Vyrnwy could be expected to be utilized under the re-deployment scenario in which the minimum direct supply rate would be reduced to 60 Ml/d. In this case direct supplies would, on average, account for 40% of total inflow, compensation and regulation releases for 22%, and flood releases and spill to 38%.

These figures indicate that a third of inflows to Lake Vyrnwy are currently released to create flood storage in the reservoir or lost as spill, and that this situation is unlikely to improve under the re-deployment scenarios investigated. The principal factors determining this relative under-utilization are the current capacity of the Vyrnwy Aqueduct, which limits the amount of 'non-firm' water that could be taken as direct supply when the contents of the reservoir are above the retention level control curve, and operation of the Water Bank.

During previous studies carried for NWW (PWSC, 1990), simulations of the SCZ system were made assuming constant regulation releases and different capacities for the Vyrnwy Aqueduct. The results indicated that, if the available aqueduct capacity were to be increased to 300 Ml/d, the average direct supply would increase to 277 Ml/d and the percentage of inflow associated with flood releases and spill would be reduced to some 9%. Given the availability of the time series of regulation releases and the detailed simulation model shown in Figure 2, these estimates should be refined if enlargement of the Vyrnwy Aqueduct features in NWW's plans for developing the SCZ system.

It must be recognised that the value of 'non-firm' Vyrnwy water to NWW can only be properly evaluated in the wider context of the SCZ system. If such analyses are to be undertaken, consideration should also be given to practical throughput rates at Oswestry Water Treatment Works and the frequency with which rates could be altered e.g. daily, weekly, monthly.

As part of NWW's investigations of alternative supply sources within the SCZ system (Ringham, Walker & Wyatt, 1994), consideration has been given to increasing current levels of abstractions from the River Dee. The possibility of operating Lake Vyrnwy in conjunction with reservoirs used to regulate River Dee flows may also provide an opportunity to improve its current level of utilization.

Further Studies of Re-deployment Alternatives

Although reservations exist regarding the validity of the regulation release time series used in the study, it is unlikely that correction of the inconsistencies noted would materially affect the results obtained. However, it is recommended that a thorough review be made of the way in which such series have been determined. Whether or not increasing use is to be made of Vyrnwy to regulate flows in the River Severn, it is obviously desirable that its operation be optimised in conjunction with other sources within the basin used for regulation purposes i.e. Llyn Clywedog and the Shropshire Groundwater Scheme. If such optimised operating policies were to be adopted they could eliminate the need to maintain a Water Bank in Lake Vyrnwy.

Any diversion of Vyrnwy direct supplies to the Severn system is likely to be politically sensitive, and proposals may need to include financial compensation to NWW to cover the costs of replacing the lost supplies by water taken from more expensive sources within the SCZ or NCZ systems. By investigating the effects of increasing the Vyrnwy Aqueduct capacity in combination with increased regulation release scenarios, it might well be possible to arrive at a solution which would maintain the current value of Vyrnwy supplies to NWW. Thus the beneficiaries of increased regulation releases might effectively fund the costs associated with increasing maximum throughputs of the Vyrnwy Aqueduct and Oswestry Treatment Works.

APPRAISAL OF THE ANALYTICAL TECHNIQUES AND COMPUTER PROGRAM EMPLOYED

Results of the analyses outlined in this paper, along with those for other regions (Cook et al., 1994), were used in determining the NRA's national Water Resources Development Strategy (NRA, 1994). To identify regional water requirements in the light of forecast demand increases, and hence the potential need for inter-regional transfers, the NRA has applied a resource allocation and investment costing program (Page, 1994). While demand and investment cost inputs to such models are unavoidably subject to appreciable margins of error, it is clearly desirable that uncertainties associated with the yields of the water resource systems included should be minimised.

It is an unfortunate fact of life that the levels of detail used in modelling studies are increasingly dictated by time and budgetary constraints rather than technical considerations. In the case of the Lake Vyrnwy evaluations the degree of sophistication employed was clearly influenced by the existence of MOSPA simulation models covering NWW's SCZ and NCZ systems. In particular, it is extremely unlikely that operating policy optimisations would have been attempted in the time allowed if the facilities incorporated in the MOSPA program had not been available.

MOSPA proved capable of efficiently providing the information required with respect to the Vyrnwy redeployment scenarios postulated, and application of its optimization functions enables a higher level of confidence to be placed on the validity of the results than might be the case with pure simulation. In addition, detailed modelling of current operational procedures raised significant questions with regard to how best Lake Vyrnwy can be utilized as a water resource.

Modelling efficiency can be considerably aided by the use of 'generalised' computer programs. Using a 'keyword' based simulation language, MOSPA simulation model input files are used to define the system topology and the order and frequency with which system components and functions are to be simulated. Model builders therefore require familiarity with the language syntax and the modelling facilities or 'tools' available. Such requirements are, however, offset by the flexibility afforded to the modeller; for example, by changing the order of simulation, it is possible to spill from a reservoir before adding the inflow or vice versa. Modellers and, arguably, users of MOSPA should have a sound knowledge of water resource/supply system characteristics including reservoir operation, abstraction licences, and related aspects.

The major attribute of MOSPA compared with other generalised models lies in the fully integrated nature of the simulation and optimisation functions, enabling the same program and simulation models to be used for a wide range of applications e.g. analysis of development options, optimisation of long-term operating policies for an existing system configuration, medium-term operating policy optimisation and the production of 'real-time' abstraction schedules (Ringham & Howard, 1994).

Although expensive to develop, generalised programs are usually economic to purchase or lease due to the number of existing or prospective users. Related advantages are likely to include : high levels of functional and code dependability; comprehensive documentation; on-going code maintenance and update facilities. Compared with specific 'in-house' programs, disadvantages include : the necessary investment in user training; reliance on the supplier for code changes due to lack of access to source code; cost of maintenance and advice; potential loss of 'in house' programming capability. Conversely, the usability of system specific programs is often restricted by poor documentation, with code maintenance and enhancement hindered if the original developers are no longer staff members.

MOSPA was developed to enable the modelling of large water resource systems and its capabilities have been continually enhanced over a period of some 10 years. For example, facilities have been added to model pool price electricity tariffs, drought order variations to abstraction licences, demand management measures (Levels of Service), medium-term operating policy optimisation and the input of real-time data via database extract files. Such enhancements have been facilitated by flexibility built into the original code.

MOSPA simulation models have been developed for analysing the performance of single reservoirs and river abstractions (for NRA-NW) and specific models for relatively small resource systems such as that supplying Lancaster (for NWW). As with the Vyrnwy model described, these exercises have generally confirmed the adequacy of the modelling facilities available, although in some cases it has been necessary for the model builder to exhibit a degree of ingenuity when representing particular features. The optimisation procedures have exhibited a reassuring level of robustness.

MOSPA was designed to run in batch mode, with data input, calculation and outputs all performed by a single, albeit modular, program. Modern programming practise is to separate these functions so as to increase 'user friendliness'. However, the program functions do not require user interaction during individual runs. A Microsoft WINDOWS based user interface is currently under development with template data entry, probably linked to a modelling database, and extensions to the existing graphical output facilities. However, given the costs associated with software development it is becoming increasingly unrealistic for 'independent' suppliers to fund such developments internally.

As the real cost of computing power continues to decrease, the integrated simulation and optimisation concept becomes increasingly viable for running on PC type and Workstation computers. While the value of operating policy optimisation does not yet appear to be universally accepted, successive applications of MOSPA illustrate the potential benefits of such optimisation even if, as in the case of the Vyrnwy model, operating costs are not specifically included.

Computer Requirements and Program Availability

The MOSPA package is written in FORTRAN and was developed on IBM-PC compatible computers; a version is available to run under the UNIX operating system as implemented by IBM (AIX).

Execution times are determined by the complexity of the system to be analysed, the length of hydrological record, the time steps employed in the simulation model, and the number of alternative operating regimes considered when optimizing operating policies. For complex systems and/or long hydrological time series a 486DX or 'Pentium' processor is recommended when running on PC's.

MOSPA is a proprietary program of Water Systems Consultants Ltd. (WSC). The simulation module was developed under contract to NWW, and commercial rights are governed by a written agreement between these two parties. WSC provides consultancy services which can include application of MOSPA to specific systems. The package is available for lease or purchase by individual utilities or agencies, subject to certain limitations on application. License costs vary with number of computers on which program to be installed and which optimisation modules required.

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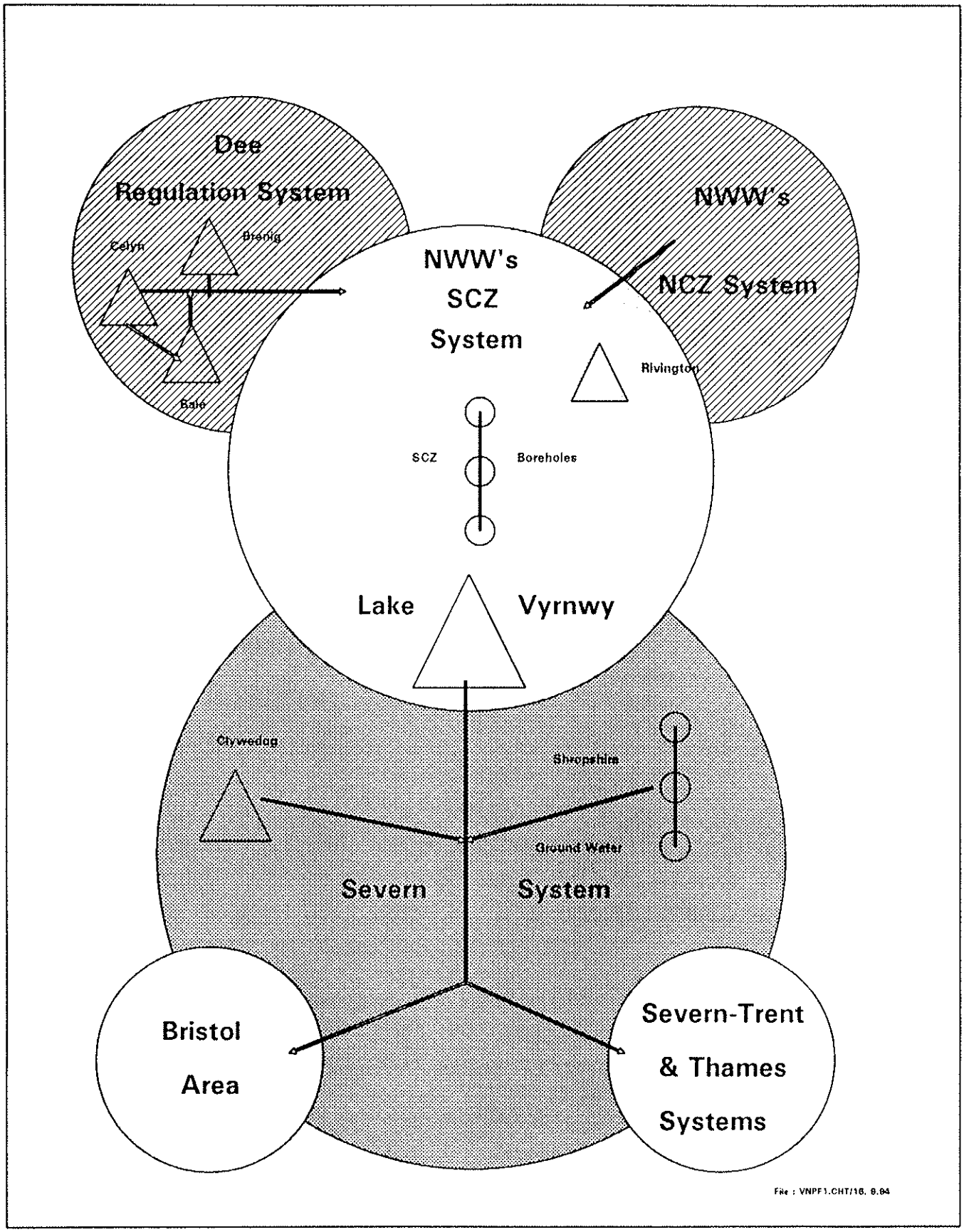


Figure 1 : Water Resource Systems Influencing Use of Lake Vyrnwy

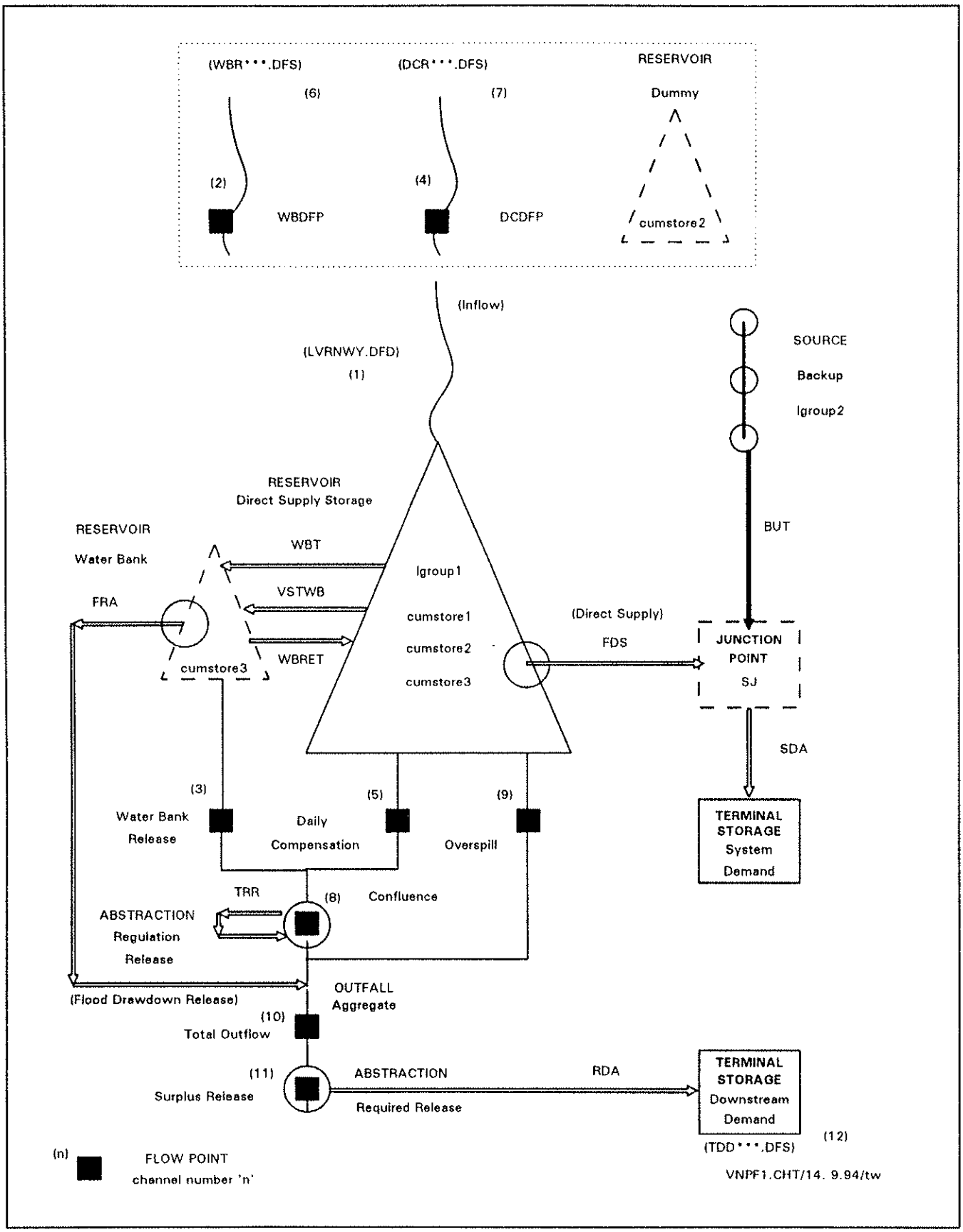


Figure 2 : MOSPA Simulation Model of Lake Vyrnwy including Water Bank

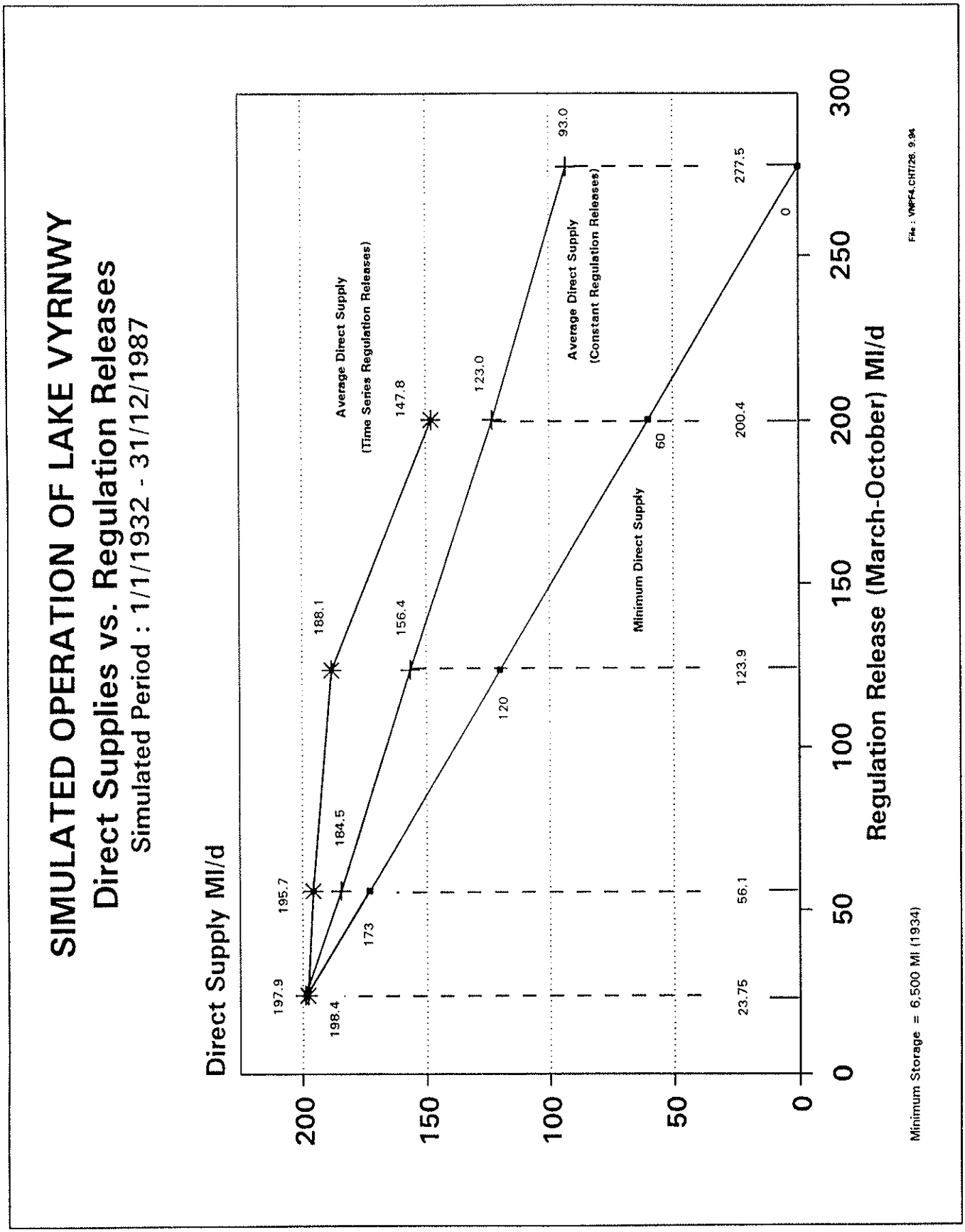


Figure 3 : Relationships between Vyrnwy Direct Supply Rates and Regulation Releases

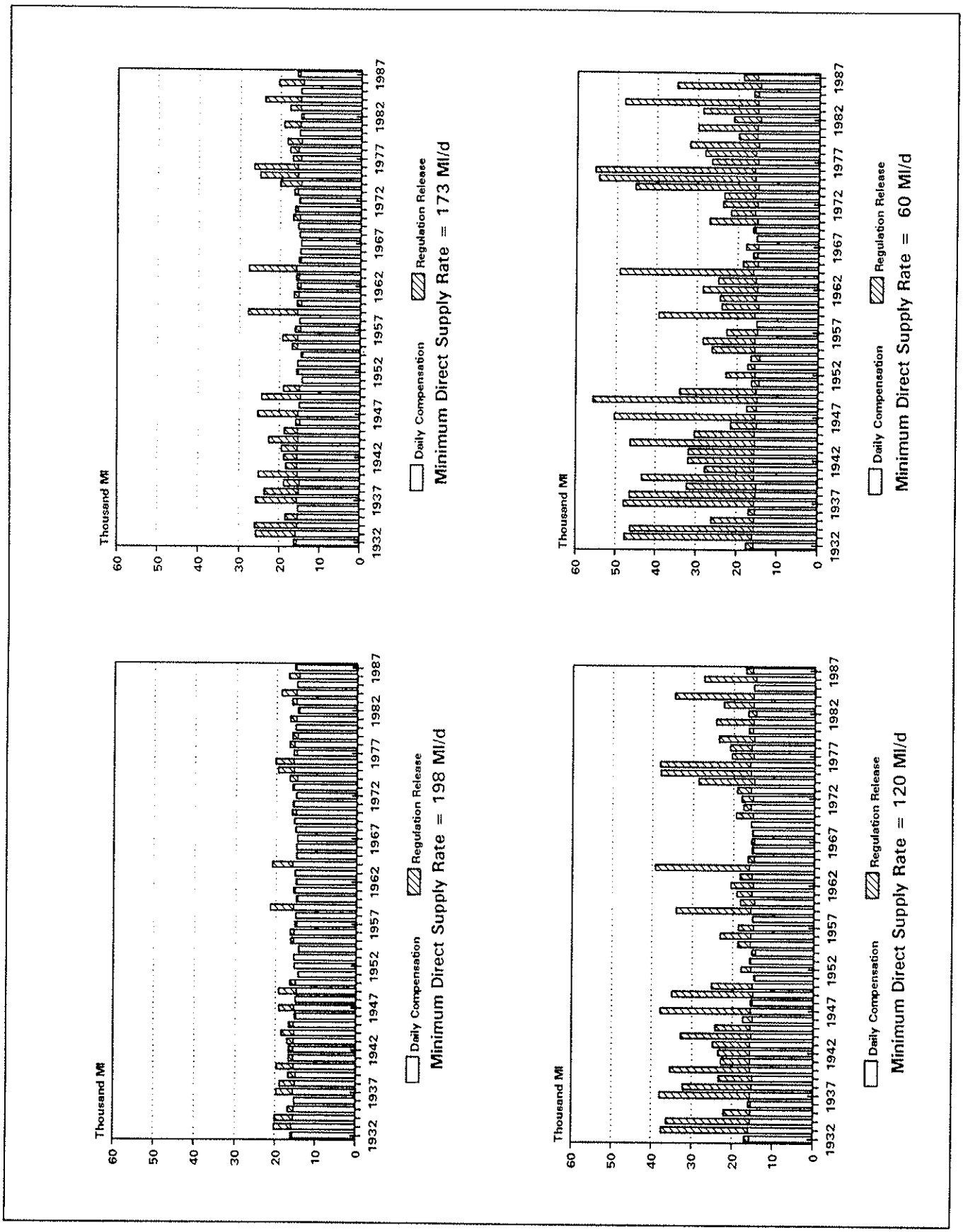


Figure 4 : Annual Compensation and Regulation Release Time Series (1932 - 1987)

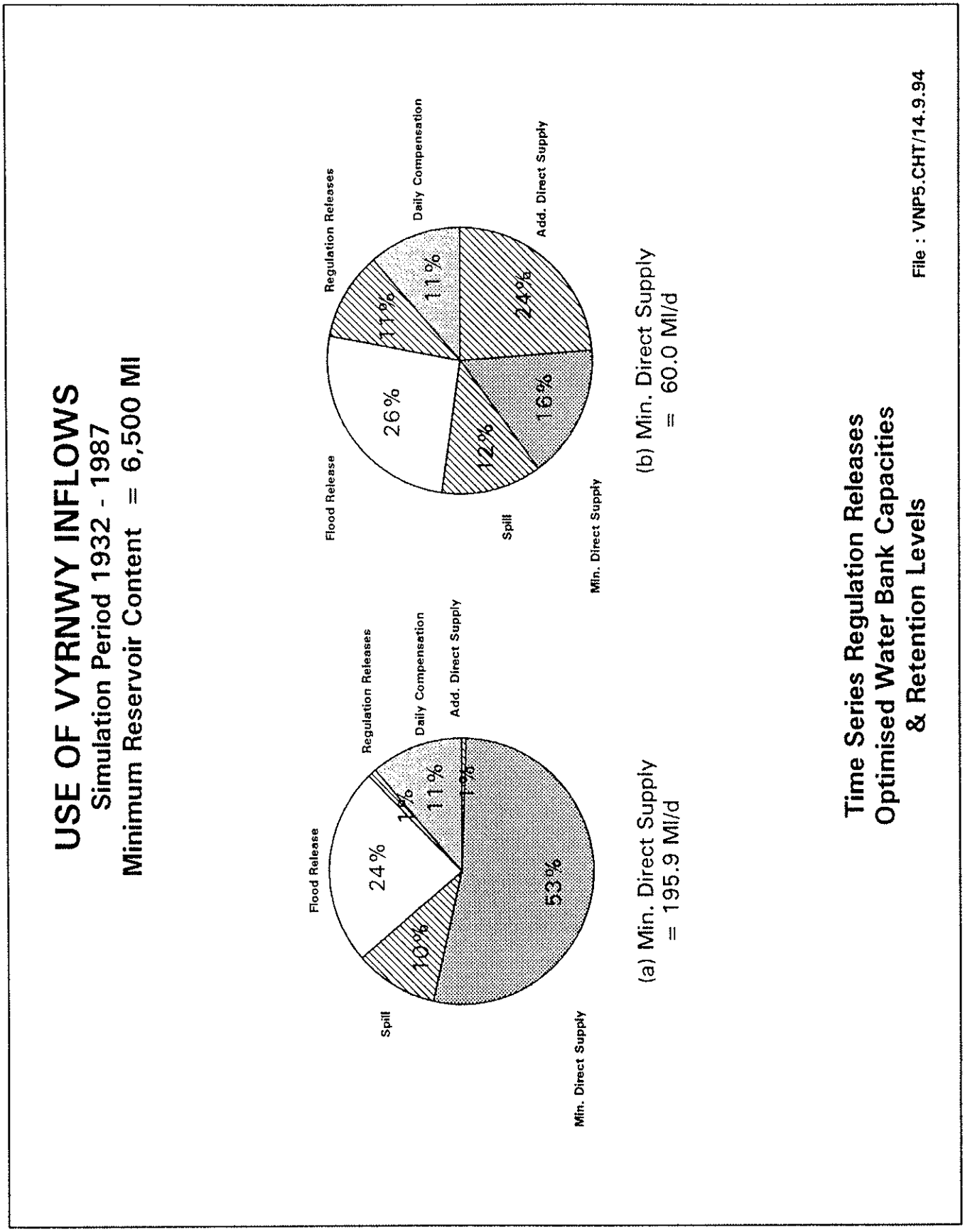


Figure 5 : Vyrnwy Inflows Use with Minimum Direct Supplies of 195.7 and 60.0 Ml/d

The RESPLAN Model and its Application to the NRA National Water Resources Strategy

Chris Page[1]

ABSTRACT

This paper describes the background to the use of models to analyse the costs of water resources development programmes to meet future demands, leading to the development of the RESPLAN model. A description is given of the principal features of RESPLAN and its application to the NRA's (National Rivers Authority) national water resources development strategy, which was completed in 1994.

INTRODUCTION

Many different types of computer model exist to assist the planning and operation of water resource systems. One of the most common is a simulation model of the operation of one or more resources over a long period of hydrological record to determine the yield of the system in relation to specified reliability criteria. Such models may also optimise control rules to minimise the cost of operating a system. Examples of these models are given by Cook, Fawthrop and Watts (1994) and Smithers and Wyatt (1994). Both relate to the performance of a system at a given time.

Long term planning models

The type of model considered here is concerned with the analysis of development programmes to meet forecast demands on a regional or national basis over, say, 30 years. It is essentially concerned with capital investment decisions, and is used to determine which resources should be developed, when they should be developed and to which areas of demand they should be allocated. Such a model does not involve the hydrological modelling or control rule optimisation featured in the other two types of model. However, it does use the results from these models as part of its input data.

The main reasons for using this type of model are:

- the large amount of work involved in manually costing a programme
- the large number of options to be considered
- the interlinked nature of water resource systems, in which apparently local decisions may influence opportunities for the rest of the system
- the ease with which sensitivity analyses can be carried out
- the ease with which plans can be updated as data are changed.

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The RESPLAN model was developed to fulfil this long term planning role, and the purpose of this paper is to describe the background to the development of RESPLAN, the allocation technique which it uses, and its application to the NRA's 1994 national water resources development strategy.

EARLIER LONG TERM PLANNING MODELS

The application of computer models to select and cost future programmes of water resources development was first undertaken in the UK in the 1970's by the Water Resources Board (WRB). Two models were developed and these provided the analysis behind the Board's national strategy produced in 1973.

Both models idealised the problem as a set of demand centres for areas comprising discrete water supply systems, a set of sources - either existing or potential, and a set of links connecting sources and demands centres. The selected programme of development was represented as a series of flows from sources to demand centres at pre-defined dates spanning the period under consideration at, or near to, least discounted cost (or net present value). Expressed in this way, the problem appears to be a classical linear programming problem - the trans-shipment problem - for which several efficient solution techniques exist. However the trans-shipment method is not applicable because:

- it caters for flows at only a single instant in time;
- it does not cater for fixed capital costs incurred before a source or link is used;
- it does not cater for non-linear cost functions.

Allocation techniques used in the WRB models

The two models developed by the WRB are described by Armstrong and Clarke (1972) and O'Neill (1972).

In the first, known as RACS (Resource Allocation and Costing System), the order of introduction of sources was pre-specified and approximate overall unit costs were calculated for each link. Each time period was considered sequentially and flows were allocated to links on the basis of their ranked unit costs. In the second, the technique of mixed integer programming was used. This is a variation of linear programming in which some of the variables can only have the values 0 or 1 - representing whether or not a source or a link is developed in a particular period. The method involves linear approximations being made to cost functions.

In 1974 water resources planning became the responsibility of the new regional water authorities (RWA's), and Anglian Water Authority (AWA) reviewed its requirements for a long term planning model. Both the WRB models were considered, but found to have shortcomings. The RACS method could lead to some demands not being met although surplus resources were still available and, because of the summing of capital and operating costs to a single figure, may lead to an inefficient allocation in terms of total costs. (Some of these shortcomings were, however, reduced by subsequent enhancements.) The mixed integer programming model, although theoretically capable of finding the minimum cost programme, required excessive computing resources unless very small systems were being modelled.

THE DEVELOPMENT OF RESPLAN

These shortcomings led AWA to develop its `Regional Planning Model', which later became known as RESPLAN.

The allocation method used in RESPLAN is based on a heuristic approach, i.e. one which dispenses with rigour and exactness and in exchange is characterised by flexibility and practicability. As a consequence it is not so limited by computer processing power and time constraints as some optimisation techniques, but still allows detailed representation of the water resources system. The main features of the method are outlined below, and are described in more detail in the RESPLAN User Guide (Anglian Water Services, 1993) and by Warn and Page (1984).

Allocation technique used in RESPLAN

The method is an iterative one, in which a series of costed programmes (known as plans) are produced, cost data from one iteration being used as the basis for the next one. The procedure does not converge to a least cost allocation, but over, say, 100 iterations finds a good estimate of the least cost allocation. During each iteration, each time period is considered sequentially.

The concept of `discounted unit cost' is used throughout RESPLAN. This is the total discounted capital and operating cost divided by the total discounted flow; it is a measure of the relative attractiveness of different components and reflects the time taken for the component to be fully utilised.

The principal feature is the use of Vogel's Approximation Method (Llewellyn, 1964). At each stage of the allocation, a choice has to be made of the link to which an allocation is next made based on a matrix of discounted unit costs of meeting different demands from different sources. For each demand centre, there is a `lost opportunity cost', i.e. the extra cost of meeting the demand from the second cheapest rather than the cheapest link. The demand centre with the highest `lost opportunity cost' is the next to have a source allocated to it, the link chosen being the cheapest available for that demand centre.

The unit costs are updated after each allocation is made from a source to a demand centre to allow for the effects of fixed capital costs. Thus before, say, a source is used, the unit costs will include both capital and operating costs, but once an allocation is made from that source, the capital cost element is subtracted to represent the lower marginal cost of using that source.

USING RESPLAN

RESPLAN was written in Fortran and was initially run on AWA's Honeywell mainframe computer. Data and results files were edited and viewed using a text editor. Since privatisation of the water industry, Anglian Water Services have updated the system to run under MS-DOS on a PC and have added a graphics interface using GEMVDI. This enables the user to construct a network diagram of the system on the screen using a mouse, and to input data via a series of templates. It also allows the results of an allocation to be superimposed on the network diagram and to be displayed and printed. A variety of graphs may also be produced showing time series and costs for selected parts of the network.

BASIC FEATURES OF RESPLAN

It is beyond the scope of this paper to give a full description of how to use RESPLAN, and this is best achieved by consultation with the detailed User Guide or experienced users. However an outline is given below of the basic features of the model, and the previously introduced concepts of sources, demand centres and links are expanded.

Sources: These can be reservoirs, groundwater schemes, or any other scheme which will provide additional yield. They can be new sources or existing sources which can be redeployed. For each source, the yield, possibly calculated using a hydrological simulation model, the capital and operating costs are required.

Demand centres: These are discrete water supply areas which are sufficiently integrated that any potential source can be used, directly or indirectly, to meet demands throughout the area. For each demand centre, forecast demands are required for each of the periods covered by the model. These can be either total demands or marginal demands, i.e. demands which cannot be met from existing sources.

Link Elements: These are the means of transporting water from sources to demand centres, including pipelines, pumps, intakes, treatment works etc. Capital and operating costs are required for each element, and there is a choice of using cost functions which relate costs to throughput, or individual costs for each element.

Links: These are feasible routes by which sources can meet demands, each link being defined by one source, one demand and a series of link elements. Each link element may feature in a number of links.

Periods and base years: The time span over which the development plan is required is split into periods each represented by a base year; base years are typically at one year or five year intervals.

Flows: When the yield of a source is allocated to meet a demand, the amount of demand met is referred to as a demand flow, or in this paper, as a flow.

Load factors and yield factors: Load factors relate the average flow in a link element to the demand flow; for example, if meeting a demand of 100 Ml/d involves an average flow of 20 Ml/d through a particular link element, then that element has a load factor of 20%. Yield factors are applied to source yields to reflect variations in yield which are dependent on which demands are being met; for example, if a source yield for a direct supply demand is 100 Ml/d, but for a river regulation demand is 125 Ml/d, then a yield factor of 80% is applied to the yield for the river regulation link. These factors are obtained from hydrological simulation models.

Discounted Costs: All capital and operating costs are discounted back to some start year, usually the first base year, using the current Treasury discount rate. Operating costs for the last base year are discounted to perpetuity to reflect the relative impact of high and low operating cost options beyond the time span of the plan.

Allocation and costing modes: The `allocation mode' is used, as described in the previous section, to produce a set of costed plans, the cheapest of which is a good estimate of the least cost solution. The `costing mode' is used to produce detailed output for a particular plan; this may be either the cheapest plan produced in allocation mode, or a manually modified version of this plan. It can be used to provide a manual check on the least cost solution produced by the allocation mode, or to answer `what if' questions, for example, to determine the sensitivity of the plan costs to a particular source being excluded or the costs of a link element being increased.

Results: Results from RESPLAN are produced in both graphical and text form. Examples of both are given in the next section. The graphical output takes the form of the network diagram with the flows in each link element for four selected base years shown against the element. The text output includes tables showing details of source developments, link element developments, allocation of flows to links though time, cost summaries, and checks that the allocation is valid.

THE NRA NATIONAL STRATEGY

In 1992, following the issue of a discussion paper (NRA, 1992), the NRA started work on preparation of a national water resources development strategy, which resulted in a final report earlier this year (NRA, 1994). It was apparent that the NRA needed to seriously consider options for strategic resource development that crossed Water Company and NRA regional boundaries. The main areas of marginal demand in the drier south and east could be met by within-region reservoir developments, such as the proposed Thames or East Anglian reservoirs, or by developments in the wetter north and west together with inter-regional transfers, including Severn-Thames transfers, Vyrnwy redeployment, Craig Goch, Severn-Trent transfers, Trent-Anglian transfers.

Review of models

It was decided to use a long term planning model to analyse options on a national scale. A brief review of techniques in use within the water industry revealed limited use of RACS in some regions, a continuing high level of commitment to RESPLAN by Anglian Water Services and virtually no development of allocation techniques since the mid 1970's. This can be put down to three main reasons:

- Between the closure of WRB and the setting up of the NRA there was no national organisation with responsibility for strategic water resource planning.
- The demand forecasts produced by the RWA's were considerably lower than those of the WRB.
- The development options available were relatively limited and schemes involving inter-regional transfers were rarely favoured. Options could therefore be analysed without the use of a model.

As a result it was decided to use RESPLAN for the national strategy. The model was used to find the least cost development plan for a number of scenarios, and the marginal costs of alternative plans. Running the model for different configurations of possible resource developments enabled overall costs to be considered alongside environmental considerations in developing the national strategy. What the model would not do was to take into account the constraints of existing agreements on the uses of resources, where discarding these might provide a better solution nationally. Neither would it directly take account of the costs of increased domestic metering or leakage control, although by analysing the results of different scenarios the water resources cost implications of domestic metering or leakage control policies could be compared.

Data Collation

The work on collation of data for use with RESPLAN was carried out over an 18 month period between May 1992 and November 1993. This involved a considerable effort from staff at NRA head office and regional offices, water companies and consulting engineers. Some of the key steps are described below:

Base years: The time span for the national strategy was the period from 1991 to 2021, and seven base years at five year intervals were used i.e. 1991, 1996, 2001, 2006, 2011, 2016 and 2021, although some sensitivity analysis carried out using 31 base years at one year intervals showed only minor changes in the results.

Demand centres and demand forecasts: Each NRA region was split into a number of demand centres (between 1 and 10) and demand forecasts were calculated for each demand centre for each five year period for high, medium and low scenarios (NRA, 1994), thus ensuring a consistent approach to demand forecasting across the country. It was decided to use marginal demands throughout the study; these were calculated by subtracting from the total demands the yields of existing sources and local sources (defined below). Only those demand centres for which the high scenario marginal demand in 2021 was non-zero were included in the RESPLAN analysis.

Sources and transfer schemes: Potential sources and transfer schemes to meet future demands were identified by NRA regions. The sources were separated into `strategic sources' - i.e. those involving the development of major reservoirs or inter-regional transfers, or the redeployment of existing major sources - and `local sources' - generally schemes which would meet the needs of only one demand centre, and which would be expected to be developed in preference to strategic sources. Only strategic sources were included in the analysis.

Yield data: The yields and yield and load factors for the different sources were calculated using existing models within NRA regions. For options involving inter-regional transfers where no composite model existed, it was necessary to use the output from one regional model as the input to another to obtain yields. This involved approximations having to be made. A project to develop an inter-regional hydrological simulation model is now under way to enable better yield estimates to be made.

Cost data: Studies to determine the capital and operating costs of all sources and link elements were carried out by NRA regions, water companies and consultants. As a result of the availability of these studies, it was decided not to use generalised cost functions for link elements but to use individual costs for each element. For link elements, only the costs of pipelines, pump equipment and housing, and pumping costs were included. Water treatment costs were assumed to be similar for all options and were not included. The cost data were all vetted to ensure consistent costs for all options, using a cost base date of Q3 1992.

Interpretation of data: The assembly of data for the model involved the extraction of information from a wide range of reports, and interpretation to fit RESPLAN's data structures.

The network developed from this data involved 15 demand centres, 20 sources, 93 links and 61 link elements. The network diagram is shown in Figure 1, which also shows the results of a model run. To run the model in `allocation mode' for this network for 100 iterations on a 486 PC took 3 minutes.

NATIONAL STRATEGY RESULTS

RESPLAN was applied to both the high and medium demand scenarios, but not to the low demand scenario for which no major strategic resource developments were found to be required. During the study a vast number of model runs were carried out as new options were considered or as data were updated. The results finally used were based on five runs for each of the high and medium scenarios. A brief summary of the results is given below; a fuller description of the results in the context of the options considered is given in the final report (NRA, 1994).

Extracts from a typical set of results are given in Table 1, which shows details of timing and costs of source developments, and Table 2, which shows the full allocation of sources to demands for each base year. The graphical output for this plan is shown in Figure 1, which for each element shows the flows allocated for base years 1991, 2001, 2011 and 2021, the flow for 2021 being shown in bold type at the `upstream' end of the link element.

Results for the high demand scenario

For the high demand scenario case, a baseline development plan was obtained by running the model in allocation mode, and making minor adjustments using the costing mode which resulted in reducing the cost by 2%. The baseline plan had a total discounted cost of £ 353M (using a discount rate of 6%). Key features of this plan were:

- the development of a Severn-Thames transfer followed by an enlarged Craig Goch reservoir in preference to the development of a Thames Reservoir to meet demands in London
- the development of the East Anglian Reservoir in preference to Trent-Anglian transfers to meet demands in Essex.

Further runs were carried out for the high demand scenario case to test the sensitivity of the costs to variations from the baseline plan. For example :

- the additional discounted cost of pumping Severn water direct to the London area if river to river transfers from the Severn to the Thames were found to be unacceptable on environmental grounds was an additional £ 104M.
- the effect of developing a Thames reservoir in preference to Severn-Thames transfers and Craig Goch was an additional £ 284M discounted cost.

Results for the medium demand scenario

A similar set of model runs was carried out for the medium demand scenario. The discounted cost of the baseline case was £ 65M. This involved the development of the Severn-Thames transfer but no new reservoir to meet demands in London, and the development of the East Anglian Reservoir to meet demands in Essex.

The large difference between the baseline costs for the high and medium demand scenarios, i.e. £ 353M against £ 65M, indicates the scale of impact on water resources development costs of different levels of domestic metering and leakage control.

CONCLUSIONS

The use of a model to analyse capital investment options for highly interlinked water resources systems over a long period is considered to be essential. The allocation algorithm used in RESPLAN model balances the requirements to be able to represent a water resources system in adequate detail and to find a least cost development programme to meet demands over a 30 year period. RESPLAN has been in continuous use for nearly twenty years and was found to be well suited to the analysis of options for the NRA's national water resources development strategy.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the contribution of former colleagues, John Brew and Tony Warn, in developing the RESPLAN allocation algorithm and software, and the help and support of Jerry Sherriff, NRA Head of Water Resources, during the application of RESPLAN to the NRA national strategy. RESPLAN has been used under licence from Anglian Water Services Limited. The views expressed are the author's own and not necessarily those of the NRA.

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FIRST BASE YEAR	SOURCE NAME	YIELD IN 2021 (TCMD)	CAPITAL COST (£M)	DISCOUNTED CAPITAL COST (£M)	DISCOUNTED OPERATING COST TO 2021 (£M)	DISCOUNTED OPERATING COST BEYOND 2021 (£M)	TOTAL DISCOUNTED COST (£M)
1991	Derwent Valley	40	.000	.000	.000	.000	.000
1991	Vyrnwy	147	.000	.000	.000	000	.000
1991	Kent Resr	40	.000	.000	.000	.000	.000
1996	Carsington	140	.000	.000	.000.	000	.000
1996	Severn(Unsuprtd)	146	.000	.000	.000.	000	.000
2001	Chelmsford Efflt	30	.000	.000	.000.	000	.000
2001	Shropshire Gw	155	.000	.000	.000.	000	.000
2001	Severn Reuse	114	.000	.000	.000.	000	.000
2006	E. Anglian Resr	174	69.400	34.504	.000.	000	34.504
2006	Thames Reuse	36	.000	.000	.000.	000	.000
2011	Birmingham Gw	50	4.400	1.478	.769	.856	3.103
2011	Craig Goch	629	60.500	22.477	.000	.000	22.477
2016	Huntington	74	36.900	10.244	1.109	3.307	14.661
2021	Thames Resr	262	400.000	82.982	.701	4.338	88.021
TOTALS FOR SOURCES			**571.200**	**151.686**	**2.579**	**8.501**	**162.766**

Note that for some sources which show operating costs as zero, the operating costs are attributed to a link element from that source.

Table 1 : Typical source development details.

SOURCE NAME	DEMAND NAME	FLOWS THROUGH TIME (TCMD)						
		1991	1996	2001	2006	2011	2016	2021
E. Anglian Resr	NORTH ESSEX	0	0	0	0	11	21	28
E. Anglian Resr	SOUTH ESSEX	0	0	0	9	32	50	60
Chelmsford Efflt	SOUTH ESSEX	0	0	16	30	30	30	30
E. Anglian Resr	LONDON	0	0	0	81	81	81	81
Thames Resr	LONDON	0	0	0	0	0	0	27
Severn(Unsuprtd)	LONDON	0	96	146	146	146	146	146
Vyrnwy	LONDON	0	0	0	15	7	0	0
Craig Goch	LONDON	0	0	0	0	110	160	172
Shropshire Gw	LONDON	0	0	42	31	0	0	0
Thames Reuse	LONDON	0	0	0	2	18	28	36
Severn Reuse	LONDON	0	0	5	32	61	86	105
Thames Resr	OXFORD/SWINDON	0	0	0	0	0	0	38
Craig Goch	OXFORD/SWINDON	0	0	0	0	20	31	0
Shropshire Gw	OXFORD/SWINDON	0	0	0	2	0	0	0
Severn Reuse	OXFORD/SWINDON	0	0	0	0	0	0	2
Shropshire Gw	WESSEX	0	0	0	0	7	38	64
Severn Reuse	WESSEX	0	0	0	0	0	0	7
Vyrnwy	WEST MIDLANDS	0	0	0	31	0	0	0
Craig Goch	WEST MIDLANDS	0	0	0	0	40	136	234
Shropshire Gw	WEST MIDLANDS	0	0	12	41	99	59	24
Carsington	EAST MIDLANDS	0	44	112	158	175	175	175
Birmingham Gw	EAST MIDLANDS	0	0	0	0	31	50	50
Craig Goch	EAST MIDLANDS	0	0	0	0	0	33	85
Derwent Valley	SOUTH YORKSHIRE	40	40	40	40	40	40	40
Kent Resr	MID KENT/FLKSTNE	2	5	8	12	16	24	31
Shropshire Gw	BRISTOL	0	0	17	34	49	58	67
Vyrnwy	NORTH WEST	81	70	94	118	141	147	147
Huntington	NORTH WEST	0	0	0	0	0	19	44
TOTALS		**123**	**255**	**492**	**782**	**1114**	**1412**	**1693**

Table 2 : Typical allocation of sources to demands in each base year.

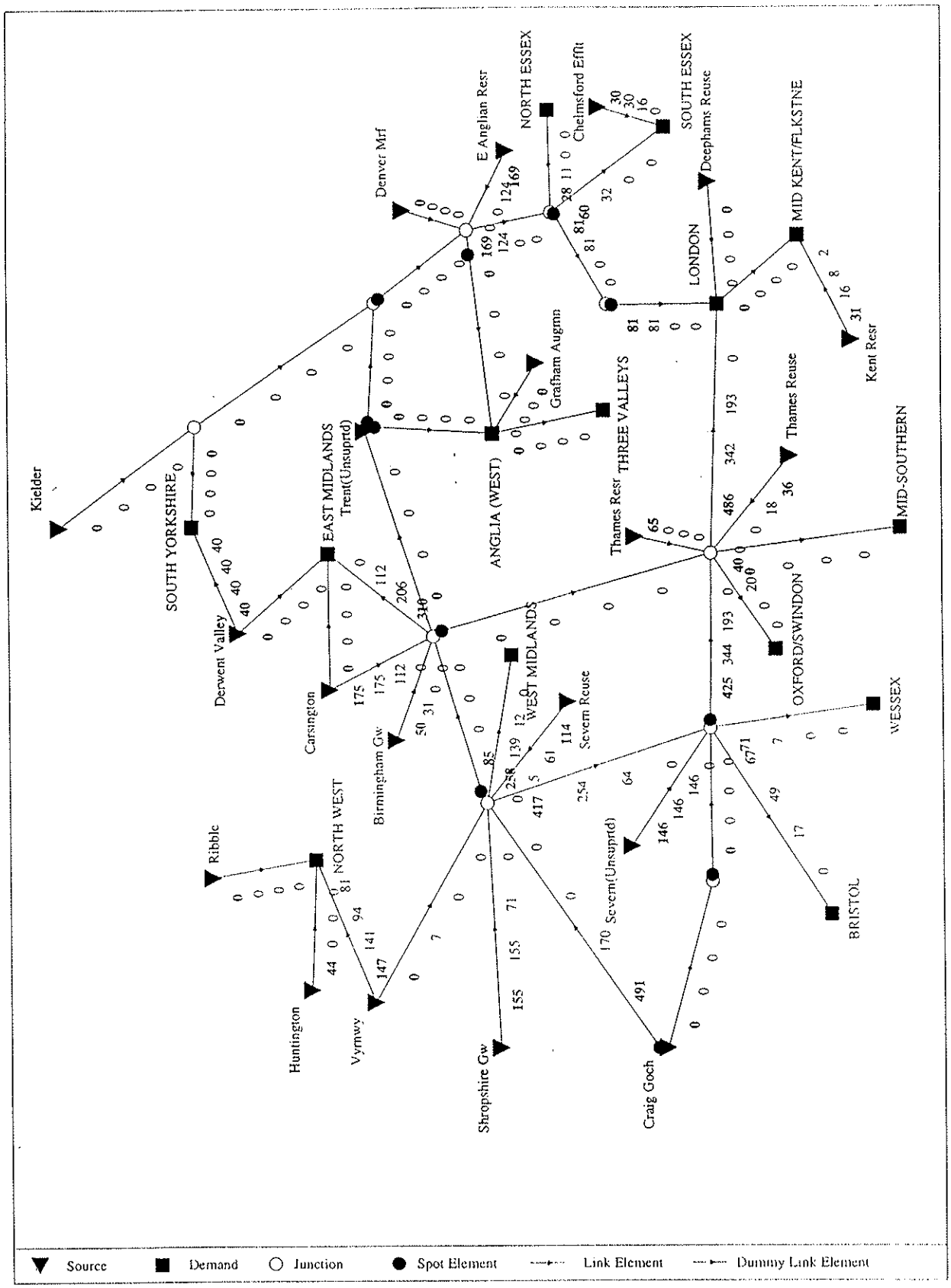


Figure 1 : Graphical output of flows in Ml/d for base years 1991, 2001, 2011 and 2021 (2021 figures in bold type)

RFFS AND HYRAD: INTEGRATED SYSTEMS FOR RAINFALL AND RIVER FLOW FORECASTING IN REAL-TIME AND THEIR APPLICATION IN YORKSHIRE

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INTRODUCTION

Real-time flood forecasting systems aim to predict the actual flood hydrograph a short time ahead in support of flood warning and control. They rely on access to up-to-date information from telemetry of river levels, raingauges and other hydrometric data to maintain the accuracy of flood forecasts. There is also a growing requirement for flow forecasting systems which provide predictions not only of floods but of the full range of flows. Such forecasts are required for extended lead times, often several days or even months ahead, to support decision-making concerned with drought management, intake protection and pollution control. These requirements have posed new challenges in model formulation and software design.

In the development of flow forecasting systems it has been customary to develop case-specific applications with the mathematical modelling software configured to the specific river network of interest. An early example in the UK was the Dee Flood Forecasting System implemented in 1975 (Cole *et al*, 1975). Modification of models to accommodate new forecast points or telemetry data, or transfer of the technology to another river basin, has often required extensive and expensive recoding of computer software. In addition, the scope of requirements for forecasting has widened from providing localised warning for a few flood-prone sites, to whole regions, extending over tens of thousands of square kilometres. Within a region there may be several river networks each requiring forecasts at hundreds of locations. The need for configurability and a modular approach to system design, as a means of dealing with system complexity, has become increasingly apparent. Maintaining system resilience at all times in an automatic way, particularly to cope with loss of data from telemetry, is also clearly an essential requirement of such complex real-time systems.

It is against this background that the River Flow Forecasting System, or RFFS, has been developed . The opportunity for development arose through a commission by the National Rivers Authority (NRA) to develop a flow forecasting system for the rivers of Yorkshire, with Logica UK Limited serving as prime contractor with special responsibilities for the shell (database and interfaces to telemetry and users) environment. This allowed past work on flood forecasting models and updating techniques at the Institute of Hydrology, carried out under the MAFF Flood Protection Commission, to be consolidated and extended. The result has been an advanced RFFS Hydrological Kernel software product for operational forecasting and off-line model calibration. Figure 1 depicts the shell and kernel structure of the system environment of the RFFS.

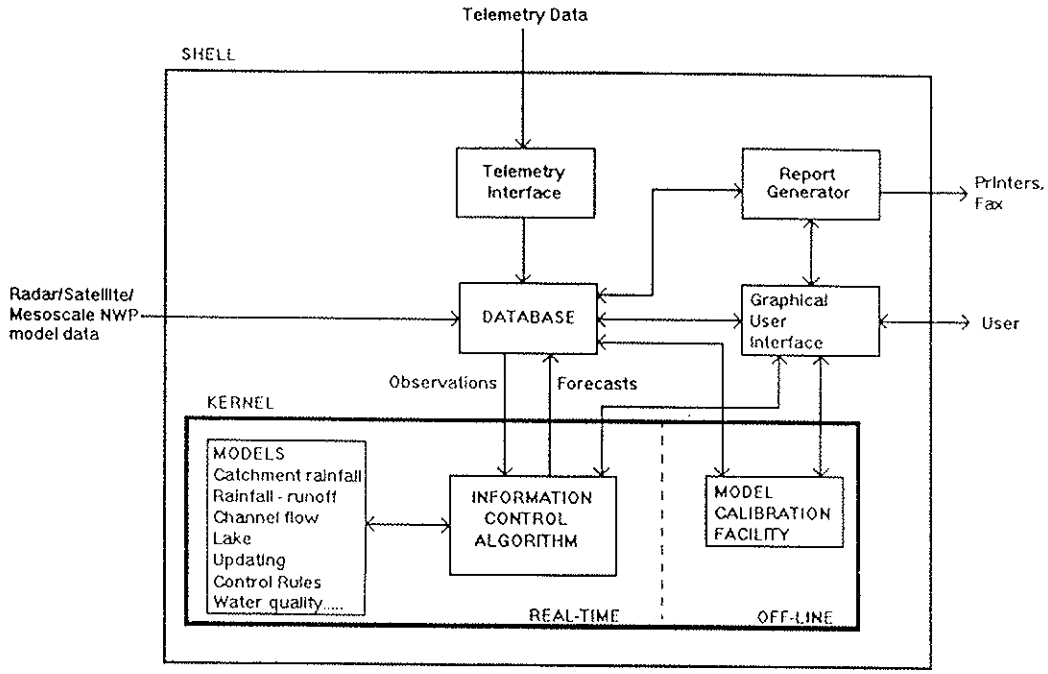


Figure 1 System environment of the RFFS

The operational requirements of the Yorkshire RFFS are set down by Cottingham and Bird (1991) and aspects of the design of the system are addressed by Moore *et al* (1990). An outline of how the requirements have been met through an Information Control Algorithm, or ICA, and a Model Calibration Facility are described by Moore and Jones (1991) and Moore (1993). It is the purpose of this paper to provide a broad outline of the functionality of the RFFS, to describe its implementation in Yorkshire and to briefly report on other applications and developments of the RFFS in the UK and overseas. These include the recent integration of a weather radar processing and display system, called HYRAD (HYdrological RADar system), into the RFFS forecasting environment.

THE RFFS

The River Flow Forecasting System, or RFFS, supports a wide range of functionality. As well as incorporating models designed to operate over the full flow range, a generic algorithm structure allows new model formulations to be added as requirements change or advances in modelling are made. The algorithms currently available range from setting a constant value to represent a reservoir compensation release, to models representing snowmelt, catchment runoff, and channel flow in both non-tidal and tidal river reaches. The hydrological channel flow routing model, KW, whilst based on a kinematic wave formulation allows for flow-dependent wave speeds, washland storage attenuation and embedded stage-discharge relations through simple empirical functions (Institute of Hydrology, 1992a). Such a model can be calibrated without expensive survey data. At the other extreme of complexity, a hydrodynamic model based on the one-dimensional Saint Venant equations is available for tidal river modelling. In this case, the generic model algorithm structure has allowed a gate control rule to be incorporated within the overall formulation: an example gate control and

level forecast using this rule is shown in Figure 2. The algorithm interface also allows the rule to be overridden with a user-defined gate control sequence as part of a "what if?" decision-making process, or to reflect control decisions effected manually.

All the models are provided with updating facilities which allow recent telemetered data to be used to improve model forecasts. In the case of snowmelt and rainfall-runoff models, internal adjustments are made to the water contents of conceptual storages within the models to make the model output accord better with observed values. For models involving channel flow, simple error predictors are used which aim to predict future errors based on the dependence seen in present and past model errors: these predicted errors are then used to improve the initial forecasts. An example of a flow forecast using the PDM rainfall-runoff model (Institute of Hydrology, 1992b) is shown in Figure 3. A recent assessment of operational rainfall-runoff models confirmed the suitability of the PDM model for real-time use (Moore *et al.*, 1993). Calibration facilities provided within the RFFS allow calibration of both models and updating procedures.

Not only is the RFFS configurable in terms of the model algorithms it can employ, but it can also be configured to any river network without expensive recoding. Further, an existing model for a river network can be modified to accommodate, for example, new telemetered river gauging sites. This is achieved through the use of an Information Control Algorithm, or ICA, which employs a data-defined model network structure to control access of telemetry data required to make forecasts, and to control the order of execution of the models working down the river system. It is also possible to select only parts of a complex model river network model to be run, through the concept of user-defined Subnetworks. These can be configured, for example, to only invoke forecasts of headwater catchments for flash flood forecasting: running a time-consuming tidal hydraulic model is avoided and frequent forecast updates can be made. During the production of the forecast the near-current values of the state variables, such as water contents of stores in the various models, are stored and used on subsequent runs for model initialisation, thus avoiding a long "warm-up".

System resilience to data loss is assured in two ways. At sites within the river model network missing data are simply replaced by forecasts made by model components upstream. On the extremities of the network, model algorithms are used which compensate for data loss based on user-defined principles of substitution. For example, in the case of rainfall required for a rainfall-runoff model, radar data could be used as a first priority, substituted for by data from raingauges, allowing for any combination to be missing, and then a typical rainfall used as a backup. This ensures that catchment rainfall required as input to the model is always present. Updating of models further down the chain of models representing the river network, using telemetered river flow measurements, controls the propagation of errors downstream.

THE HYRAD SYSTEM

The HYRAD (HYdrological RADar) system complements the RFFS by providing a weather radar data acquisition, processing and display system specifically tailored for real-time hydrological forecasting applications. The system receives radar data in real-time directly from single-site radars as well as radar products from Bracknell, which include the Europe-wide COST73 image, the national composite Network image, the Frontiers actual image and the Frontiers rainfall forecasts (Met Office/NRA, 1994). These data are held in HYRAD's Spatial Image Database, SIDB. The high resolution single-site radar fields are automatically

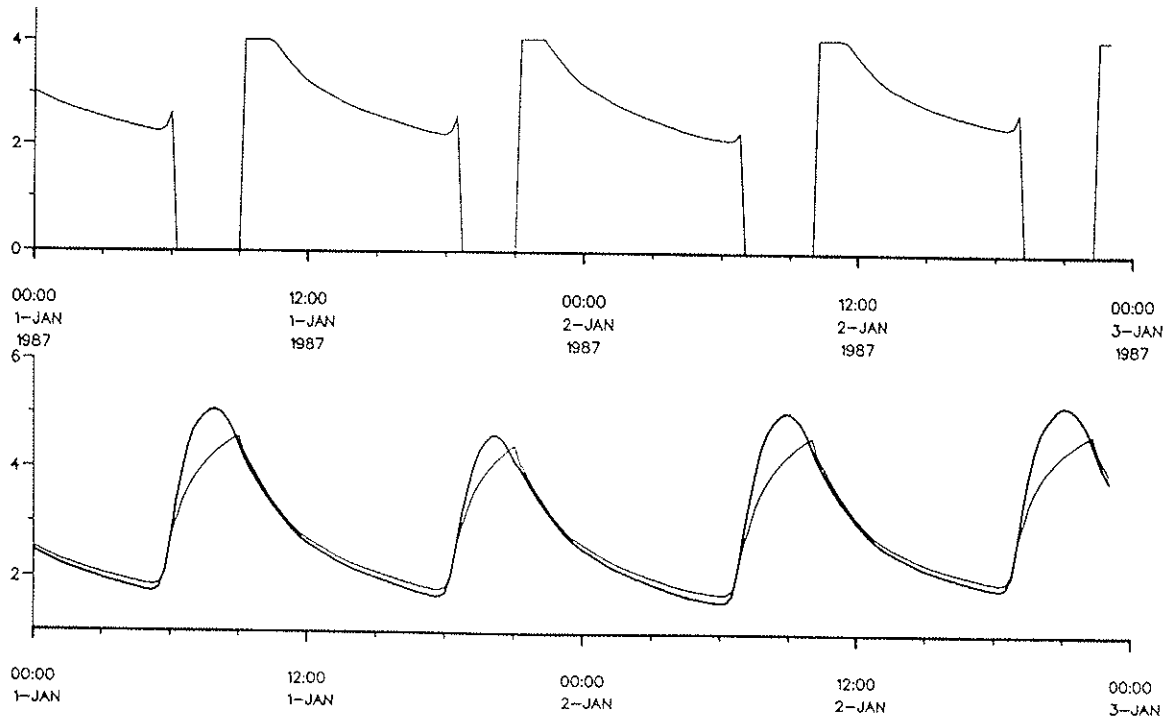


Figure 2 *Simulation of the automatic control of the Derwent tidal barrier at Barmby within the Yorkshire River Flow Forecasting System. Note the gate closure in the top graph as the tidal Ouse water level (bold line) rises and how the Derwent level (thin line) rise is restricted as a result.*

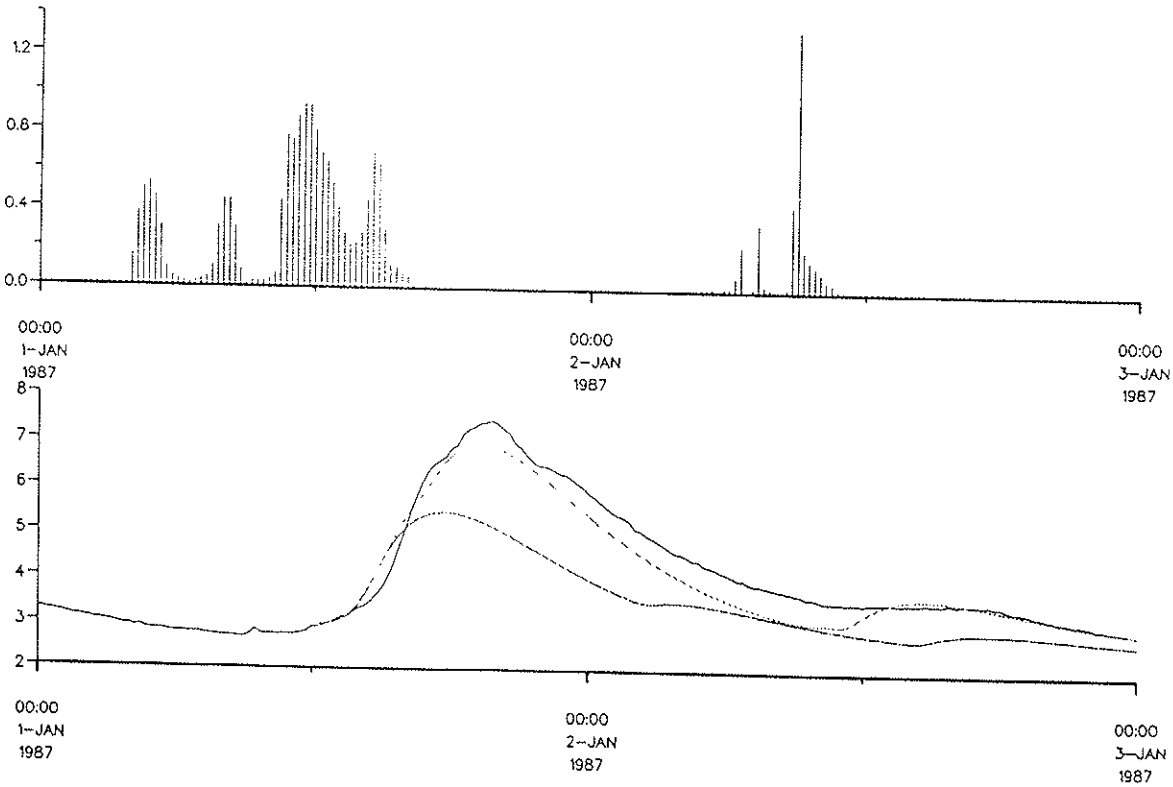


Figure 3 *Flow forecast for the River Dove at Kirkby Mills using Church Houses rainfall: the upper forecast assumes perfect foreknowledge of rainfall whereas the lower forecast is based only on observed rainfall up to 12:00 1 January 1987 and a backup rainfall profile after this.*

accessed in real-time by HYRAD's processing kernel, HYRADK. This corrects for transient clutter and permanent anomalies in the field, performs raingauge calibration of the radar, and makes rainfall forecasts, typically out to two hours ahead. The processed observed rainfalls together with the forecasts are further processed to derive catchment average rainfalls which are passed as time series to the RFFS database for use in flow forecast construction. The processed rainfall fields are returned to the HYRAD database where they can be accessed for display purposes, along with the other images held. The radar reception, database and processing system are resident on a server machine, which in Yorkshire is a VAX, but could equally well be a UNIX or PC server. PC client machines are used to support the display of HYRAD images via a file-server connection (Figure 4). The HYRAD Radar Rainfall Display System is Windows 3.1 based and supports display of the image types previously mentioned along with HYRAD's own calibration and forecast products. Displays are highly configurable to meet users' specific requirements and a set-up option allows users to store their preferred configurations for easy and quick retrieval. Figure 5 presents a typical HYRAD display.

Further details of the methods used in HYRAD's processing kernel are given in Moore et al (1992a, 1992b, 1993a). A multiquadric surface fitting method applied to calibration factors, formed as a modified ratio of raingauge to coincident radar estimates of rainfall, is used for radar calibration. Figure 6 shows the order of improvement in accuracy that might be expected, on average, from this approach over an area of 3600 km^2 with modest relief, depending on raingauge density. Radar rainfall forecasting is based on first inferring the speed and direction of storm movement from two displaced images using a shrinking-grid search method which performs a final direct interpolation in the forecast error field. Forecast construction advects forward the current field whilst imposing a smoothing towards the field average value with increasing lead time. A particular advantage of HYRAD for real-time flow forecasting is that the calibrated and forecast images are available within a minute of receipt of the radar data, compared to the 40 minute delay incurred by the national Frontiers forecasts. However, the two products are complementary. Whilst the HYRAD forecasts are generally more accurate (Figure 7), their dependence on a single radar means that exhaustion of the forecast field starts to occur beyond lead times of 2 hours. The composite field used by Frontiers guarantees availability of forecasts for lead times up to 6 hours. An assessment of the two rainfall forecasting methods, when used with operational rainfall-runoff models for flood forecasting, is reported in Moore *et al.* (1993b).

USE OF RFFS AND HYRAD IN YORKSHIRE

Forecasting requirements

The rivers of Yorkshire, dominated by the dendritic River Ouse and its tributaries rising in the Pennine hills to the west and the North Yorkshire Moors to the north, drain an area of approximately 13,500 km^2. Snowmelt on the Pennines has been a major factor of some of the major floods experienced in the past. Across Yorkshire there are about 5000 houses in unprotected floodplains and the associated total potential annual benefit of timely warnings is estimated to exceed £1m. One flood in January 1982 caused extensive damage in York and Selby with 800 properties and 18,700 hectares of agricultural land inundated. The RFFS has been primarily set up to meet the basic forecasting requirement for provision of a four-hour warning of flooding on the middle and lower reaches of the main rivers within Yorkshire, including the tidal River Ouse.

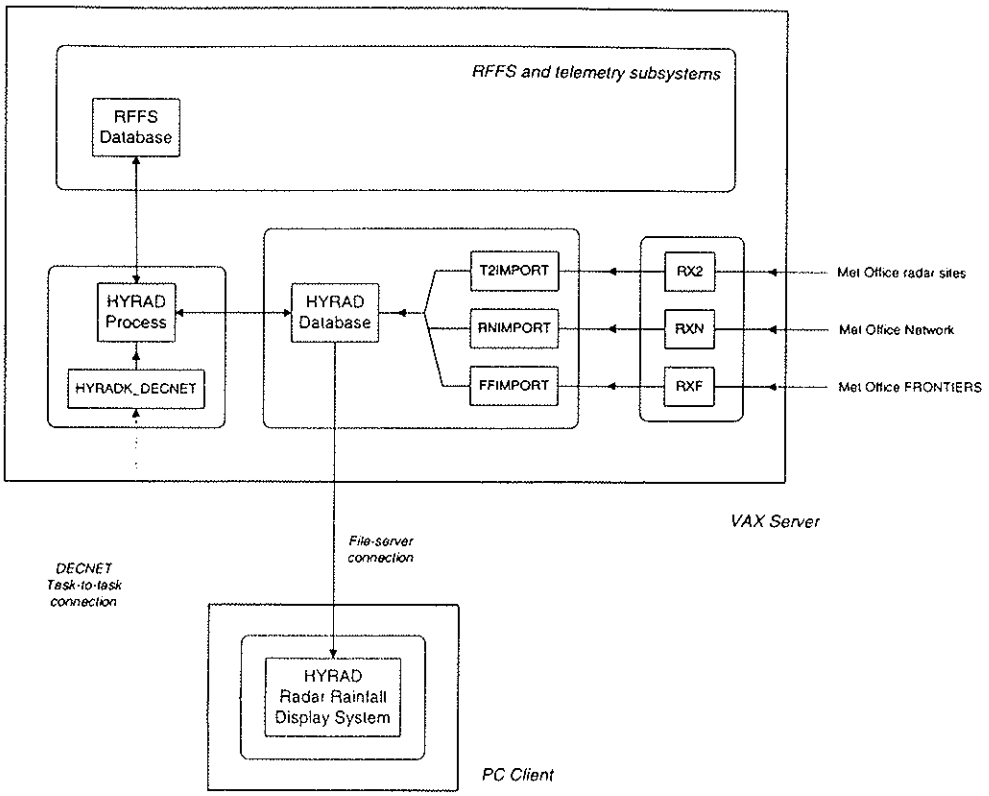


Figure 4 *HYRAD system architecture*

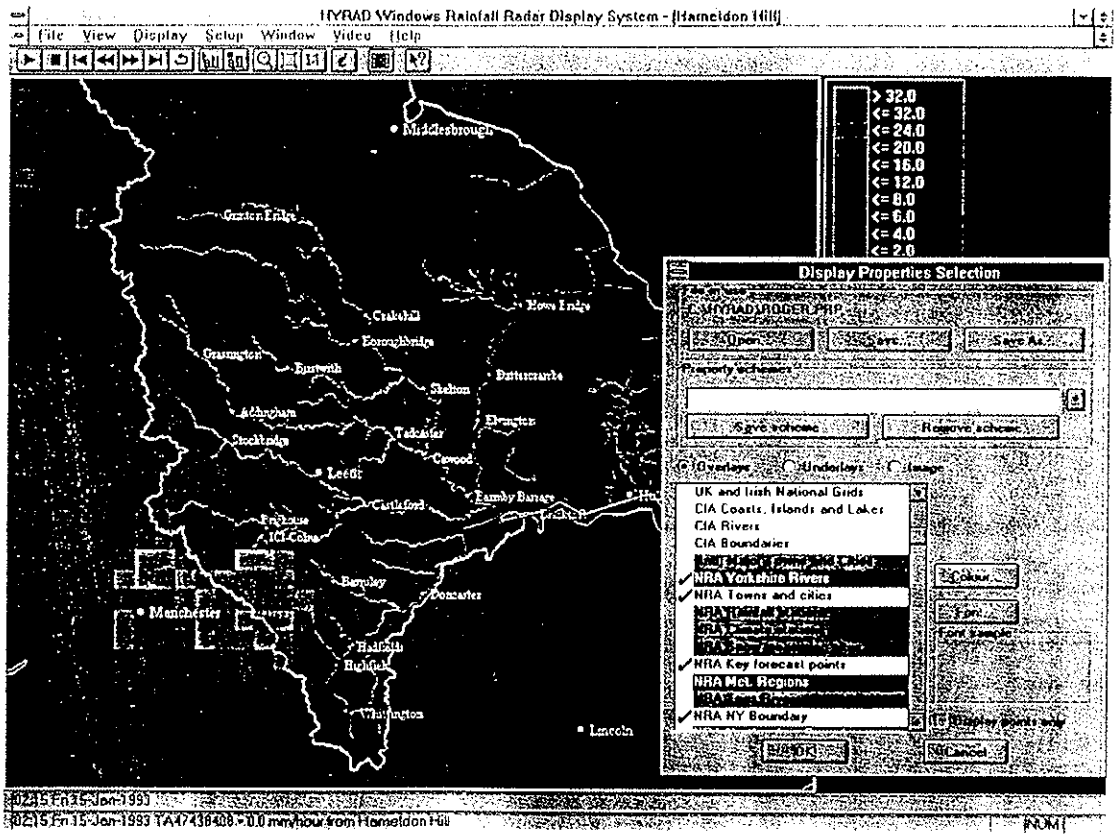


Figure 5 *HYRAD radar display*

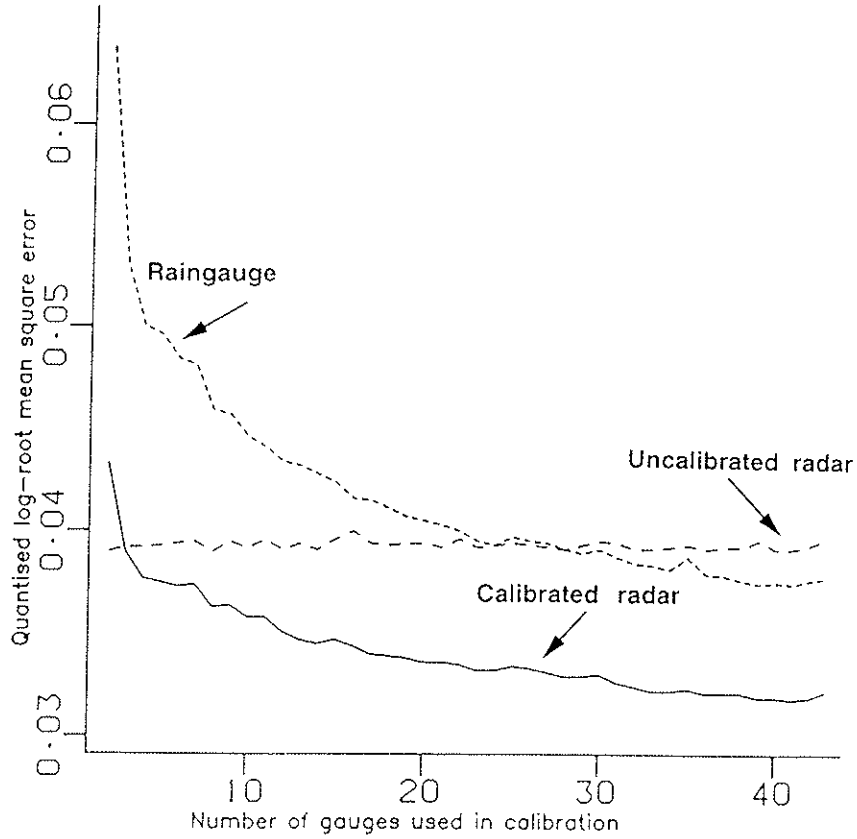


Figure 6 *Accuracy of HYRAD calibrated radar, compared to uncalibrated radar and raingauge-only estimates, as a function of gauges used; average results for 13 events for a 3600 km² area*

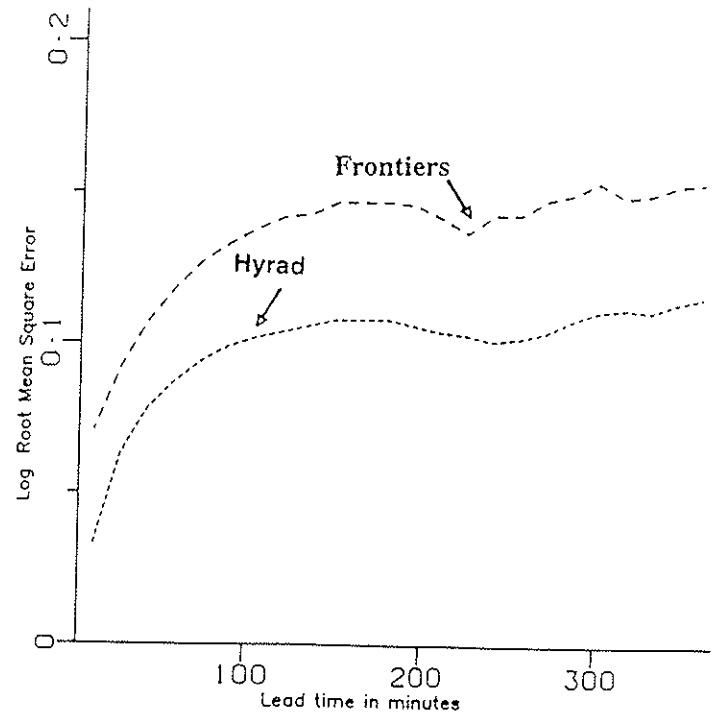


Figure 7 *Performance of HYRAD and Frontiers radar rainfall forecasts for a range of lead times; 15 minute rainfall totals for 14 storm events over London*

Accurate forecasts throughout the full range of flows are also needed to meet operational requirements for management of water abstractions and river regulation, operation of land drainage pumping stations, and input to time-of-travel models for pollution incidents. The potential benefits of low flow forecasting of Yorkshire's rivers are difficult to quantify but there are clearly enormous savings to be gained from improved operational efficiency during droughts, increased reliability of water supply, reduced investment in capital schemes and improved water quality management.

Complications in modelling Yorkshire's rivers are caused by the great extent of tidal influence, by the large number of off-river washland storage areas with fixed controls, by the complexity introduced by the river regulators on the Don and Rother river systems in the southern part of the region, and by the barriers at the mouths of the rivers Derwent and Hull.

RFFS Configuration

Configuration of the RFFS to the rivers of Yorkshire has established a pre-defined set of over a hundred forecast points selected by the NRA. The addition of forecasting points, to meet new NRA requirements, or the inclusion of new measurement sites is a relatively easy operation and has occurred several times in practice. Calibration facilities are provided for use by the staff who will be involved in the future development of the forecasting system. The modelling system incorporates the following types of modelling components - rainfall-runoff model, snowmelt model, hydrological channel flow routing, a hydrodynamic tidal reach model, and representation of river control structures and washland storages. Updating techniques are incorporated to 'correct' the forecasts and maximise on the use of the large volume of data which is made available in real-time by the telemetry system.

The RFFS Hydrological Forecasting Kernel has been set up within a shell developed by Logica UK Ltd. The shell provides a database and handles all the data inputs such as telemetry data from the Logica MC2000 system, weather radar data streams, storm tide warnings and surge predictions received by telex, manually-entered data, and telexed weather forecasts from the local weather centre. Astronomical tide predictions are generated by software within the shell in support of the system's tidal forecasting procedures. The shell also provides a user interface and reporting facilities.

System access and alarm handling

Forecasts in a variety of formats are accessible to any of the offices (particularly the Area and District Incident Rooms) with computer workstations served by the data communications network. A range of user privileges configured by the system manager allows differing levels of interaction with the system. The system is accessible using portable terminals over the public telephone system, via a secure remote dial-in facility which allows staff to gain full access from home to the region's data communications network and computers. A 'help' facility provides information on how to perform various actions on the computer system and information from the flood forecasting, warning, and operations manuals.

Alarms generated by the network of telemetry outstations are passed from the telemetry system to the RFFS, which then intelligently combines alarms and alerts one or more duty officer as appropriate via radio-pager or mobile phone.

Alarms to duty officers can also be generated from forecast model runs, including the automatic daily run made at 7 am using data collected overnight by the telemetry system. Other alarms can be generated by the receipt of storm tide warnings, or weather radar systems.

Decision support

Facilities are provided for real-time testing of the effects of different scenarios for future rainfall: HYRAD forecasts, Meteorological Office synoptic area forecasts, manually entered user forecasts, or the selection of one of a number of rainfall profiles to be applied as a forecast of rainfall are the options available.

Testing the effects of different ways of operating regulators and barriers, individually or in groups, is also possible; the cumulative effects downstream can be examined. This can be done to a limited extent in real-time and can also be used with data from previous events as a design tool for future operating strategies. The decision-support or 'What if?' facilities are provided by enabling users to edit copies of the data extracted from the modelling database and thus they can run the modelling system without affecting the data in the main database. This functionality should allow the NRA to operate its series of regulator gates to maximum effect in controlling flood waters.

Telex and fax facilities

Telex and fax messages can be received and sent direct from the forecasting computer. Weather forecasts from the Leeds Weather Centre are received by telex; such messages are automatically incorporated into the routine morning forecast run. Storm tide warnings are received by telex and the duty officer is automatically notified by radio-pager.

The system holds a set of standard colour-coded fluvial and tidal flood warning statements, which can be sent by flood response officers via telex and/or fax direct from the RFFS to one or more preconfigured recipients (typically Police and Local Authorities). Warnings can be sent fully automatically on receipt of an alarm, or as a result of model forecasts; there are examples of both in current operational use.

Operational use

Operational use of the RFFS in Yorkshire was initially limited by the availability of telemetry outstations. In February 1992 the system began to be used in earnest for one particular catchment. In the early hours of Wednesday 12th February a tip composed largely of dried sewage sludge slipped into the river Colne downstream of Huddersfield in West Yorkshire, completely blocking the river channel (Pelleymounter, 1992). Temporary pumping arrangements were replaced by a diversion channel within a week but channel capacity was severely restricted for the following two months, and the flood risk significantly increased. Flood warnings were required by a major chemical works, only a short distance upstream of the blockage, with a six hour lead-time to allow an orderly shut-down of the works. This watercourse has a catchment area of 245 km^2 and a mean annual flood of 128 m^3s^{-1} at Colne Bridge gauging station, a short distance downstream. Previously there was no flood warning system for the catchment and only one river level and one rainfall telemetry outstation.

The RFFS was the only possible source of forecasts of river flows and levels. A small network of outstations was installed within a few days. Since the time of concentration of the catchment is approximately 4.5 hours, in order to provide six hour warnings, flow forecasts had to rely heavily on rainfall forecasts. The RFFS incorporated a rainfall-runoff model giving forecasts for the Holme tributary which is scaled up as a representation of the Colne itself and another tributary, Fenay Beck. The combined flow was routed downstream to give a forecast for the site of the blockage, calibration being based on the gauging station record at Colne Bridge. A forecast within 5% of the observed peak flow was obtained, assuming perfect foreknowledge of rainfall and upstream levels. Operational forecasts were highly dependent on rainfall forecasts from the Meteorological Office, particularly at higher lead times. Locally generated radar rainfall forecasts, available through HYRAD, along with the national Frontiers forecasts, now provide valuable alternatives for lead times of 2 to 6 hours.

By April 1993, progress on telemetry outstation installation coupled with experience gained in the use of the RFFS was sufficient to allow forecasts upstream of York to be used for routine flood warning. Most recently, access to vastly improved data now available from the telemetry system has allowed a general programme of model reconfiguration and recalibration to be started, with the prospect of extending forecasting and warning to other rivers. With the combining of the Northumbria and Yorkshire NRA regions to form the single NRA Northumbria and Yorkshire Region, extension of the RFFS to the rivers of Northumbria is also under consideration.

Whilst the RFFS was designed to accommodate rainfall from weather radar from its inception, a decision was made to configure the initial implementation using raingauge data. This decision reflected uncertainty in the quantitative accuracy of weather radar, especially over the Pennine hills, and the already large scope of the implementation task. A decision to commission the HYRAD system was made in 1993, an initial form supplied in March 1994 to support immediate operational requirements and final acceptance of the system occurred in June 1994. A trial configuration of the RFFS to make use of HYRAD's observed and forecast catchment average rainfalls occurred in September 1994. An important feature of the RFFS configuration is that it allows the use of weather radar to be switched in and out, depending on the perceived reliability of radar at the time. For example, use of radar during conditions conducive to bright band, due to melting precipitation in the radar beam giving anomalous intense rainfall, can be avoided. The sensitivity of flow forecasts to whether processed radar or raingauge data are used can also be explored, providing one indicator of forecast uncertainty and reliability.

OTHER DEVELOPMENTS

The RFFS's configurability and transportability has been demonstrated through the use of the kernel software as the basis of Clyde RPB's White Cart Water Flood Forecasting System (Anderson, *et al*, 1992). This supports flood warning to the southern parts of Glasgow, making forecasts for 7 sites using telemetry data from 6 river gauging and 4 raingauge stations. The RFFS kernel software is also used in Hong Kong where a pilot flood forecasting system runs on a SUN UNIX workstation, and makes forecasts for the 70 km^2 Indus basin in the New Territories. Use of a 5 minute time step for this rapidly responding catchment has demonstrated the system's flexibility to choice of model and data time-step. The applications in Yorkshire, the Clyde and Hong Kong demonstrate that the RFFS kernel is largely machine independent (transfer from a VAX to Data General and UNIX computers) and suitable for both large, regional and small catchment implementations. Model Calibration Facilities within

the RFFS have also been supplied to the Thames Region of the NRA in support of a flood warning system for London and the Lee Valley (Haggett *et al*, 1992). The RFFS forecasting kernel is currently being configured to an initial set of 30 forecast points in the Thames basin using the NRA's CASCADE system as the system shell environment.

A strategy for implementation of the RFFS throughout the Anglian region of the NRA has been developed, where a total of 600 requirements for flow forecasts have been identified, the majority for flood warning but others for managing water transfers and licensing at lower flows (Moore *et al.*, 1993c). The Anglian Flow Modelling System aims to provide a unified windows environment on UNIX workstations and PCs for water management during floods, droughts and water pollution incidents through to the next century. In the context of the Yorkshire RFFS, a recently completed study (Institute of Hydrology, 1994), examined the feasibility of capitalising on the generic nature of the RFFS to incorporate a water quality model algorithm in a future release of the System.

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Drought management modelling for isolated systems: *Droughtwatch*

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Abstract

As a drought develops it is important to know how each reservoir can continue to maintain a given rate of draw and to have some idea of its prospects to refill. Such information should be readily and quickly available. This paper describes how these requirements were provided in a PC environment for North West Water Ltd. The implementation uses proven methods of critical period single reservoir analysis. It provides information of reservoir behaviour for a variety of risk levels, under minimum historic inflows or for a repetition of a specified historical sequence.

Introduction

For single surface water supply reservoirs, the relationship between reservoir capacity, yield and reliability is often examined through a critical period analysis. In an operational sense, the same general methodology can also be used to establish operating rules and to specify a control curve which describes, for each point in the calendar, the minimum storage required to meet a particular rate of draw at some specified reliability. These methods have been developed over a number of years in actual practice and have proved robust and effective instruments of water resource and drought management. Critical period techniques are dependent on long sequences of historical inflow data, used either for simulation studies, or to specify minimum historic sequences, or to construct statistical estimates of cumulative inflows. However, such data is often unavailable, and to circumvent this problem, corresponding data from a hydrologically similar catchment are used after applying some suitable re-scaling.

During a drought it is sometimes necessary to deviate from normal strategic operating policies because conditions may be more severe than those under which the policies were designed. Droughts are not a common occurrence, but it is essential for the effective management of the resource system that techniques are available to advise water supply managers as to the most appropriate action to be taken as an incipient drought situation develops. In many surface water resources, a group of individual reservoirs are operated jointly to supply a number of demand zones. The sophistication of the operational strategies deployed varies from water undertaking to water undertaking. Nevertheless, as a drought develops and the prospects of some restriction in water supplies heighten, the need to assess the residual resources increases. Although it is the overall capacity of the water resource system to meet demands which really matters, there is a justifiable need to determine drought susceptibility and recovery prospects on a reservoir by reservoir basis. For a reservoir of given capacity and inflow characteristics, the water undertaking might typically wish to know the following:

1. Is the reservoir above or below its control curve for the current rate of draw?

2. Given the current storage level, what is the estimated yield (maximum uniform rate of draw) for a given inflow condition and when would the critical storage condition occur?

3. What will be the pattern of storage for given demand and inflow conditions starting from a given storage condition?

4. What are the prospects of refill from the current storage condition for a given rate of draw?

Such information can then be used to assist the overall management of the resource, suggesting adjustments to maximum rates of draw from individual reservoirs, transfers between reservoirs, the need for drought orders, reduction in compensation waters and so on.

Critical Period Analysis

One of the established methods of answering such questions is through critical period analysis, which in turn is due to Rippl (1883), who was concerned with finding a design method for reservoir capacity estimation. Rippl took the historical record as typical of future inflow patterns and the critical period within that record was used to determine the required capacity to meet a specified (constant) demand. For operational purposes, the same general methodology can be used to determine an envelope of minimum storage requirements against time of year which would ensure that a given rate of draw could be sustained against any portion of the historical record. (see Figure 1) This envelope of minimum storage requirements is termed a control curve.

Instead of using the historical record as a perfect pointer to the future, the historical data can be searched to provide the minimum historical cumulative inflows for each starting date (eg for each 1st of the month) and for each duration (typically up to 24 or 36 months). To provide some notion of drought risk and reliability of supply, the historical record can be used to fit probability distributions to these cumulative inflows for each starting date and duration. In this way, the value of the p% non-exceedance, n-month cumulative inflow starting from date *dd:mm* can be estimated for any given probability level p, any given duration n and any starting date *dd:mm*. This derived data can be used for design (capacity estimation) or such operational purposes as the construction of a control curve.

Applications in the North West of England

There has been a notable tradition of development and application of these critical period methods within North West England, much of it deriving from the work of Law (1965), and including the work of Walsh, Pearson and Walker (see for example Walsh et al (1988); Pearson & Walsh (1982); Walsh & Walker(1989)). The focus of the earlier studies was often Stocks Reservoir, for which an extensive (derived) inflow record existed stretching back to 1927. Stocks Reservoir in the Pennines is a part of what is termed the Northern Command Zone (NCZ) of North West Water Ltd and which comprises a large number of raw water

sources. These include: over 80 groups of small impounding reservoirs in the Pennines which were developed originally as local sources; Thirlmere and Haweswater Reservoirs in the Lake District, river abstractions from the Lune & Wyre, and groundwater sources in the Fylde. Supplies from the NCZ currently total around 1200 Ml/d on average, with approximately one third of this produced from the smaller reservoir sources.

Operating policies have been derived for each of the water resources systems which show when it is necessary to utilise the pumped sources in order to safeguard the ascribed level of supply reliability (Walker & Wyatt (1987)). They also show when it is possible to overdraw the cheaper, usually reservoir, sources at rates above their reliable yield in order to minimise operating costs, yet not jeopardise the reliability of supplies to the customer. This provides guidance for routine operation of the region's water resources. Sometimes these policies have to be modified in response to a drought or other unexpected event. Whilst events such as these are, by their nature, not a frequent occurrence, it is essential for the effective management of the water resources system that techniques are available to provide decision support when such circumstances arise. (see for example Howard et al (1994)) It is important that the status of these smaller reservoirs can be quickly and readily assessed and the appropriate information is disseminated to those involved in their operation. To meet this requirement, the established methodology was implemented for North West Water Ltd by Heriot-Watt University and resulting in a PC-based decision support system called *Droughtwatch*.

Control curves

As explained earlier, the traditional basis of reservoir management is the control curve (Walsh et al (1988)), which gives for the ascribed yield, the reservoir storage required at any time of the year in order to survive a design drought of specified severity. The control curve ordinates are based on an analysis of net additions to storage and calculated from cumulative inflows of specified severity, cumulative draw to supply and compensation releases. The raw control curve ordinate S_{t_0} for the some time of year t_0 is usually calculated on the basis of monthly data and can be calculated according to:

$$S_{t_0} = \max_{t}\left[D_t + C_t - Q_t^p\right] \qquad (1)$$

where

S_{t_0} = Control curve ordinate for time t_0, giving the storage required to meet the given draw to supply and compensation flows for the p% drought inflows

D_t = cumulative draw to supply from time t_0 to $t_0 + t$

C_t = cumulative compensation & other releases from t_0 to $t_0 + t$

Q_t^p = p% cumulative inflow sequence from t_0 to $t_0 + t$

t = various durations from 1-month up to (say) 36-months

Similar calculations are carried out for each month t_0. The envelope defined by a plot of S_{t_0} versus t_0 defines the control curve. The ordinates S_{t_0} are usually adjusted to account for temporal discretisation and other effects. Two curves are generally used within North West

Water. An upper curve is calculated for the design yield at a p = 2% ("1 in 50 year") drought inflow; a lower curve is calculated corresponding to a less severe drought.

Actual inflow data for many of the small local reservoirs are generally insufficient to support robust statistical estimates of cumulative drought inflows. Instead, the extensive data inflow record from the Stocks reservoir - suitably re-scaled - is used as the statistical basis for the inflows to most of the local sources. The basis of the re-scaling is based simply on annual average flows, so that for any duration t, the coefficient of variation at the local source reservoir is maintained at the same value as at Stocks Reservoir. On this basis, this also means that the p% non-exceedance, n-month cumulative flow for Stocks can be simply re-scaled to give the corresponding flow statistic for the local source.

Monitoring the risk to supply and the prospects of refill

In order to establish the risks of not being able to maintain supply at current levels, an assessment known as "fixed starting dates" analysis can be carried out for each local source. Using the same cumulative inflow probability distributions referred to earlier, a set of cumulative monthly inflows at a range of return periods and durations can be determined. Once the cumulative monthly inflows for different return periods have been calculated, they can be used in conjunction with the known current reservoir level and abstraction rate to determine the envelope of minimum storage values under different runoff conditions over the coming months according to a variant of equation (1):

$$V_{t_0+t} = V_{t_0} + Q_t^p - D_t - C_t \qquad (2)$$

where V_{t_0} = Reservoir storage at time t_0
and other terms are as defined previously.

The risk of failure is thereby indicated, together with the months in which such failure would occur. The greatest value of p and the corresponding value of t which makes V_{t_0+t} go negative for given values of V_{t_0} , D_t and C_t, determines the risk of failure. The value of t indicates the time at which the failure would occur. A variation of this analysis can also be used to show the maximum uniform demand D_t which can be supported from the source, under the different runoff conditions, as parameterised by the probability value p.

Access to such information for a number of reservoirs across a supply zone allows abstraction rates to be adjusted so that the risks to supply across the zone are equalised or otherwise acceptable to the water supply manager. The analysis can also show by how much the demand must be lowered in order to meet the required risk criterion, indicating to water supply managers the reduction in water usage required from such measures as demand management, introduction of special legal powers to abstract outside normal environmental safeguards or introduction of an alternative and/or emergency source.

As the drought begins to abate and the reservoirs refill, it is important to know when routine operating policies can be reintroduced and rates of draw returned to their normal values. The prospects of refill for a given level of current storage and current rate of draw can be determined from another variant of equation (1):

$$V_{t_0+t} = V_{t_0} + Q_t^p - D_t - C_t \qquad (3)$$

The lowest value of t which causes V_{t_0+t} to exceed the reservoir capacity indicates when the reservoir will first spill for the specified probability level p.

Monitoring rainfall

As an adjunct to reservoir analyses of the type described above, it is common practice to analyse antecedent rainfall conditions and to set these into some kind of historical context. Preceding and forecast rainfall totals levels offer a valuable guide to drought severity. Rainfall is routinely monitored at several water supply catchments. The *Droughtwatch* system allows any specified (eg current) cumulative rainfall pattern to be compared to an archived record. For example, a rainfall total of 123mm occurring over a 28 day period ending on March 9th can be ranked against all other 28 day totals ending on the same date. If the end date is not of interest, the specified event will be ranked against all other rainfall totals over all 28 day periods in the record. If desired, the corresponding comparison can be made using just part of the record, say the last 15 years. In this way contemporary rainfall episodes can be compared to the historic record in order to establish their return; comparison can also be made with those historic rainfall events which are known to have placed the water resources system under stress.

The *Droughtwatch* system

Droughtwatch is a menu-driven piece of software which can be configured by the user to analyse a set of reservoirs. The version implemented by NWW Ltd and NRA (NW) to control and monitor the resources in the North West is configured to deal with over 80 reservoirs/reservoir groups. A set of system utilities allows new reservoir groups to be added by the user. The user can specify the month by month pattern of intended draw to supply and compensation releases for each reservoir, together with its maximum and minimum allowable storage levels. The user can also specify the initial storage and one or more cumulative inflow sequences and then simulate the corresponding pattern of reservoir storage. The choice of inflow sequences can be any of the 1%, 2%, 5%, 10%, 20% cumulative drought inflow sequences, the average cumulative inflow sequence or the minimum historic cumulative inflow sequences. To compare prospective reservoir behaviour with previous drought experiences, *Droughtwatch* can also access any selected actual historical sequence of flows and perform a simulation of storage using these values.

Droughtwatch screen displays

An example of the corresponding graphical screen display is shown in Figure 2, which depicts the behaviour of the Coldwell reservoir (one of four reservoirs in the Burnley 2 Zone of the Ribble District). The situation depicted envisages a total draw to supply plus compensation of 0.9 + 1.5 = 2.4Ml/d, whereas the control curve corresponds to the ascribed yield of just 1.7Ml/d. As the figure shows, from an initial storage of 268Ml on 1st July (which is below both the control curves), the reservoir would fail during October at the specified total rate of draw under minimum historic drought inflows. It would just survive the 2% drought and would perform quite adequately under average inflows, spilling in January of the following year. For any of the chosen inflow sequences, the display can be toggled to show the timing and magnitude of any spill and any shortfall in demand and compensation requirements, as shown in Figure 3.

In addition to this graphical output, *Droughtwatch* provides other pertinent information in the form of a series of summary tables. Figure 4 gives firm yield information for all reservoirs in the group under a variety of inflow conditions. For example, for the Cantclough & Hurstwood Reservoir, with initial storage at 32% of active capacity, it can be seen that the yield under 2% drought inflows would be just 7.7Ml/d (plus 4.9Ml/d compensation) against the firm yield of 10.7Ml/d (plus 4.9Ml/d compensation) that would be obtained given appropriate initial storage.

Figure 5 provides storage pattern information on all the reservoirs in the district for their given initial storage, compensation and supply demands, and assuming average inflow conditions. Such information gives an idea of reservoir behaviour should there be a break in the drought such that inflows were to return to normal levels. The storage volumes in the 9 months ahead are given as a percentage of active capacity. The letter 'S' denotes that the reservoir would spill.

Information on the time of failure for each reservoir for a range of inflow severities is given in Figure 6. More detailed spill information is contained in a further screen display (Figure 7), which summarises the prospects of refill for each of the reservoirs in the district under a range of inflow conditions. All screen displays can be output to a laser printer.

During normal patterns of storage/inflow/demand the *Droughtwatch* System is used routinely on what might be termed a casual basis. As an incipient drought develops, *Droughtwatch* comes into much more regular and systematic use as an aid to balancing supplies across the water resource system, and resource information is disseminated to operational staff. As ever greater demands are placed on the regional sources, then it is appropriate that these too are subject to regular scrutiny. Correspondingly, these resources have been included as a reservoir group within *Droughtwatch*, and the major drought management decisions are geared to the status of these strategic sources.

Technical and Hydrological Limitations

As explained, the Droughtwatch system is based on analysis of a single reservoir using flow data and statistics based on those from a suitable site elsewhere and simply re-scaled according

to mean annual flows (thereby preserving the coefficient of variation). The limitations are therefore centre on the validity of single reservoir analyses within complex reservoir systems and the validity of data transformations from one catchment to another.

Reservoirs are often part of a more complex resource system and so cannot be regarded as a simple, single supply reservoir providing the sole means of meeting a demand. For an integrated system of sources, the notions of individual reservoir yield and reliability are less easily defined and determined. For a complex resource system the proper approach to resource management is to take a holistic or systems approach, in which the interactions of different components are properly taken into consideration and some overall objective function is optimised. Nevertheless, as the system begins to approach the failure envelope, as will happen with a drought, so-called optimal solutions are likely to become less robust. The emphasis shifts from cost minimisation to the simple priority of meeting demand at some acceptable level of service. The robust assessment of reservoirs on a one by one basis therefore provides the water resources manager with a feel for the susceptibility of a particular source and the extent to which it may have been overdrawn. *Droughtwatch* offers an ideal tool for this aspect of water resources management.

The simple scaling of data from one catchment to another using the ratio of their mean annual flows has the virtue of simplicity, but is of questionable validity. Under this assumption (which preserves the coefficient of variation) any cumulative flow statistics and corresponding percentile exceedance values are also in the same scaling. Even within a hydrologically homogeneous region, it might be expected that the flow variability in larger catchments would be rather different to that in smaller ones, and that the coefficient of variation should not be preserved in any transformation of data at one site to another. Among the other ways of transforming data from one catchment to another are a simple linear transformation or a power law transformation:

$$Q_2 = A.Q_1 + B \qquad (4)$$

or

$$Q_2 = A.(Q_1)^B \qquad (5)$$

Transformation (4) can be fixed by reference to a pair of percentiles on each catchment (eg mean flow and the 95 percentile exceedance value). This particular transformation has some theoretical shortcomings in that it not a positive to positive transformation. Nevertheless, it does allow a cumulative flow statistic Q_{2t}^p at one site to be related directly and easily to that Q_{1t}^p at another.

On the other hand, the power law transformation does ensure that all flows are positive, but has the drawback that cumulative flow statistics at one site cannot be directly related to those at the other. Instead the flow record as a whole has to be transformed and the statistics of flow for various duration and starting months must be re-worked from scratch.

Exploration of these and similar methods might be rewarding. In the meantime, and despite the drawbacks referred to, the existing method of simple re-scaling at least puts the assessment

of each reservoir in the system on the same footing, leaving the water resources managers to use their experience to temper the conclusions as appropriate.

Software/Hardware Specifications

The *Droughtwatch* software was developed using Borland Turbo C 2.01 on a Compaq 386 personal computer, with hard drive and VGA graphics, running MS-DOS 3.3 and should run on any 100% PC compatible with the equivalent specification. *Droughtwatch* is totally configurable by the user. Reservoirs and reservoir data can be added, or the current database altered. Interaction with the user is via 'Pop up menus' and 'Input Boxes', and context sensitive interactive help is available throughout. Once all the statistical data is loaded into the database, users can very quickly assess the drought potential of any zone or examine in more detail the particular behaviour of one of more of the reservoirs. The analyses and graphical displays are produced within seconds and can be dumped to a laser printer.

Summary

The major aspects of the *Droughtwatch* system have been briefly described. A full assessment of drought related information can be undertaken and corresponding hard copy information easily and quickly prepared. The system is in regular use by NWW Ltd, enabling them to produce more management information more quickly. A copy of the software using an identical database is in use by the National Rivers Authority (NW Region).

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Figure 1 Graphical representation of how a control curve ordinate is determined

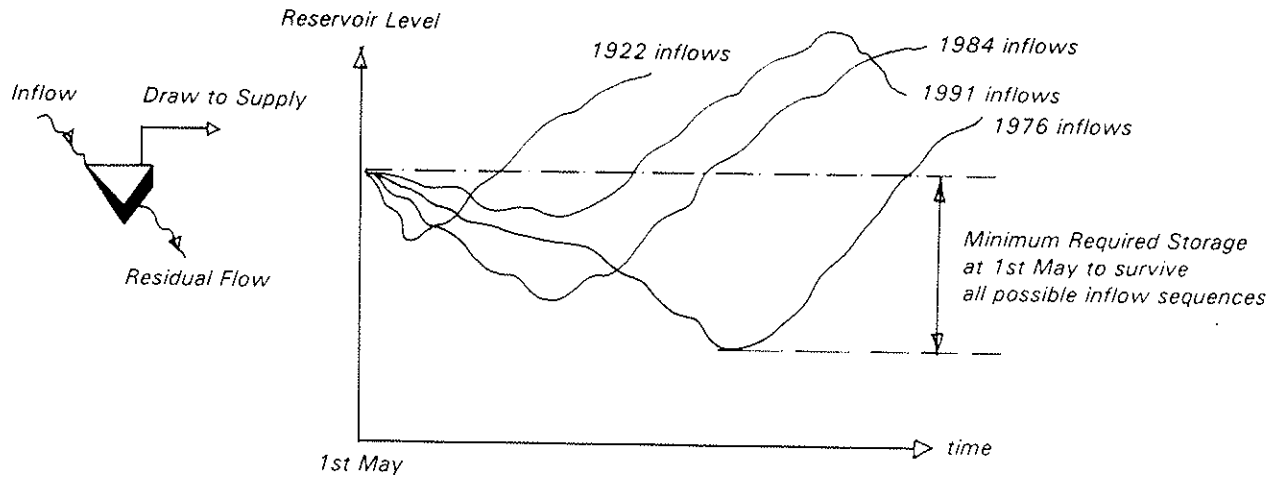


Figure 2 Droughtwatch output/screen display:
Reservoir Simulation:
Coldwell Reservoir, Burnley 2 Zone, Ribble District

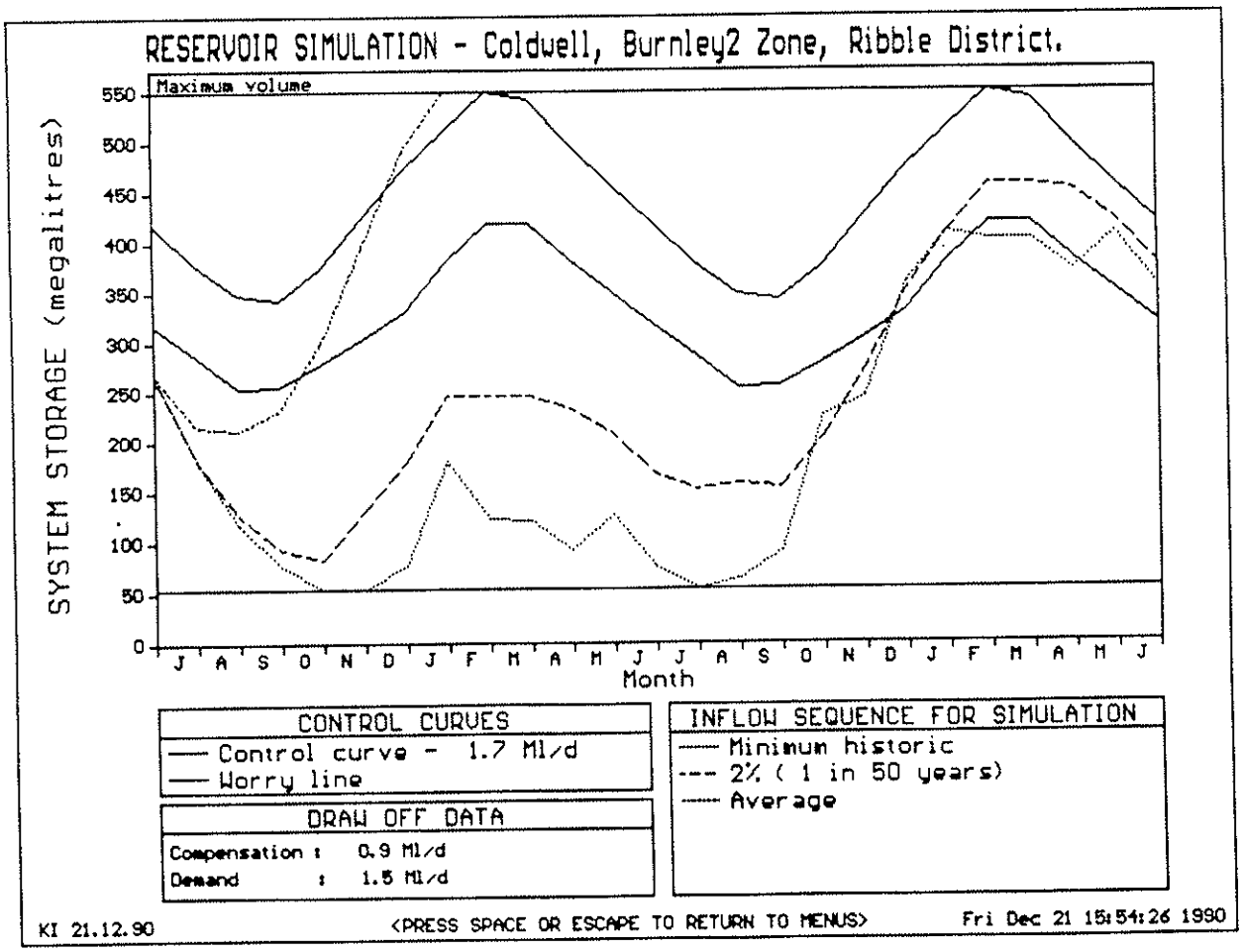


Figure 3 Droughtwatch output/screen display:
Pattern of deficits in supply under minimum historic flow conditions:
Coldwell Reservoir, Burnley 2 Zone, Ribble District

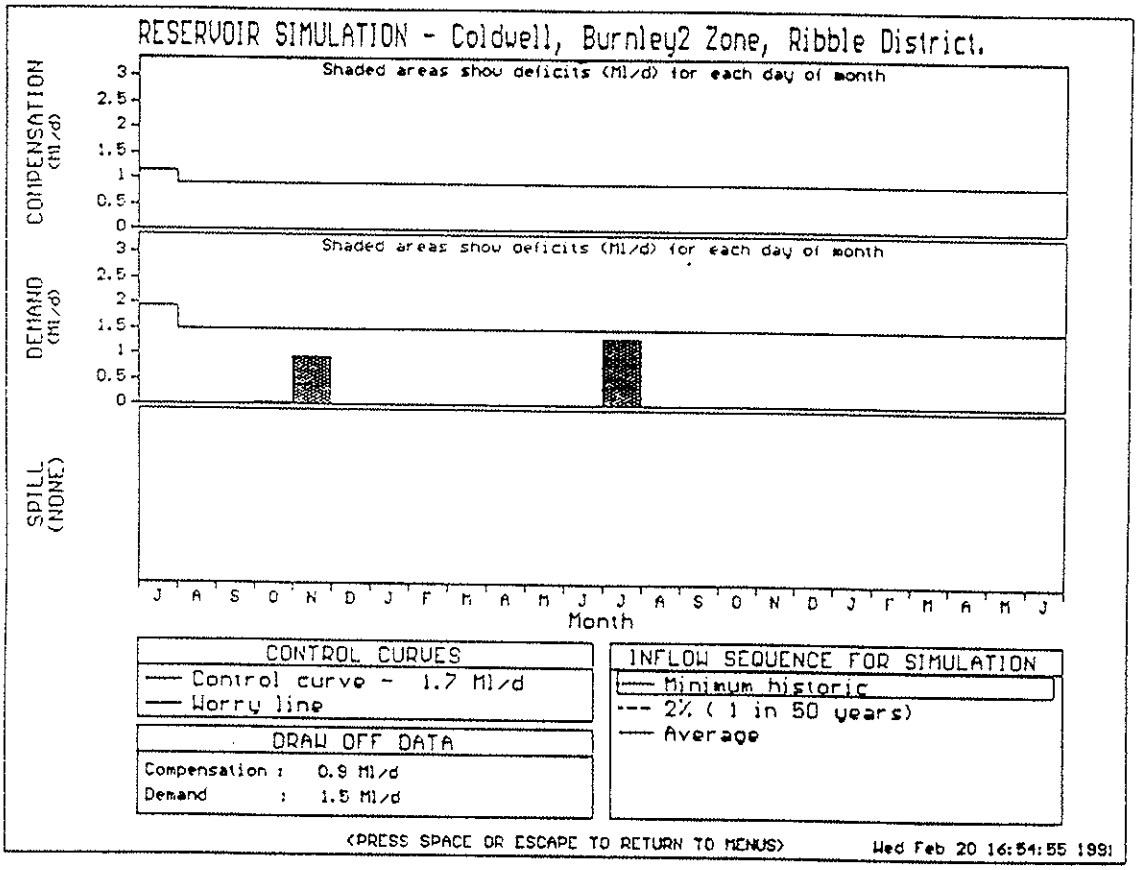


Figure 4 Summary Table
Firm yields of reservoirs for various inflow conditions
Burnley 2 Zone

Ribble District, Burnley2 Zone
Estimated supply yield under different inflow conditions
Starting 1st of JULY

Reservoir	Comp Ml/d	Demand Ml/d	Initial Storage %Full	MH	1%	2%	5%	10%	20%	Av
Churnclough	0.7	2.1	40	1.9 5	2.2 4	2.3 4	2.6 4	2.9 4	3.2 15	3.8 15
Laneshaw	1.0	1.3	36	1.1 2	1.2 3	1.3 2	1.5 2	1.8 2	2.3 2	3.6 2
Cantcl+Hurstwood	4.9	10.7	32	5.8 5	7.0 4	7.7 4	8.7 3	9.8 3	11.4 3	15.1 15
Colduell	0.9	1.5	43	1.3 5	1.6 4	1.7 15	1.9 15	2.0 15	2.2 15	2.7 15

Upper: Estimated supply yield (Ml/d)
Lower: Critical period (months ahead)

NB Compensation and Demand are at default settings.
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Figure 5 Summary Table
Storage pattern for given initial storage and assuming average inflows
Burnley 2 Zone

Ribble District, Burnley2 Zone

Pattern of storage with average inflow at stated releases

Starting 1st of JULY

Reservoir	Comp Ml/d	Demand Ml/d	Initial Storage %Full	1	2	3	4	5	6	7	8	9 (storage volume, months ahead)
Churnclough	0.7	2.1	40	30	31	37	52	75	36	S	S	S
Laneshaw	1.0	1.3	36	33	53	89	S	S	S	S	S	S
Cantcl+Hurstwood	4.9	10.7	32	18	16	18	30	48	66	83	90	92
Coldwell	0.9	1.5	43	32	32	36	50	69	89	S	S	S

NB Compensation and Demand are at default settings.

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Figure 6 Summary Table
Time of failure under various inflows at given releases
Burnley 2 Zone

Ribble District, Burnley2 Zone
Water Storage Situation
Starting 1st of JULY

Reservoir	Comp Ml/d	Demand Ml/d	Initial Storage %Full	MH Month during which system will fail	1%	2%	5%	10%	20%	Av
Churnclough	0.7	2.1	40	OCT	NF	NF	NF	NF	NF	NF
Laneshau	1.0	1.3	36	AUG	AUG	NF	NF	NF	NF	NF
Cantcl+Hurstwood	4.9	10.7	32	AUG	AUG	AUG	SEP	SEP	NF	NF
Colduell	0.9	1.5	43	OCT	NF	NF	NF	NF	NF	NF

NB: NF = no failure in next 24 months, Next = fails in second year.
NB Compensation and Demand are at default settings.
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Figure 7 Summary Table
Prospects of refill under various inflows at given releases
Burnley 2 Zone

Ribble District, Burnley2 Zone
Prospects of refill under different inflou conditions
Starting 1st of JULY

Reservoir	Comp Ml/d	Demand Ml/d	Initial Storage %Full	MH	1%	2%	5%	10%	20%	Av%
				Estimated maximum storage (%full) in next 12 months						
Churnclough	0.7	2.1	40	30	38	47	61	75	93	S
Laneshau	1.0	1.3	36	S	S	S	S	S	S	S
Cant, H'uood, Suin	4.9	10.7	32	22	24	28	33	40	54	92
Colduell	0.9	1.5	43	26	32	39	52	65	82	100

NB Compensation and Demand are at default settings.
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An Integrated Approach to Modelling Water Resource and Supply Systems

John Ringham[1], Ken Howard[2] & Timothy Wyatt[2]

ABSTRACT

The paper outlines the structure of an integrated system for modelling water supply operations from 'source to tap'. Modules are provided by generalised computer programs for simulating the performance of water systems and optimising long, medium and short-term operating policies. Details are given of how the modelling system is being implemented by North West Water Ltd. (NWW), together with indications of future developments.

INTRODUCTION

NWW provides water and wastewater services to some seven million customers. The types of raw water source, and the approximate percentages of total water abstractions supplied by them, are : 168 impounding reservoirs (65%); 55 river, stream and lake intakes (25%); 240 borehole sites (10%). Raw water is processed at some 190 treatment works which feed approximately 42,300 km of water main.

As part of its drive to improve levels of service to customers and obtain greater efficiency of operation, in 1992 NWW requested Water Systems Consultants Ltd. (WSC) to make an appraisal of the company's water supply system modelling requirements and to put forward proposals for implementation of their suggestions (WSC, 1992). This report outlined the concept of an integrated system of mathematical models accessing a common database.

Although similar ideas had been advanced some twenty years earlier (Wyatt, 1973; Donachie, Howard, Mawer & Wyatt, 1973), such a system would then have been confined to installation on a mainframe computer, and facilities for constructing and interrogating databases of the necessary magnitude and complexity were in their infancy. At the time, some considered that the costs associated with assembling and actualising the necessary data would be prohibitive.

Implementation of the integrated modelling system by NWW is now considered to be a practical proposition due to :

- the wide geographical and multi-functional responsibilities of the company;
- the advances made during the intervening period in distributed computing power;
- the availability of software for the creation and maintenance of the associated databases.

The feasibility of such a system has been enhanced by advances made within NWW towards :

- automated data collection and control systems;
- the development of corporate databases for key operational data.

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MODELLING MODULES

WSC's report identified six separate modules which would cover NWW's requirements. In identifying the required modules, detailed consideration was given to the types of system to be analysed and the time frames over which their performance would be simulated or optimised. In doing so, the following conventions were adopted :

- a (Water) Resource System consists of a number of surface and groundwater sources feeding a series of demand centres through pumping stations, treatment works, major (transmission) aqueducts and terminal storages. The quantities of water available from one or more sources will typically be constrained by hydrological conditions, storage provisions and abstraction licences;

- a (Water) Supply System consists of a number of disparate sources feeding a series of demand centres via pumping stations, trunk mains and service reservoirs. In such systems the maximum outputs from any source are not considered to be constrained by hydrological conditions;

- a (Water) Distribution System consists of a number of service reservoirs, and possibly pumped supplies, feeding a series of demand nodes via (booster) pumps, valves and pipes;

- Long Term : analysis of (hydrological) systems over a multi-year time series assuming that the system configuration, costs and annual demands are constant from year to year. The principal objectives in such analysis are to model the effects of both seasonal and over-year hydrological persistence, reservoir storage and multi-year abstraction licences;

- Medium-Term : analysis of resource and supply systems subject to annual licence constraints or, in the case of resource systems, where long-term cost and reliability aspects can be reflected by end-of-period stored water values;

- Short-Term : analysis of supply and distribution systems over a daily or weekly period, taking account of pump failures, mains bursts, rapid changes in demands and service reservoir levels.

When defining the functions of the modules, it was not felt necessary to propose modelling techniques radically different than those which have already been developed for application within the water supply industry and elsewhere. Thus the emphasis was on 'evolution' rather than 'revolution'.

However, it was recognised that major efforts would be required in order to :

- combine the individual modules to form a fully integrated system;

- develop the necessary links to the corporate and ancillary databases;

- construct man/machine interfaces to ensure that the full potential of the modelling system would be exploited.

Table 1 provides a description of each module and its intended usage; the associated analytical time horizon, time step, and run frequency; the principal data inputs and outputs; the selected analytical technique, reasons for selection and associated limitations; interactions with other modules; the current implementation status and scope for future development.

Table 1 : Description of Integrated Modelling System Modules
(Sheet 1 of 4)

MODULE NUMBER, DESCRIPTION AND USAGE		TIME HORIZON	TIME STEP	RUN FREQUENCY	PRINCIPAL INPUTS	PRINCIPAL OUTPUTS
1	**Resource and Supply System Development Planning.** - Minimise total discounted capital and operating costs over a specified planning horizon.	1 - 30 years with varying demands and system configur-ations.	Monthly or Annual	Annually or if any significant changes made to new project parameters or future demand forecasts.	Planning horizon, discount and inflation rates. Unit and fixed operation and maintenance costs. Estimated capital costs of possible system additions (distributed over construction period). Net salvage costs for retired components. Timings of component additions and retirements. Average operating quantities for alternative system configuration/demand combinations (by component and cost item).	For each alternative develop-ment plan, the net present worth, discounted cash flow.
2	**Long-Term Operations Planning for Hydrologically Constrained Systems.** - Optimise long-term system and component operating policies. Investigate relationships between operating costs, supply reliabilities and environmental protection constraints. Demonstrate compliance with required Levels of Service. Determine system yield.	Multi-year with fixed (annual) demand and system con-figuration.	Part day or daily	Annually or if any significant changes made to the system configuration or the forecast demand.	System configuration including component capacities and maximum throughputs. Daily, annual and 3-yearly abstraction licences. Flow dependent licences. Compensation releases and maintained flows. Unit chemical costs and dosage rates (by treatment plant and season), and blending constraints. Pumping rate/kVA functions and electricty tariffs. Drought management measures. Annual demands by demand area, either seasonally varying or as time series. Hydrological time series (historic). Individual reservoir control curves. Alternative system operating regimes. Required reliability (maximum reservoir drawdowns, and/or allowable frequency for imposing drought management measures e.g. OFWAT Levels of Service DG1 & DG4).	Optimized long-term system operating policies. Results of simulating system performance with a given operating policy (in printer and spreadsheet compatible files) : - monthly quantities and costs - frequency analysis of reservoir contents - abstraction licence utilisation - daily reservoir levels and component throughputs - long-term values of stored water (by month and state) - graphical output (system storage and operating policy)
3	**Medium-term Operations Planning for Hydrologically Constrained Systems** - Provide daily abstraction and system component throughput schedules. Analyse effects of hydrol-ogical and component availability scenarios on supply reliability, environ-mental conditions and operating costs.	12 months.	Part day or daily	Weekly or if any significant changes made to component availabilities, river levels, or the forecast demand.	As above, but with : Current reservoir storage states. Forecast component availabilities i.e. based on planned (maintenance) and forced outages. Short-term hydrological forecasts and medium-term scenarios e.g. median and extreme. Cumulative source abstractions. Short and medium-term demand forecasts e.g. climate related. Target Levels of Service. Forecast electricity charges (e.g. Pool Prices). Forecast chemical dosage rates e.g. dependent on source water quality.	Target source abstraction and and component throughput schedules : - daily for next week; - weekly for next month; - monthly for next year. For the next twelve months : - budget operating costs by component; - cumulative abstractions from each source and unused licenced quantities. - reservoir storage trajectories; - incidence of any drought management measures.

Table 1 : Description of Integrated Modelling System Modules (Sheet 2 of 4)

MODULE	ANALYTICAL TECHNIQUE SELECTED	REASONS FOR SELECTING TECHNIQUE	LIMITATIONS OF SELECTED TECHNIQUE	INTERACTIONS WITH OTHER MODULES	CURRENT STATUS / FUTURE DEVELOPMENT
1 **Resource and Supply System Development Planning**	Cash flow analysis of user specified alternative development plans. Plans constituted by estimated operating and capital costs for each month or year of planning period.	Allows for variations in operating costs as a function of demand, system configuration and supply reliability. Should ensure that systems can be operated as planned, and eliminate planning and operational inconsistencies.	No guarantee that least cost development plan will be identified. However, number of practical and feasible development options usually limited, and non-optimality risk slight when a sufficient number of alternative plans analysed.	To Modules 2, 3, 4, 5 : Scheduled changes to water resource and supply systems configurations.	Cash flow analysis program is available but has not been implemented. Inputs from other modules could be automated via the modelling database.
2 **Long-Term Operations Planning for Hydrologically Constrained Systems**	Integrated simulation and non-linear optimisation. Generalised simulation for modelling different water resource systems. Generalised stochastic DP (dynamic programming) used for operating policy optimisation. Search procedure for the determination of maximum demand that could be supplied (system yield).	Essential to accurately model the effects of hydrological presistence, only considered feasible by using simulation. Part-day or daily time step required to accurately model (river) flow variations and complex electricty tariffs. Operating policy optimisation requires analysis of non-linear sequential decision process, hence Dynamic Programming.	Penalty factor used to link the simulation and optimization modules does not guarantee mathematical optimality of the solution. However, the results indicate significant savings possible when compared with alternatively derived policies. Although user must define the alternative operating regimes, number of practical options is usually limited. Fixed annual system configurations, although component availabilities can be varied on calendar monthly basis. Execution times significant for complex systems.	To Module 1 : Expected (average) long-term operating costs for system configuration / demand level / supply reliability combinations as defined by alternative development plans. To Module 3 : Long-term stored water values for optimising medium-term operating policies and abstraction schedules.	Computer program MOSPA developed, installed on PC & IBM RS/6000 computers. MOSPA simulation models constructed for NWW's NCZ and SCZ strategic systems, and for Vyrnwy sub-system. Development of 20 local system models planned. Model of Lancaster system completed. MS-WINDOWS run-time environment (MOSES) under development; will include template editing of input data files, the graphical presentation of outputs and links to modelling database.
3. **Medium-Term Operations Planning for Hydrologically Constrained Systems**	Integrated simulation and non-linear optimisation. Generalised simulation for modelling different water resrource systems. Deterministic dynamic programming (DP) used for optimisation of operating policies.	Essential to accurately model the effects of hydrological presistence, only considered feasible by using simulation. Part-day or daily time step required to accurately model (river) flow variations and complex electricty tariffs. Operating policy optimisation requires analysis of non-linear sequential decision process, hence Dynamic Programming.	Penalty factor used to link the simulation and optimization modules does not guarantee mathematical optimality of the solution. Although user must define the alternative operating regimes, number of practical options is usually limited.	To Modules 4 & 5 : Target abstractions from aggregated sub-systems e.g. lumped groundwater sources. To Module 6 : Target abstractions from single, hydrologically constrained sources e.g. rivers and reservoirs.	Computer program MOSPA developed, installed on PC & IBM RS/6000 computers. Current reservoir contents, lake levels, chemical dosage rates and unit costs input from database extract file. Abstraction schedules can be stored on NWW's OMS database for subsequent transmission to system managers. DROUGHWATCH' program used for monitoring status of individual reservoirs.

MODULE NUMBER, DESCRIPTION AND USAGE	TIME HORIZON	TIME STEP	RUN FREQUENCY	PRINCIPAL INPUTS	PRINCIPAL OUTPUTS
4 **Medium-term Operations Planning for Linear Water Supply Systems.** - Provide optimised daily abstraction and system component throughput schedules, with ranked alternatives.	12 months.	Part day or daily	Weekly or if any significant changes made to component availabilities or the forecast demand.	Daily, monthly and annual abstraction schedules for hydrologically constrained and lumped sources. Electricity tariffs. Unit electricity costs (e.g. Pool Prices). Chemical unit cost and dosage rates. Daily and annual abstraction licences. Component capacities. Limits on service reservoir drawdowns. System demand profiles. Blending or similar joint constraints. Forecast availability of system components. OFWAT Levels of Service (DG1 & DG4).	Source abstraction and component throughput schedules and list of least cost alternatives : - daily for next week; - weekly for next month; - monthly for next year. For the next twelve months : - budget operating costs by component; - cumulative abstractions from each source and unused licenced quantities.
5 **Medium-term Operations Planning for Non-Linear Water Supply Systems.** - Provide optimised daily abstraction and system component throughput schedules, with ranked alternatives.	12 months.	Part day or daily	Weekly or if any significant changes made to component availabilities or the forecast demands.	Daily, monthly and annual abstraction schedules for hydrologically constrained and lumped sources. Electricity tariffs. Unit electricity costs (e.g. Pool Prices). Chemical unit cost and dosage rates. Daily and annual abstraction licences. Component capacities. Limits on service reservoir drawdowns. System demand profiles. Blending or similar joint constraints. Forecast availability of system components. OFWAT Levels of Service (DG1 & DG4). Data on system hydraulics i.e. pump head/flow curves, friction losses.	Source abstraction and component throughput schedules and list of least cost alternatives : - daily for next week; - weekly for next month; - monthly for next year. For the next twelve months : - budget operating costs by component; - cumulative abstractions from each source and unused licenced quantities.
6 **Pump Scheduling and Valve Setting.** - Production of least-cost pump and valve setting schedules which meet specified Levels of Service standards. Production of least-cost schedules for individual pumping stations, taking account of pump efficiencies, hydraulic interaction, and energy costs e.g. pool price tariffs.	1 to 7 days.	Part-hour/ hour.	Dependent on availability of actualised data. e.g. 15 minutes for telemetered input, daily for manual input.	"Fixed" data (Manual) : Electricity tariffs. Limits on pressures. Limits on service reservoir drawdowns. Component capacities. Pump outputs and efficiencies. Forecast availability of system components. System demand profiles. "Current" data (Manual or via Telemetry) : Service reservoir levels. Component status e.g. pumps. Flows and pressures.	Short-term operating schedules indicating : - pump start/stop times; - valve settings; - operating costs. Schedules presented to system operator for confirmation and implementation, or in the form of telemetry commands. Simulated results of applying schedule over the optimisation period showing, in both tabular and graphical form, predicted flows, pressures and reservoir levels.

Table 1 : Description of Integrated Modelling System Modules
(Sheet 3 of 4)

Table 1 : Description of Integrated Modelling System Modules (Sheet 4 of 4)

MODULE	ANALYTICAL TECHNIQUE SELECTED	REASONS FOR SELECTING TECHNIQUE	LIMITATIONS OF SELECTED TECHNIQUE	INTERACTIONS WITH OTHER MODULES	CURRENT STATUS / FUTURE DEVELOPMENT
4 **Medium-Term Operations Planning for Linear Water Supply Systems**	Linear Programming with specialist matrix generator and report writing software.	Large numbers of system components & demand areas results in large number of constraints and variables to be optimised. Use of standard LP solution package to reduce software development costs. For large systems produces optimised schedules more rapidly than the non-linear methods used in Module 5.	Linear constraints, output and objective functions. 'Maximum Demand' electricity tariffs require mixed integer formulation which may result in excessive execution times.	To Module 6 : Target abstractions from individual boreholes and associated pumping stations. To Modules 2 & 3 : Cost and quantity data for the representation of lumped sources within major resource system models.	Formulated as 'Small Source Linear Optimisation System' based on standard MPS input and output formats for use with commercial linear and mixed-integer solution packages.
5 **Medium-Term Operations Planning for Non-Linear Water Supply Systems**	Integrated Simulation and Non-linear Optimisation. Use of 'system response' functions based on the results of 'off line' network analysis runs and integral simulation model, coupled with gradient search 'hill climbing' optimisation.	Hydraulic interaction within supply system can result in significant non-linearities in the outputs available from individual components and hence production costs.	Not suitable for very large systems due to excessive computation times.	To Module 6 : Target abstractions from individual boreholes and associated pumping stations. To Modules 2 & 3 : Cost and quantity data for the representation of lumped sources within major resource system models.	Specific model of the Fylde Borehole system under development. Model takes account of hydraulic interaction of borehole pumps feeding a common main, and quality differences in source water.
6 **Short-term Pump Scheduling and Valve Setting**	Integrated Simulation and Non-linear Optimisation. Software required to give revised schedules every at 15 minute intervals or on request. Fast execution therefore essential, and hence the use of 'system response' functions based on the results of 'off line' network analysis runs and integral simulation model.	When interfaced to telemetry system, revised schedules may be required at, say, 15 minimute intervals. Thus fast execution times essential. Rules out 'on-line' use of network analysis programs for analysing response to large numbers of variable combinations. Hence use of 'system response' surfaces and gradient search optimisation technique.	In common with most non-linear optimization techniques, convergence to the optimum solution is not guaranteed. User must specify penalty values applicable if specified operating constraints violated e.g. distribution pressures or reservoir levels outside target ranges. However, such values indicate the costs associated with maintaining particular levels of service.	From Module 3 Target abstractions from individual, hydrologically constrained, sources. From Modules 4 or 5 : Daily source abstraction schedules and ranked alternatives. To Modules 4 or 5 : Demand forecasts and component availabilities.	Original software developed for North Surrey Water Co. and used by Yorkshire Water (Hull). Program SYMCO now being implemented for NWW's Oldham supply system. When linked to telemetry system, possibility to use such data for 'on-line' re-calibration of network representation i.e. automatic adjustment in the light of changing system response e.g. re-valving.

As indicated in Table 1, the modules feature a number of different optimisation techniques including linear, dynamic and non-linear programming methods. These reflect the fundamental nature of the problem to be resolved; e.g. dynamic programming for sequential decision making, linear programming for linear or quasi-linear systems, and directed search algorithms where system responses or constraints exhibit significant non-linearities.

With the exception of Module 4 all modules incorporate simulation models of the water resource or supply system for evaluating the objective functions and constraint compliance. A major attribute of this approach is that the simulation models can be run independently of the optimisation procedures, enabling the evaluation of current operational procedures and 'what if' scenarios associated with extreme events and alternative system development options.

Descriptions of the water resource or supply systems are input via data files and the associated computer programs thus need to be amended only when there are changes to the structure of the functions currently available e.g. new methods of costing, licence structures etc. Cost details may include electricity tariffs (unit prices, maximum demand, availability charges etc.), chemical (treatment) costs, labour and maintenance costs.

The main information flows between the modules are illustrated in Figure 1, within which the modules are shown in decreasing order of analytical time horizon. Thus the time horizon associated with Resource System Expansion Planning (Module 1) is likely to span several years or decades, while for Pump Scheduling and Valve Setting (Module 6) system performance would be optimised over a 24-hour or weekly time period.

It can be noted that a number of systems may be modelled using more than one of the modules. For example, when deriving operating policies for regional systems using Modules 2 & 3, individual boreholes may be considered as an aggregated source. The 'high level' policies produced indicate the target abstraction from the borehole group, but the quantities to be taken from each individual borehole will be determined using Modules 4 or 5, within which detailed consideration is given to physical, quality, and cost aspects affecting operation of the sub-system.

A major aspect of the integrated modelling concept is the use of a common database to ensure the validity and consistency of information employed. However, it is essential to recognise that data requirements may differ significantly between modules and that modelling data may need to be stored in a different form from that used to monitor other aspects of the business. When establishing the modelling database structure, careful consideration therefore needs to be given to :

- the way in which information relating to individual system components is stored and can be aggregated or disaggregated for modelling at different levels of detail;

- differentiating between data associated with existing and planned components, and between recorded and forecast data;

- the way in which information is passed between each application program or module;

- the degree to which the data base will be automatically updated, and the way in which user's are advised of changes which may affect their modelling assumptions;

- security of input and output files within a multi-user computing system.

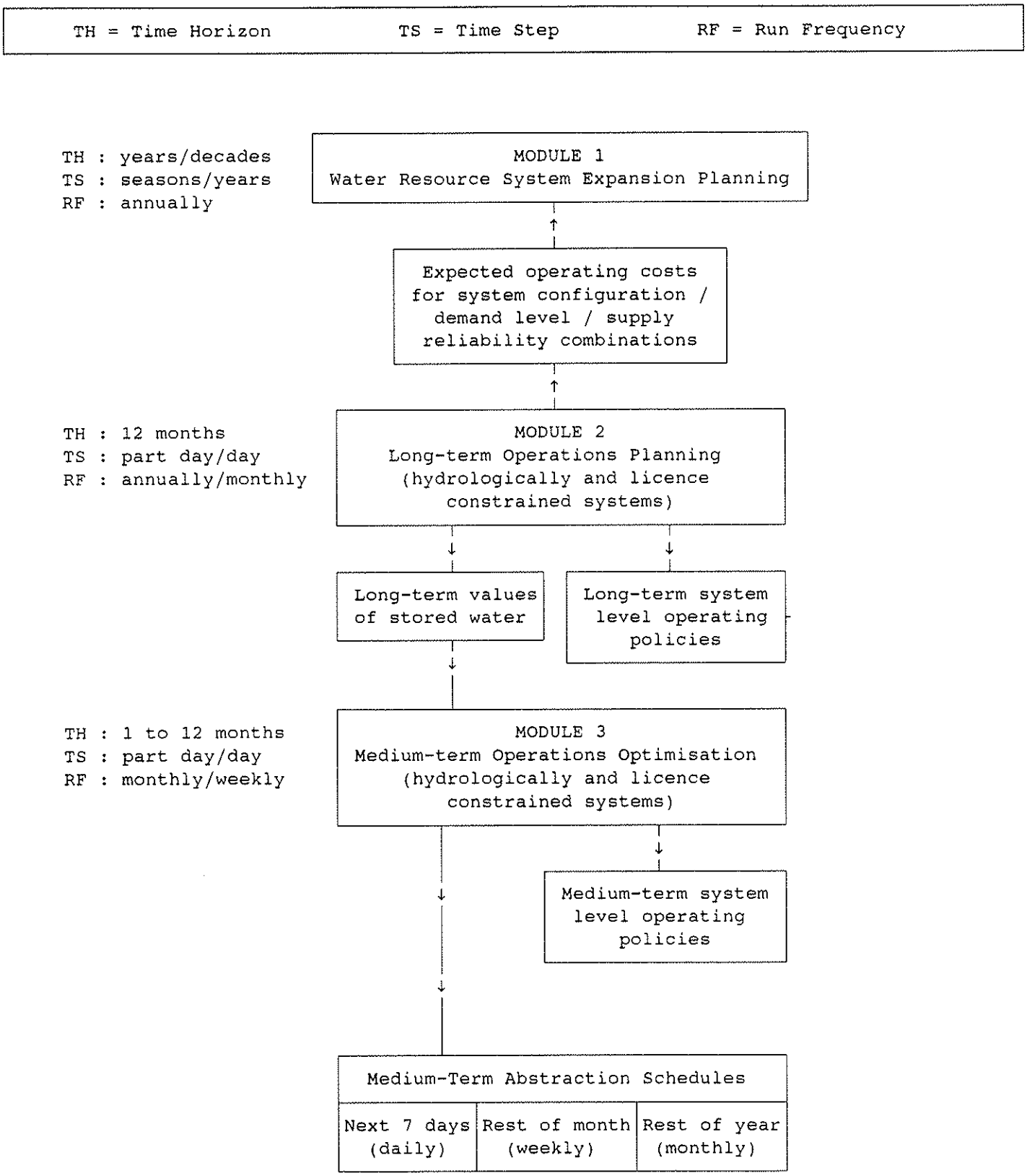


Figure 1 : Component Modules and Main Information Flows (Part 1 of 2)

TH = Time Horizon TS = Time Step RF = Run Frequency

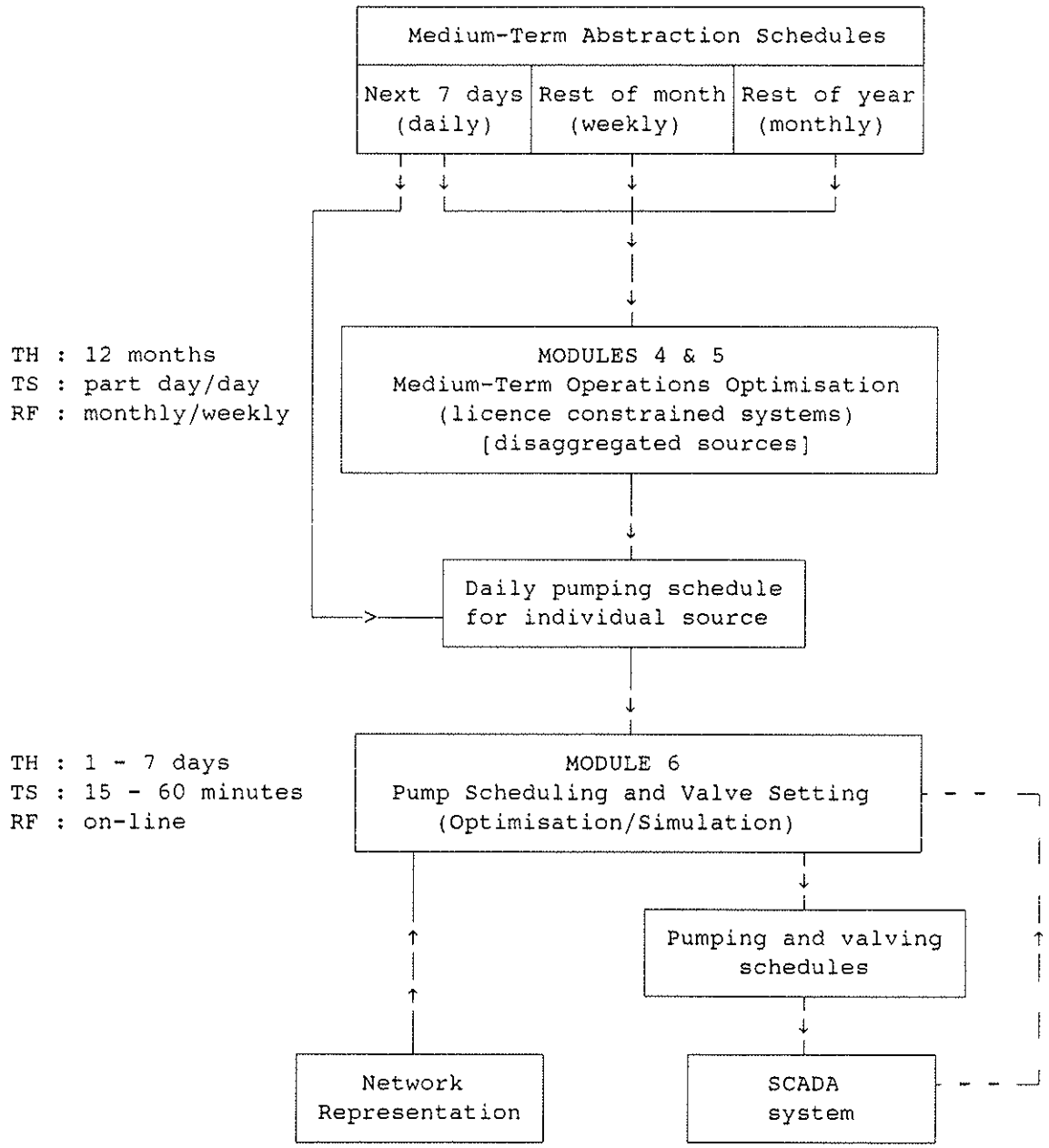


Figure 1 : Component Modules and Main Information Flows (Part 2 of 2)

Experience shows that the development and testing of application programs is greatly aided by the availability of realistic data sets. Similarly, it is all too easy to underestimate the resources required for the collection and verification of such data and the resolution of unforeseen problems which can arise when a database is populated.

IMPLEMENTATION OF MODULES 2 & 3

Over the last decade the MOSPA computer program has been used to derive long-term operating policies for NWW's regional water resource systems (Walker, Walsh & Wyatt, 1989). These policies are designed to minimise the average operating costs that would have been incurred over the historic hydrological sequence, and assume 'steady-state' conditions in terms of system configuration and demands to be satisfied. The program has also been used to provide long-term operating cost estimates associated with different system configuration, demand level and supply reliability combinations considered when planning future system developments. Thus MOSPA fulfilled the requirements for Module 2 of the integrated modelling system identified in WSC's appraisal report (WSC, 1992).

Following consideration of this report, NWW requested WSC to proceed with enhancement of the existing MOSPA package so that it could also fulfil the functions associated with Module 3. This work involved the development and implementation of facilities to :

- read current data stored on the corporate database;
- optimise medium-term operating policies using a deterministic dynamic programming algorithm;
- provide production schedules indicating the target quantities of water to be taken from individual and grouped sources, and the expected loadings on treatment works, pumping station and aqueducts over a 12 month period.

Concurrently, the capabilities of the MOSPA simulation routines were extended to enable the modelling of drought management measures (Howard, Smithers, Walker & Wyatt, 1994), and half-hourly fluctuations in electricity tariffs ('pool prices').

With these enhancements, greater use can now be made of the comprehensive simulation facilities of the program, which enable detailed modelling of the hydrological and physical characteristics of a water resource system to be combined with accurate costing of variable treatment and electricity costs.

APPLICATION OF MODULES 2 & 3

To aid the effective use of Modules 2 and 3 on IBM RS/6000 workstations, an X-Windows interface was written which enables the user to :

- copy and edit the data input files required to execute a MOSPA run;
- view the output files produced;
- store selected results within the corporate database.

Information held in the corporate database is input to MOSPA via an 'extract' file. This file currently provides data relating to :

- contents of storage reservoirs;
- river flows;
- chemical dosage rates and unit costs;
- cumulative abstracted quantities.

MOSPA simulation models have previously been constructed for NWW's Northern and Southern Command Zone systems and the associated hydrological, physical and cost data is now being updated. Preliminary models also exist for some 20 'local' supply systems which have links to the regional resource networks. As the requisite data is obtained and validated, these models will be combined to provide a fully integrated representation of NWW's water resource system.

IMPLEMENTATION OF MODULE 5

Within the current MOSPA model of NWW's Northern Command Zone system, abstractions from the Fylde Aquifer are modelled as two separate groups of boreholes. However, in reality :

- there are some 40 individual boreholes subject to group abstraction licences;
- there are significant variations in the pumping water levels associated with the individual boreholes, the characteristics of the installed pumps, and hence the electrical energy required to abstract the same quantities of water;
- on account of feeding into common mains, the delivery from individual boreholes can be dependent on whether or not others are being operated;
- the proximity of certain boreholes to one another can result in interactions in local water levels within the aquifer i.e. the static heads to be overcome by individual borehole pumps can be a function of whether neighbouring boreholes are being operated;
- sustained borehole pumping, such as may occur during a prolonged drought, can produce non-uniform reductions in pumping water levels within the aquifer;
- the quality of water produced varies between individual boreholes and can result in the need to operate borehole combinations which differ from those that would minimise pumping costs;
- opportunities arise to 'blend' Fylde Aquifer water with that from other sources and hence reduce treatment costs.

Decisions on which combination of Fylde Boreholes should be operated to provide a given daily output are currently made by experienced personnel, taking into account factors which include those outlined above. However, it is recognised that the complexity of the problem, and the substantial costs associated with borehole operation, justify the introduction of a more rigourous optimisation procedure. Accordingly, WSC are currently developing a PC-based decision support system for short and medium-term operation of the Fylde Borehole system. While this software is being specifically developed to model the Fylde system it may form a prototype for a generalised program capable of fulfilling the requirements identified as being supplied by Module 5 of the integrated modelling system.

IMPLEMENTATION OF MODULE 6

Computer program SYMCO (SYstem Management and Control Optimisation) was originally developed and installed for the North Surrey Water Company (Moss & Howard, 1988). A version of the software is currently used to control pressure variations within Yorkshire Water's Hull distribution system by providing 'on-line' schedules for pump and valve operation (Howard, Rosindale and Thomas, 1993).

NWW has recently commissioned WSC to construct input data files which will enable SYMCO to be used as a decision support system for optimising short-term operation of their Oldham water supply system. Based on telemetry data on service reservoir levels, SYMCO will initially provide the system manager with pump and valve operating schedules which minimise operating costs while complying with user specified constraints.

Implementation of SYMCO for the Oldham system is being undertaken as a pilot study to enable NWW to assess the potential benefits of the software and the feasibility of remote operation.

PLANNED DEVELOPMENTS

Decisions on proceeding with further module developments and applications must be justified in economic terms and, to assess the scope for cost savings, it is necessary to identify the number of systems to which each of the proposed modules could be applied.

The potential benefits of operating policy optimisation are closely related to the system configuration, and to the demand and operating constraints imposed. The scope for operational economies will normally increase with the margin between supply and demand, and in the case of highly constrained systems, 'optimisation' may be equivalent to identifying a feasible solution. As a result it is extremely difficult, and potentially irresponsible, to estimate the magnitude of potential savings without conducting a thorough analysis of a particular system.

However, account must also be taken of the other potential benefits that can be associated with enhanced modelling capabilities and data management. These are likely to include :

- closer control of supply reliability and, in particular, conformity with legally prescribed levels of service;
- crystallization of operational experience;
- improved budget forecasting and monitoring;
- quicker response to unforeseen conditions such as pump failures, pipe bursts, pollution incidents, water quality problems, adverse hydrological conditions and demand variations;
- improved bases for planning the development of systems, and investigating the effects of changes to electricity tariffs, abstraction licences and compensation requirements;
- more efficient use of abstraction licences and, hence, possible increases in the effective system yield.

When implementing future modules particular consideration will be given to the use and structure of a common modelling database and simulation language syntax to define system configurations and data categories. At the same time, it is planned to extend the scope of information automatically retrieved from databases to cover :

- forecast availabilities of system components such as treatment works, pumping stations and aqueducts, taking into account planned and emergency maintenance work;
- short and medium-term demand forecasts;
- short and medium-term flow forecasts.

CONCLUSIONS

The provision of an integrated 'source to tap' modelling system such as that outlined in this paper represents a major investment in information technology. While such investments must be economically justified, adequate consideration needs to be given to potential benefits other than those that can be directly related to operating cost minimisation.

Even with the use of proven techniques and existing application programs, it is essential to establish a clear understanding of how these can be integrated to form a comprehensive modelling system. In doing so it is necessary to have an adequate appreciation of the strengths and limitations of individual techniques, and the nature of the water resource and supply systems to which they will be applied.

Prior to the implementation of such a system, a thorough analysis must be made of the information to be stored, associated database structures, and procedures for data collection and up-dating. In particular, it should be recognised that modelling requirements may differ markedly from those associated with 'day-to-day' management functions.

The full potential of a modelling system such as described will only be realized if the users are adequately trained and have confidence in the results produced. A consistent 'look and feel' can be provided by man/machine interfaces; however, the development costs of such interfaces should not be underestimated.

The inclusion of detailed cost estimating procedures within water resource and supply system models means that the results are increasingly of direct use to managers as well as specialist engineers and hydrologists. In themselves, the disciplines imposed by modelling techniques can often promote improved understanding of system behaviour and contribute to wider levels of expertise.

The modules outlined in this paper are generalised in the sense that the topology and characteristics of a given system are entirely defined by the input data. Thus, associated with any particular module, there are likely to be a large number of data files defining individual systems. While the provision of such generalised modules is likely to be extremely cost effective, account must be taken of the resources necessary to construct and validate the performance of new models in addition to those required for the collection and validation of input data and interpretation of results.

The use of models such as those described are capable of yielding significant improvements in the efficiency with which water resource and supply systems are operated. While, by definition, models will always be simplifications of reality, experience in their application coupled with increasingly reliable input data should, over time, reduce the gap between 'theory and practice'.

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Eureka EU 487 : A decision-support system for integrated river-basin planning

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Abstract:

Eureka EU 487 is an on-going, collaborative research programme aimed at developing a comprehensive decision-support system for integrated river-basin planning. Its purpose is to assist government agencies, river-basin commissions etc. with the efficient management of water resources in terms of both quantity and quality, having particular regard for the aquatic environment. By combining Geographic Information Systems, database technology, modelling capability, optimisation techniques and Expert Systems, it is possible to improve the quality of decision-making in an area which is becoming increasingly complicated. The objective is to provide what appears to be a seamless system which is both comprehensive and easy to use, with the flexibility to evaluate all aspects of the overall problem.

1 Introduction

1.1 Structuring the approach

Traditionally, the use of modelling techniques for river-basin planning has required the services of a specialist to configure the system, evaluate different scenarios and interpret the results on behalf of the manager. Sometimes this requires the use of a series of separate models since most can only cater for one aspect of the overall problem. Thereafter, it would be left to the manager to determine the appropriate course of action based largely on experience rather than objective assessment. In river-basin planning, this is likely to entail allocating scarce resources between competing interests and minimising the negative impacts between incompatible activities. Few of these decisions are trivial and many involve substantial expenditure. Moreover, environmental legislation is becoming increasingly complex. In the past, major schemes have been promoted with little consideration as to how they relate to other river uses, let alone the environment. Now the requirement is to integrate environmental considerations into the scheme selection rather than simply producing an impact statement following the completion of the outline design.

Looking to the future, it would seem preferable that the person responsible for the planning process should undertake the analyses rather than rely on some third party. If managers are to be persuaded to try these techniques for themselves, they must be effective and simple to use, with all the complexity hidden from the user. Obviously, this approach has its dangers

inasmuch that inexperienced users will not necessarily appreciate the limitations of the techniques being deployed. However, within the foreseeable future, advances in software engineering will be able to supplement user-experience by fitting models automatically, not allowing models to be run outside the parameter range for which they have been calibrated etc. In this type of situation, it seems likely that the importance of modelling techniques will be relegated to that of an analytical kernel in a decision-support system, with the emphasis placed on the quality of the decision rather than the elegance of the model. Eventually, the actual mechanics of deriving the "best" solution within the constraints prescribed could largely become transparent, always providing the manager was conversant with the subject matter being addressed.

1.2 Collaborative Research Programme

To this end, a major research programme was initiated in January 1992 with the aim of developing a sophisticated decision-support system for integrated river-basin planning. The full list of participants associated with Euroenviron Project No. 487 are:

* University of Bologna, Italy;
* University College Cork, Ireland;
* University of Newcastle upon Tyne, United Kingdom;
* International Institute for Applied Systems Analysis, Austria;
* Thames Water International, United Kingdom;
* Ansaldo Industria Spa, Italy.

Whereas the universities are concentrating primarily on the analytical techniques, the International Institute for Applied Systems Analysis has assumed the responsibility for software integration and packaging whilst Thames Water International has undertaken the prototyping. The project has Eureka status, having been agreed by the appropriate Minister of State for the various countries involved. The Department of Trade and Industry is funding approximately half of the UK costs which will amount to some US $3 million over a five-year period. The UK contribution represents about 20 percent of total project costs.

2 Eureka Project No. EU 487

2.1 Concept

The scope of the system will eventually include not only rivers, aquifers and estuaries but also lakes, reservoirs and coastal waters, in terms of both water quantity and quality. For each application, the software package will be customised to allow the manager to address a wide range of planning issues such as:

* determining the limits of sustainable development;
* evaluating the impact and hence the cost of implementing new environmental legislation;
* deciding what, where and when new resources should be developed;
* quantifying the need for and the potential of irrigation;
* assessing the environmental impact of water-related developments;

* formulating strategies for river and groundwater pollution-control programmes;
* etc.

The complexity of these issues means that no single software program would be capable of coping with every eventuality. Therefore, the approach adopted has been to create a flexible, modular package which allows selection of the components required to manage a particular river basin.

The system under development is designed to integrate Geographic Information Systems (GIS), database management systems (DBMS), modelling capability, optimisation techniques and Expert Systems. At the present time, the system comprises GIS and database coupled to an increasing number of analytical components including water-resources planning, groundwater pollution, surface-water pollution and agricultural water use. New components such as estuaries and hydrologic processes are currently being added and existing components expanded to include additional models and optimisation techniques. Provided the new components comply with generic interface definitions, there are no limits on the capability to replace existing or add new models. Indeed, it is likely that most components will eventually have more than one model to select from, depending on the data available and the degree of sophistication required, for example, lumped/semi-distributed/fully-distributed or one/two/three dimensional etc. Social elements and some environmental considerations have been introduced using Expert Systems, rule-based inference and qualitative reasoning. Other tools coupled to the modelling techniques will eventually provide estimates of the direct economic costs and benefits of alternative engineering proposals.

The aim has been to create a system in which the mechanics of linking one component with another is largely transparent to the user. Although time and effort will be required in customising the system for a particular river basin, its use will be as simple as possible. Communication is by means of a user-friendly interface which makes extensive use of an on-line user-guide and color-graphics to present the results. If the user is familiar with the system, he can call the appropriate model directly: if not, he will be able to describe the problem and leave the system to select the appropriate model, set the boundary conditions and estimate the parameters using an Expert System. The operation of the system has been designed for easy use. A keyboard is not normally required since all the facilities are accessed by touching the appropriate icon representing the particular component. Moreover, the controls for operating a model will be familiar inasmuch as the icons mimic a video-recorder viz. play, pause, and stop. In this way, the manager is able to make rational use of the system without an in-depth knowledge of modelling techniques. Within any one component, options can be evaluated. Thereafter, since the effects of one component can be carried over to another, the impact of, say, groundwater abstraction on river-water quality can be estimated. In this way, a detailed and comprehensive assessment can be undertaken from which the preferred solution would be selected.

2.2 System Architecture

The philosophy adopted is that of a completely open, modular system with different degrees and mechanisms of coupling at various levels of integration. The core system is a set of conventions, standards, tools and a common language for problem representation rather than any specific software system.

The basic architecture which is illustrated in Figure 1 comprises:

(i) a *main program* that co-ordinates the individual tasks and provides access through a menu of options by means of either a single screen with triggers to individual applications/modules or in more complex situations, an Expert System module for co-ordinating individual components in a problem specific manner;

(ii) a *Geographic Information System* that stores, displays and analyses all geocoded information (satellite imagery, maps etc.) which is Arc/Info, GRASS compatible or specifically developed for a particular application;

(iii) a generic *Database Management System* that provides access to non-spatial data (treatment works details, time-series data etc.) which again can be a commercial package or a dedicated file-handling system for a particular application;

(iv) at least one or in most cases, several simulation/optimisation/Expert Systems *models* which use data from both the GIS and DBMS or the equivalent functional modules;

(v) a set of *pre-* and *post-processors* for use with these models that mainly support editing of input data and the visualisation/analysis of model output;

(vi) a *user-interface* with access to the various functional components of the system and the various help/explain files.

2.3 Computing Requirements

The system can be ported to a variety of different workstations including the SUN Sparc 10, the IBM RS 6000 and the DEC 5000. A typical hardware configuration might be:

* 64 MB processor
* 2 GB internal disk drives
* an 8-bit color-graphics system with a screen resolution of 1280 x 1024
* thermal-wax printer

The software requirements are:

* UNIX version SVR4 operating system;
* X II R4 or higher plus MIT x lib graphics environment;
* GRASS or Arc/Info (DLG) compatible Geographic Information System;
* SQL or embedded SQL database management system;
* RPC, TCP/IP or NFS off-line interfaces for real-time data acquisition;
* ANSI/ISO 'C' and FORTRAN 77 (90) compilers.

3 Components

3.1 Geographic Information System

All spatial data are contained within the GIS. This comprises satellite imagery, digital elevation data and digitised maps. Satellite imagery is used primarily to locate features within the basin and can take a variety of forms namely, true colour, landcover, vegetation and urban areas/water. Other examples of map information that can be incorporated includes solid geology, drift geology, soil types, irrigated areas etc., on which various boundaries, rivers, estuaries, roads and such like, can be superimposed to provide composite images. An example of the map displays (unfortunately in black and white) is given in Figure 2. The vertical stacking sequence of the overlay (i.e. which overlay goes on top of what) can be specified by the user and each map individually edited by switching on/off features. Similarly, colours can be assigned to any attribute in the legend if any contrast needs to be increased. Moreover, there is an arbitrary zooming feature should greater detail be required. As a result, the GIS has proved to be an extremely flexible tool for linking spatial information.

3.2 Database

The database contains a mixture of static (name, location, type of works etc.), slow-moving (processes used, works configuration etc.) and dynamic (quantities, performance etc.) data, all of which are coupled to the GIS. Features such as aerial photographs of the works can be included, together with the type and layout of the equipment installed, thereby providing easy reference to the company's asset base. Similar arrangements exist for river-gauging stations, meteorological weather stations, automatic river-quality monitors etc. For each of these facilities, time-series data (hydrometric variables, water-quality determinands, process performance etc.) are available and can be displayed in a variety of ways. Long records can be scrolled and segments extracted for display at a higher resolution using a variety of different scales, logarithmic for example (Figure 3). Other utility programs will eventually allow the patching of historic records for missing data or even generating synthetic data where necessary.

3.3 Agricultural Water Use

In many countries, agricultural water use, particularly irrigation, comprises the dominant form of water use. Therefore, the Food and Agriculture Organisation's CROPWAT model has been included in the Agricultural component. Much of the data required are contained within the GIS (topography, land use, soil types etc.) and the database (rainfall, evapotranspiration etc.). Given the various crop types to be considered, it is possible to estimate the potential irrigation need, having regard to the type of irrigation (surface, spray, drip etc.) and agro-economics (produce value, fertiliser costs etc.). This is achieved through a series of questions and answers by means of qualitative reasoning rather than a formal Expert System.

3.4 Water Resources

A water-resources simulation model (WRM) has been written specifically for this project. Originally, it had been intended to use an existing proprietary model for the design of water-resource systems. In the event, having regard to the time and effort that would have been involved in adapting an existing model, it was felt that starting again would be easier. After all, the specification for WRM required little more than an accounting procedure with the capability of being configured from the linkages in the database. The only decision-support element included so far is an Expert System for selecting the 'best' reservoir site for development. This comprises a basin-wide screening process (Figure 4) which takes into account geographic factors (suitable topography, source of water, devoid of population etc.) water-resource factors (resource value, storage capacity, re-fill characteristics etc.), engineering factors (suitable geology, development costs, construction materials etc.) and environmental factors (visual and social impact, terrestrial ecology, archaeology etc.). By using rules for qualitative assessment and reasoning in place of physical laws, the system can also represent concepts such as perceptions, expectations and public awareness which are difficult to quantify but nonetheless important for decision-making.

3.5 Hydrological Processes

Each component will eventually have a number of models of increasing complexity, addressing a wide range of purposes. Within the hydrological processes component, at one extreme there is a simple rainfall/runoff model (RRM), at the other there is the complex Système Hydrologique Européen (SHE), with the prospect of a semi-distributed model (ARNO) in between. RRM is a spatially-lumped, daily-timestep model whose primary function is data-infilling. In the design of water-resource systems, tributaries with only short periods of historic flow records are a common problem. One of the possibilities for generating pseudo-historic flow data is to use a rainfall/runoff model such as RRM. If, however, there is a requirement to understand the hydrological processes in depth for, say flood-plain mapping, then it is likely that one of the other two models would be selected, depending on the data availability. The SHE model is a fully-distributed finite-difference model of both surface and subsurface flows with variants for soil erosion/sediment transport (SHESED). The suite of programs is currently being re-written to be compatible with the interactive nature of Eureka EU 487. Even then, there are still problems to be overcome owing to the size of the model.

3.6 Groundwater Pollution

In the case of groundwater, work is in progress to select and fit the most appropriate model automatically, having regard to the objectives of the investigation and the amount of data available. For groundwater models, it is necessary to estimate not only the model parameters but also the boundary conditions. This is being formulated as an Expert System, using the solid geology overlay, digital elevation data, groundwater levels etc. from the GIS and database. As for the models themselves, a finite-difference representation (GWPM) of groundwater flow and contaminant transport has already been incorporated (Figure 5) and the more sophisticated TRACE 123 system is currently being installed. These models can be used for predicting the likely consequences of agro-chemical pollution, organic spills, landfill leachates and saline intrusion. However, in a decision-support system, prediction of the likely consequences is only the first stage. Thereafter guidance is required as to the most

appropriate course of remedial action. If that includes the use of, say, scavenger boreholes, questions then arise regarding the number of boreholes required, their best location etc. having regard to the water quality standards prevailing and the overall cost. These decisions which are being posed as an Expert System, clearly require some interaction with the models themselves to evaluate different strategies.

3.7 Surface-water Pollution

When it comes to river clean-up schemes, the first consideration is to ascertain what the water is to be used for, public water supply? irrigation? industrial cooling? fisheries? etc. Each of these uses has its own basic water-quality requirements, frequently prescribed by law, from which the most stringent individual determinand values can be derived for each stretch of the river. Thereafter, it is a matter of identifying the consent conditions for each discharge to the river which are consistent with achieving the required river-quality standards, having regard to the carry-over effect from other upstream discharges, natural purification and the degree of in-river dilution and dispersion. This is not a trivial calculation, particularly if the consent conditions are framed in terms of, say, 95 per cent compliance. Therefore, Eureka EU 487 contains a model referred to as TOMCAT which has been used extensively for this purpose. Since the location of discharge points, river cross-sections, time-series data etc. are contained within the database, it is possible to configure the model automatically and run the future-growth scenarios generated by another component.

3.8 Future Intentions

Besides the elements already mentioned as being under development, others are planned or at least contemplated. These include 2 and 3- dimensional estuary models where flows oscillate under tidal action. Another component proposed relates to hydraulic structures for the design of spillways, river-improvement schemes, flood protection measures and the such like. Elsewhere, the aim would be to add additional capability to the existing components. For example, the Water resources component requires a mathematical programming model of the type used for national water plans. Another element urgently required is a demand forecasting model, inclusive of demand management, for use in association with several of the components. All of these and more will be added over a period of time depending on the funding available, priority being given to the needs generated by paying clients.

4 Application

4.1 Prototype System

The River Thames catchment in England has been used for the prototype application of Eureka EU 487. The Thames basin covers an area of approximately 13 000 km^2 and supports a population in the order of 12 million, including that of London. On average, about 3700 Ml/d are provided for public water supply with a further potential requirement of 1400 Ml/d in direct abstractions for industry etc. The public water-supply component alone represents about 55 per cent of the natural runoff from the freshwater portion of the catchment in an average year and correspondingly more in a dry year. However, there are some 390 waste-water treatment works processing an average of 4300 Ml/d, the bulk of which is discharged to the tidal portion of the Thames. Nevertheless, on average about 12

per cent of resources for public water supply are derived from indirect effluent re-use and during a dry summer, this figure can rise to 70 per cent locally. The same river network is used by some 250 000 anglers and 20 000 boat-owners. As such, the River Thames must be one of the most intensively used water-resource systems in the world.

Space considerations preclude a detailed description of the application to the Thames basin. It suffices to say that all of the components mentioned have at least been demonstrated using examples from the Thames catchment area apart from the Agricultural water use which uses Mediterranean data since there is little call for irrigation in the Thames basin. The groundwater contamination example is based on the recently discovered point-pollution source in the Berkshire chalk aquifer where two bomb-craters had been used to dispose of organic chemicals, shortly after the Second World War. Elsewhere, the Surface-water component has been used to predict the changes in river water-quality likely to occur as a result of the construction of a major new reservoir. Indeed, the domain knowledge incorporated in the Expert System for reservoir site selection uses the experience gained in searching for the 'best' location in the Thames basin to meet the projected shortfall predicted by the water-resources model.

4.2 Prospects

Notwithstanding Eureka EU 487 is an on-going research programme, considerable interest has already been expressed by potential clients in a number of countries, following a series of presentations and demonstrations. Indeed, the first application has already been completed as part of the Rio Lerma/Lake Chapala Masterplan in Mexico. This project had originally been conceived as a river pollution control problem whereas in reality, it was also a water-resources problem since water-abstraction, mainly for irrigation, was unsustainable even in the medium term. Whereas the initial phase was restricted to implementing the so-called "base" system (GIS, database, Water resources and Surface-water pollution components), the second phase is expected to expand the capability to include Agricultural water use and Groundwater pollution components amongst others. At the same time, the intention is to roll out the base system for other basins in Mexico.

Elsewhere, the front-end of Eureka EU 487 (GIS and database) is to be used initially as a management information system for hydrometric data from Gaza and the West Bank. Although the system was not specifically intended for this purpose, there are distinct advantages in adopting this approach. For example, it preserves the option of upgrading the system at a later date to include the Water-resources planning component which is extremely important, bearing in mind that the Palestinians will have to negotiate their fair share of the region's water resources within the next four years or so.

It is difficult to give any indicative costs of acquiring a configured version of the system since much depends on both the scale/complexity of the basin in question and the number/complexity of the components incorporated. However, most applications will only require a number of specific components rather than the entire system. Typically, the framework might cost about US $100,000 to configure with each additional component costing about the same. Data acquisition costs are even more difficult to estimate. Satellite imagery and digital elevation data again depend on scale but typically might cost in the order of US $25,000 for an entire basin. Similarly, map data in the form of various boundaries, solid geology, soil types etc. can be scanned into the system inexpensively. Thereafter, the

cost of data acquisition largely depends on the form in which the time-series data are held. If that is some form of magnetic media, the transfer costs are modest; if not, the cost of data acquisition could be a substantial portion of the overall project cost. Either way, it is important to stress that vast quantities of data are not a pre-requisite for the use of the system. On the contrary, it is possible to start in a modest way using the simpler models and gradually progress to the more sophisticated as and when the data are available.

5 Conclusion

5.1 Achievement

None of the elements of this project are entirely new. The use of decision-support systems for water-resources planning dates back to the early 1980s. Similarly, the concept of linking a mathematical model directly to GIS has been around for a number of years. Even the models incorporated into Eureka EU 487 are in the main, derivatives of those either developed previously by the various partners in the project or models which are already in the public domain. Therefore the achievements of Eureka EU 487 are largely confined to:

(i) making use of mathematical modelling available to a wider audience by simplifying accessibility;

(ii) providing the means of linking a variety of models to address different aspects of the overall problem;

(iii) assisting management with the interpretation of results and advising on the most appropriate course of action rather than simply providing an analytical capability.

The philosophy adopted for both modelling and decision-making has been 'horses for courses'. In other words, there are no pre-conceived ideas as to the 'best' model for forecasting any more than there is a 'best' solution which is appropriate in all cases. Instead, there is a choice from a range of options which can take into account the circumstances prevailing. Moreover, for the less experienced, the system will be able to assist the user with that choice.

5.2 Use of the System

Although it is recognised that it is perhaps premature to give exposure to a research project which is still under development, it is nevertheless important to receive feedback from potential clients so that their views and requirements can be taken into account. The aim of this project is to develop a capability which can be used in support of consultancy rather than selling software per se. The role of the consultants would be to configure the system on behalf of the client, provide user-training and ensure on-going maintenance support. In this way, the client is being provided with a planning process rather than a set-piece plan and if circumstances change or some of the assumptions cannot be substantiated at a later date, then the client can generate a new plan rather than watch the existing plan drift further away from reality. Clearly, the system is not going to be cheap to acquire but even if a fraction of one per cent can be saved by considering major proposals for water-resources development in a comprehensive rather than piece-meal fashion, the use of the system can be easily justified.

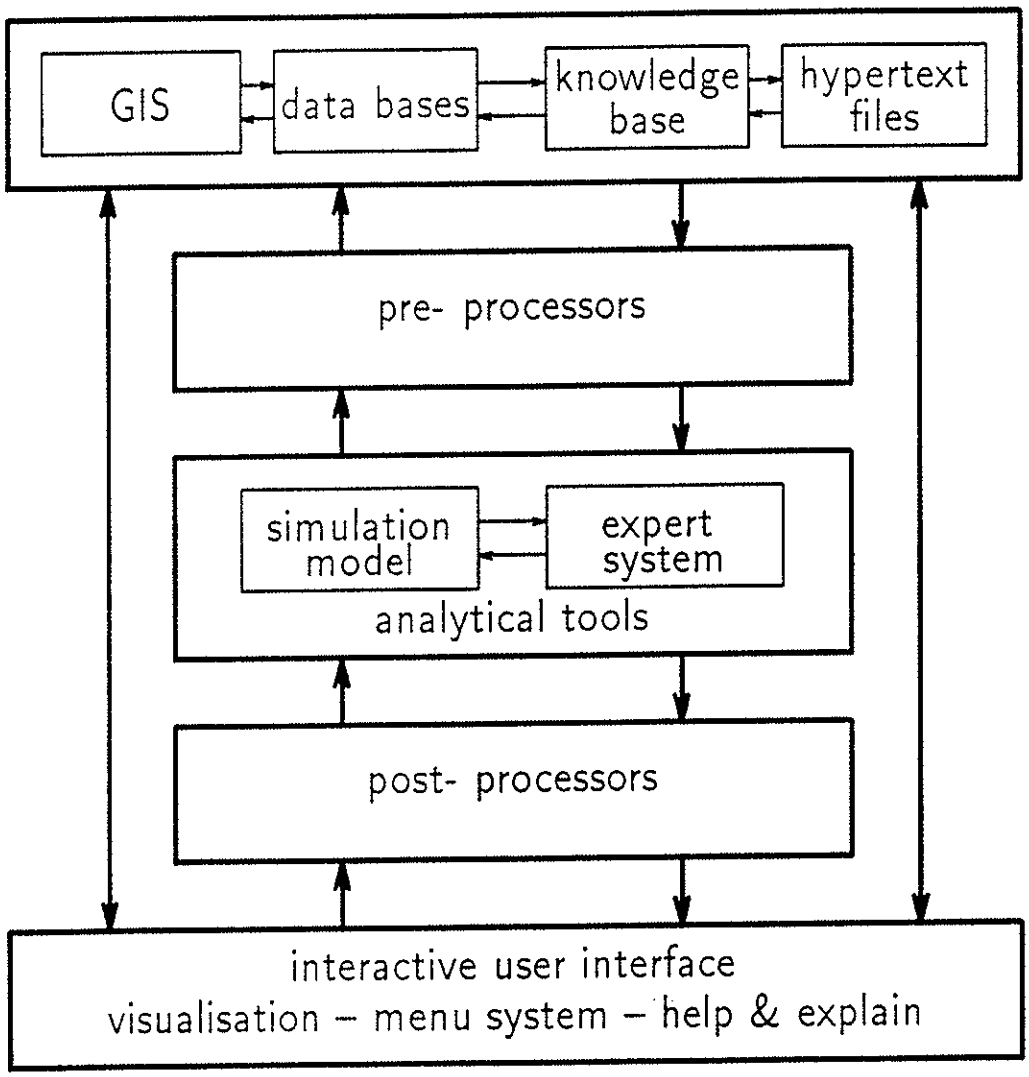
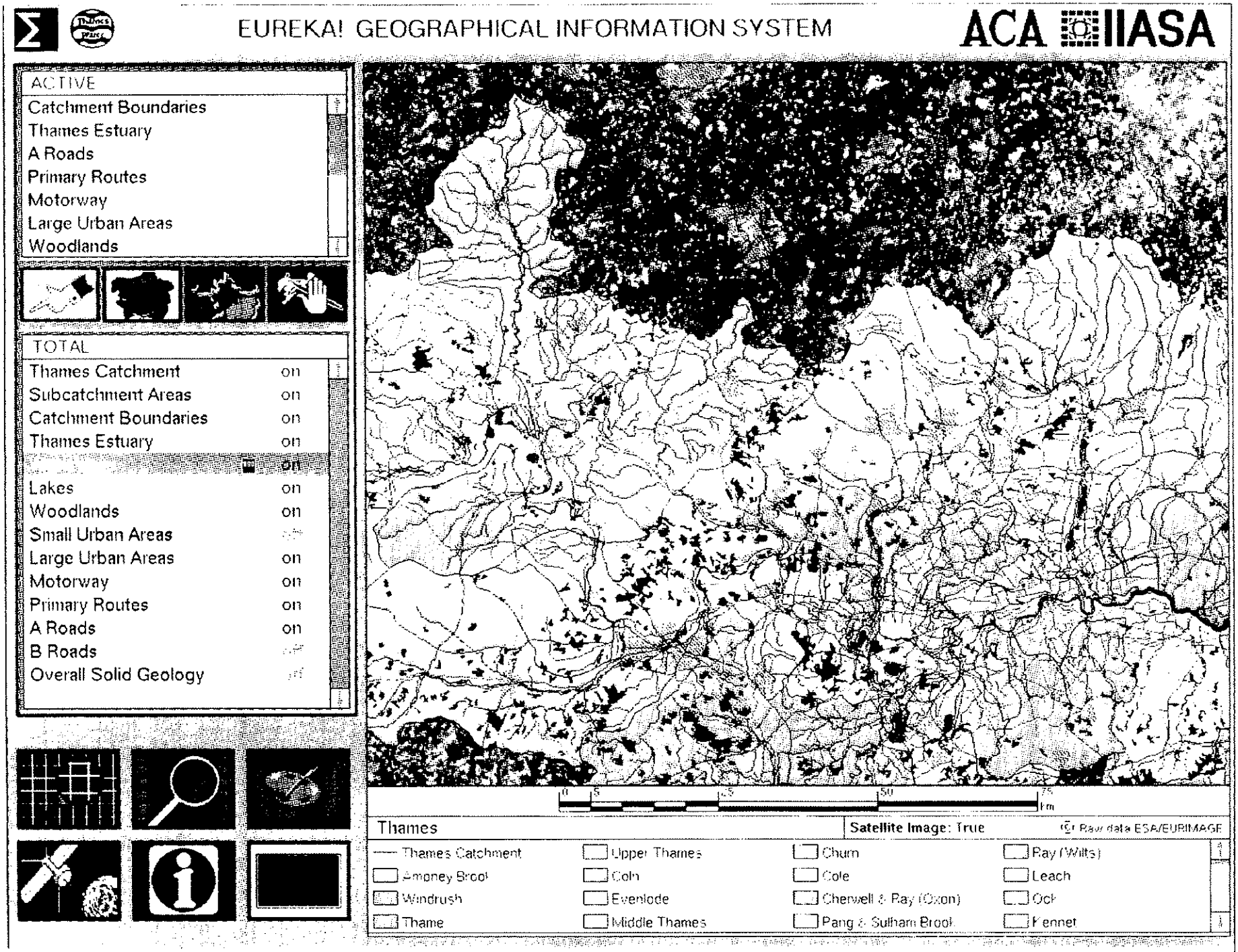


FIGURE 1: SYSTEM ARCHITECTURE


EUREKA! GEOGRAPHICAL INFORMATION SYSTEM
ACA IIASA
ACTIVE
Catchment Boundaries
Thames Estuary
A Roads
Primary Routes
Motorway
Large Urban Areas
Woodlands
TOTAL
Thames Catchment on
Subcatchment Areas on
Catchment Boundaries on
Thames Estuary on
Lakes on
Woodlands on
Small Urban Areas
Large Urban Areas on
Motorway on
Primary Routes on
A Roads on
B Roads
Overall Solid Geology
0 5 25 50 75 Km
Thames
Satellite Image: True
© Raw data ESA/EURIMAGE
Thames Catchment
Upper Thames
Churn
Ray (Wilts)
Emoney Brook
Coln
Cole
Leach
Windrush
Evenlode
Cherwell & Ray (Oxon)
Ock
Thame
Middle Thames
Pang & Sulham Brook
Kennet
Select an Option or Pick overlay from list ->
FIGURE 2: GEOGRAPHIC INFORMATION SYSTEM

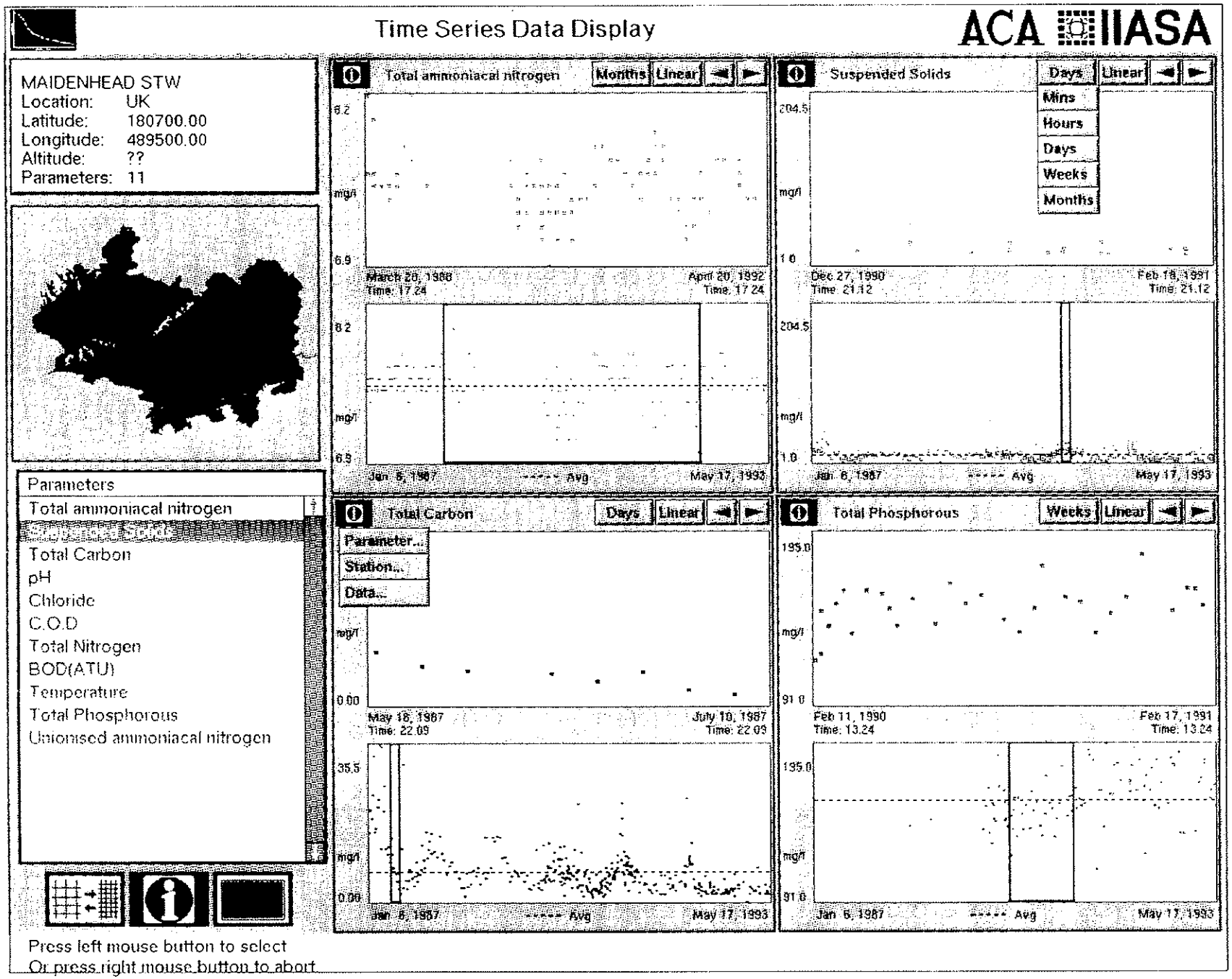


FIGURE 3: DATA DISPLAY AND ANALYSIS

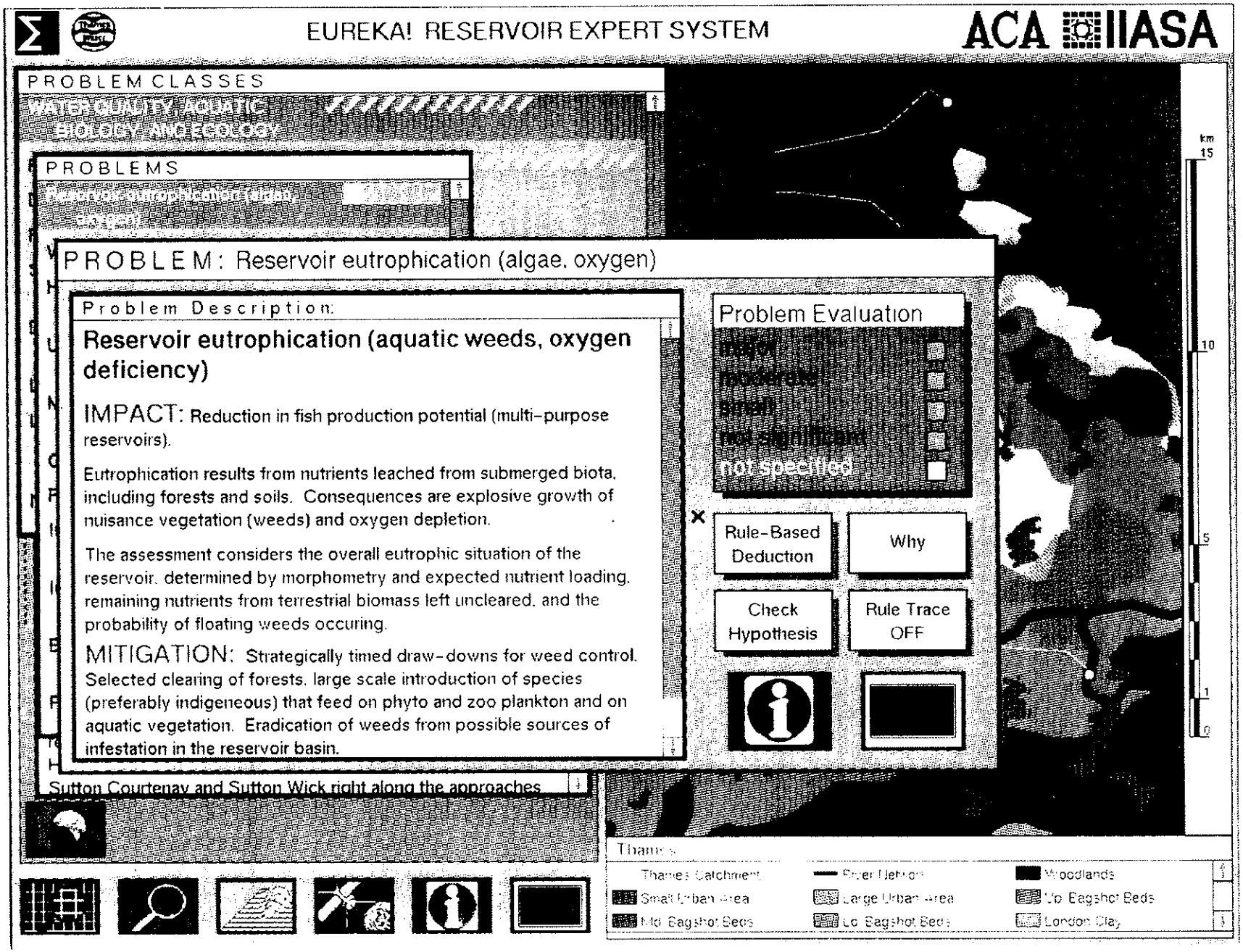


FIGURE 4: EXPERT SYSTEM FOR RESERVOIR SITE SELECTION

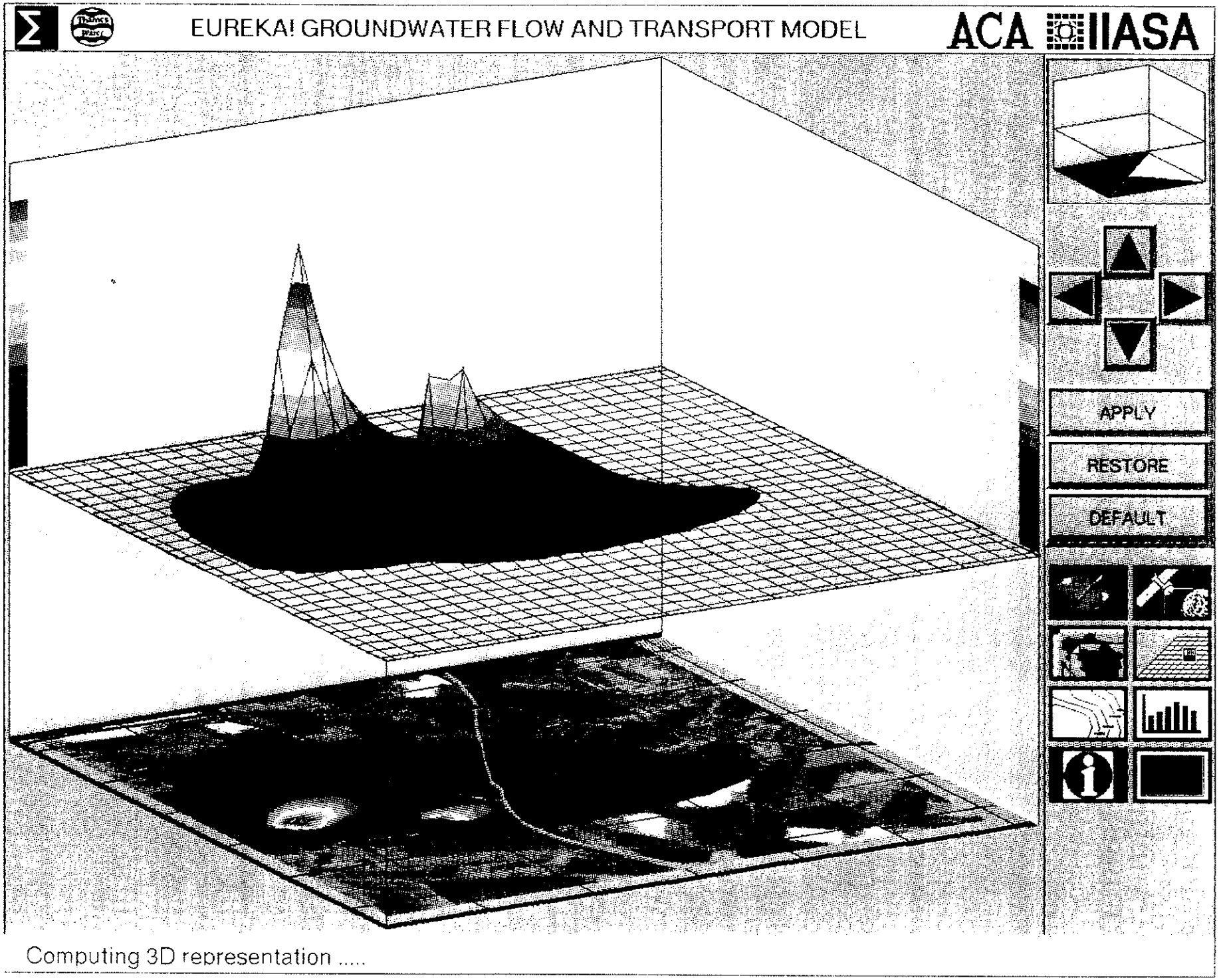


FIGURE 5: GROUNDWATER POLLUTON MODEL