AN INTEGRATED SIMULATION AND DYNAMIC PROGRAMMING APPROACH FOR EVALUATING THE PERFORMANCE OF COMPLEX WATER RESOURCE SYSTEMS AND OPTIMISING OPERATING POLICIES : METHODOLOGY AND APPLICATIONS

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1. OVERVIEW

Optimising the use of storage reservoirs within conjunctive use water resource systems has long attracted the attention of engineers and mathematicians. Increased access to electronic computers since the early 1970's has encouraged the development of a variety of approaches aimed at deriving optimal (least cost) operating policies to enable such systems to meet defined demands with specified levels of security. Techniques advocated include simulation, linear, non-linear and dynamic programming, applied both individually and in combination.

The range of techniques applied reflects the complexity of the problem to be solved, in terms both of the number of variables to be optimised and the need to adequately model system characteristics and, in particular, the effects of hydrological persistence. Many practitioners have advocated the combined use of simulation (to model hydrological persistence) and one or more formal optimisation algorithms (to determine the optimal values of operational parameters). However, few have been specific as to how the essential linkages between the two types of model are to be achieved.

Within this paper attention is focussed on a modular optimisation and simulation approach which has been developed over the past 15 years by Power & Water Systems Consultants Ltd. (PWSC), and which has been successfully applied to a variety of complex water resource systems within the UK and overseas. Topics covered include : problem definition; underlying philosophy and methodology employed in the approach; historical development and applications; example applications to water supply, and hydro/thermal power generation and irrigation systems; advantages and disadvantages of the approach, application limits and difficulties.

2. PROBLEM DEFINITION

The simplest example of a conjunctive use system is a single reservoir and one other source supplying a single demand area. In such cases the requirement is to derive an operating policy which will, for a given series of inflows, minimise the average cost of meeting the demand imposed.

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A basic operating policy is one composed of a set of twelve (monthly) reservoir storage volumes, or **retention levels**, with the take from the reservoir being dependent on whether the amount in storage at any point in time is above or below the critical value. If it can be assumed that water produced from the non-reservoir source is consistently more expensive, then an efficient rule would be for the reservoir to always supply its '**firm yield**' plus, when '**above curve**', the difference between its current storage and retention volume.

The 'firm yield' of the reservoir can be calculated by performing reservoir simulations, and the corresponding set of retention levels determined using some form of '**critical period analysis**'. Such analyses calculate the differences between cumulative inflow and demand totals and hence the minimum amount of water that must be held in storage if the 'firm yield' can be supplied in all future time periods.

Even for such a simple system complications can arise for a variety of reasons. For example, the 'firm yield' of the reservoir may not equate to an efficient rate for operating associated treatment works or the non-reservoir source, and hence the '**below curve**' take may need to be somewhat lower. Similarly, when above curve, the maximum total reservoir take may also be constrained. Further complications arise if the demand or other reservoir release requirements are subject to seasonal variations or, as is normal, the cost of water from the non-reservoir source varies seasonally or is subject to some form of licence constraint. If any of these should be the case then the above methods can no longer be relied on to produce operating policies which are optimal in terms of cost minimisation or the maximisation of supply security.

The next level of operating policy complexity is where different above and below curve reservoir takes are specified and the associated critical storage levels are optimised. Such a policy, as shown in FIGURE 1(a), can be described as a two-regime system operating policy and, as before, the current reservoir storage is used to describe the 'state' of the system at any point in time. A more sophisticated operating policy is shown in FIGURE 1(b), where a finer graduation is made between the above and below curve release rates, as may be desirable to ensure that reservoir releases are always compatible with feasible and practical operating rates. Such a policy can be described as a **'multiple regime operating policy**' composed of a number of **'alternative operating regimes**'.

As the complexity of a conjunctive use system increases the concept of using an operating policy to specify the amounts of water from reservoir sources bears re-examination. An example system featuring reservoir, river abstraction and groundwater sources, together with a possible set of alternative operating regimes, is shown in FIGURE 2. In this case it can be noted that, while reservoir storage is still used to described the current '**state**' of the system, the alternative operating regimes define the '**target**' takes from each non-reservoir source with any residual demand being met from the reservoir. The use of the word target in this context is important since the output available from the non-reservoir sources at any point in time may be restricted. For example, river abstractions will often be subject to flow dependent licences designed to maintain downstream minimum flow requirements, while groundwater abstractions are normally governed by time dependent licences imposed to avoid unacceptable depletion of the underlying aquifer.

It is also important to note that the example set of alternative regimes includes a regime under which supplies would be restricted, as might be the case when reservoir contents reach unacceptably low levels and some form of demand management would be imposed e.g. hose-pipe bans or the introduction of rota cuts.

The inclusion of such '**restriction regimes**' is an crucial element of the approach since it allows supply deficits to be constrained to defined and socio-economically acceptable magnitudes. In addition it allows supply security to be quantified in terms of satisfying a particular level of demand as, for example, in meeting '**level of service**' criteria based on the acceptable frequency and duration of supply shortfalls.

Although such measures of supply security will be conditional on the representativeness of the set of flow sequences employed, they are usually more meaningful to decision makers, and the public, than those based on hydrological probability, particularly if the latter are expressed in terms of the yield of individual sources rather than that of the integrated system.

In practice target takes associated with each alternative set of operating regimes can be specified to conform with practical operating constraints (e.g. water quality blending requirements) and efficient pumping or treatment rates. However, it can be appreciated that as the complexity of systems and the number of alternative supply sources increases, so do the number of practical regimes that could be adopted.

The definition of alternative operating regimes in this way is only useful if methods are available for optimising the associated operating policy i.e. specifying which regime should be adopted as a function of calendar month and the volume of water in reservoir storage. FIGURE 3 illustrates the form of an optimised operating policy that could be derived for the example system and the 5 alternative operating regimes shown in Figure 2. In essence the problem is to optimise each of the 60 (5 x 12) 'switching' levels such that system operating costs are minimised while meeting defined supply security levels.

The type of monthly policy illustrated in Figure 3 is often referred to as being '**stationary**' in the sense that, when applied, no knowledge of future inflows is assumed. This is an important aspect, particularly when dealing with systems which feature '**multi-annual**' reservoirs which cannot be relied upon to re-fill each year. Similar policies can be applied to multi-reservoir systems if the system state is indicated by the combined contents of one or more reservoirs and balancing procedures are used to allocate total releases between individual reservoirs.

3. PHILOSOPHY

A review of the relevant technical literature will reveal a wide range of proposed methodologies for optimising the operation of water resource systems which include storage reservoirs. Linear, Non-Linear and Dynamic Programming algorithms, as well as simulation/direct search techniques, have all been advocated as suitable methods for maximising the benefits of storage management, and arguments can be made for and against each approach.

Selection of the most appropriate method is complicated by the fact that the attributes and deficiencies of any approach are difficult to quantify, and that their relative weighting will usually vary with the characteristics of the system to be analysed. Perhaps because of this, few technical papers attempt to quantify the effects of the assumptions associated with a particular technique, and concentrate on the mathematical aspects of the algorithms produced and their application to simple, often hypothetical, systems. What are also usually missing are indications of the potential improvements compared with operating policies derived by more traditional or heuristic methods.

While simple systems are useful for explaining the mathematics of a particular algorithm, experience indicates that it is often the very complexity of real systems which raises difficulties when applying many of the formal optimisation methods proposed, and in acceptance of the results by staff of an operating utility. For example, problems often arise from inadequate consideration of the persistence exhibited by historic stream flow records, the maximum demand type charges incorporated in electricity tariffs, and the cumulative effects of abstraction licence constraints and supply shortfalls. Faced with such complications it is not surprising if engineers continue to rely heavily on simulation models and operating policies based on experience, heuristic methods or critical period analysis.

Many practitioners have advocated the complementary use of simulation and mathematical programming techniques for deriving optimal operating policies. However, few have been specific as to how the essential linkages between the two types of model are to be achieved.

The need for both arises from the fact that with mathematical programming techniques it is almost always necessary, in order to maintain computational feasibility, to limit the modelling of interactions between system components and the sequential correlations between hydrological inputs. Thus, while the algorithm may guarantee the optimality of the solution obtained, this almost certainly relates to an over-simplified representation of the real system. In contrast, the level of detail included in a simulation model is usually limited by data availability rather than computational load. The linkage problem therefore arises from the difficulty in quantifying the extent to which the optimised solution of the simplified problem will serve as an optimum operating policy for the real system.

It should be noted that, at any given time, supply and demand may be so closely matched, or the system otherwise so constrained, that the use of sophisticated techniques is rendered superfluous. Normally, however, it is desired to study system operation under future scenarios as well as present conditions, in addition to establishing what is often a complex relationship between operating costs and supply security.

It is now generally accepted that the establishment and application of a detailed simulation model should precede and accompany the application of mathematical programming techniques, and the following reasons can be offered to support this conclusion :

(i) the need to have a demonstrably authentic representation of the system which will form an agreed basis for the comparison of alternative operating policies. Since most systems exhibit 'unique' features, these must be adequately modelled if the analytical solutions, and associated computer programs, are to gain acceptance by those charged with day-to-day management of the system being studied;

(ii) only with simulation can adequate recognition be given to the persistence found in almost all hydro-meteorological data series, and it is normally essential to demonstrate operational performance of a system over a historic sequence of events, if only to establish acceptable reliability criteria;

(iii) secondary operating decisions, non-explicit constraints and time dependent costs can be incorporated within a simulation model without great difficulty. For example, rules to allocate stored water between reservoirs, flow and climatologically dependent releases, water quality and amenity constraints, and demand charges associated with electricity tariffs.

Given the availability of an adequately detailed simulation model it is of course possible to investigate alternative operating policies and select one or more which most closely achieve the required objectives. For some simple systems a 'trial and error' approach may indeed produce solutions close to the optimum. However, as the complexity of a system increases, the number of possible operating policy variable combinations will generally rise exponentially and the computational load associated with such an approach becomes unrealistic.

During the late 1960's and early 70's, the Economics Division of the UK Water Research Association (now Centre) investigated a number of methods for deriving operating policies for systems that featured significant reservoir storage. Initial attention focussed on 'On/Off' type control rules for systems where desalination plant could be used to supplement surface water resources.

Alternative algorithms, based on Dynamic Programming and Gradient Search respectively, were developed to optimise such operating policies, and it was shown that both were capable of improving on the results obtained with rules derived using critical period analysis [1]. Linear Programming techniques, and derivatives such as the 'Out-of-Kilter' algorithm, were not seriously considered due to implicit difficulties in adequately modelling stream flow persistence and the non-linear nature of water resource system response.

An essential feature of both the techniques applied was the incorporation of simulation models as an integral component of the optimisation procedure. Using the Gradient Search or 'hill climbing' approach, the control levels were considered as variables to be optimised and the simulation model used as the evaluative function. In the Dynamic Programming method, the simulation model was used to evaluate operating policies derived using a value iteration algorithm.

The advantage of these methods over critical period analysis can be attributed to their considering operating costs over the whole of the flow series simulated, rather than just minimising costs during the most critical periods of reservoir draw-down.

It became apparent that the same techniques were equally applicable to other conjunctive use systems [2], and in 1973 both the Dynamic Programming and Gradient Search methods were used to derive operating policies for Empingham pumped storage reservoir in the UK (now Rutland Water). These policies specified the number of pumps to be operated on the Rivers Welland and Nene as a function of the calendar month and the volume of water held in storage [3]. With nine alternative pump combinations being defined, this application represented a significant extension of the methodology used to derive 'On/Off' type policies in previous studies.

However, at that time the available algorithms suffered from a number of potential drawbacks :

(i) significant requirements in terms of computer memory and execution time;

(ii) in the case of the Dynamic Programming Algorithm employed, a lack of generality which necessitated substantial re-programming work for application to a specific system;

(iii) inadequate explanation and program documentation.

Since the early 1970's fundamental changes have taken place which encourage the application of such techniques when deriving operating policies for water resource systems. These include :

(i) the increased complexity of many water resource systems and the greater opportunities for conjunctive operation;

(ii) a substantial rise in energy costs and an increased awareness of the need to minimise operating costs;

(iii) increased recognition that water is a finite resource and acceptance that it may be economically desirable to subject consumers to supply restrictions on a planned, although infrequent, basis;

(iv) heightened public awareness of ecological issues, and the wish to improve controls on the aquatic environment;

(v) a transformation in computer capabilities, costs and availability;

(vi) the introduction of structured data bases, often linked to telemetry systems, which can provide rapid access to the requisite information for 'real time' applications.

Appreciation of the similar problems faced by many UK and overseas utilities in managing water resource systems with significant reservoir storage led PWSC to further develop the original WRA simulation/stochastic dynamic programming approach. This has resulted in the development of two computer program packages : MOSPS for application to hydro/thermal power generation systems and MOSPA for application to water resource/supply systems.

In summary, the integrated optimisation/simulation approach places prime importance on producing operating policies which are practical and can be readily compared with alternatives via a detailed simulation of the system being analysed, rather than guaranteeing absolute 'optimality' in mathematical terms. Results obtained in applying the package to many different systems indicate that the methodology is robust, and that the policies produced can yield significant benefits when compared with those derived using less sophisticated techniques.

4. METHODOLOGY EMPLOYED

The MOSPS and MOSPA computer programs combine generalised simulation and stochastic dynamic programming modules in a fully integrated run-time environment, and they are briefly described in the following sub-sections.

4.1 MOSPS Simulation Module (SYSIM)

In MOSPS the module SYSIM is used to simulate the operational performance of integrated water resources and hydro/thermal power generation systems. For a defined combination of system configuration, imposed demands and operating policies, SYSIM simulates system performance over a multi-annual hydrologic time series using a monthly time step and employs generalised subroutines for reservoir and hydroplant modelling, load dispatch simulation, data input and the output of results.

Physical interactions between elements of the water resource system are defined by code representing the links between existing and potential components of the network, enabling the user to data-specify whether individual elements are to be included in a given simulation. Principal features of the SYSIM model are:

- detailed representation of interconnected generating units, reservoirs, conveyances, irrigation and consumptive demand areas as they currently exist or may develop in the future;

- consideration of concurrent streamflows and water requirements as time series, thus taking explicit account of temporal and spatial hydrological variations;

- user specification of system operating policies for co-ordinating and optimising power and/or water supply system operation as a function of reservoir contents, including the imposition of supply restrictions.

- provision of detailed information on the coverage of electricity, irrigation and water demands, and on power system operating (fuel) costs;

- hydroelectric plant capacities considered as a function of net head, discharge rate, taking into account daily regulation at 'run-of-river' plants and downstream re-regulation (pondage) limitations;

- load dispatch simulation based on specific operating cost criteria, taking into account scheduled and unscheduled outage and minimum stable load constraints on thermal plant;

- quantification of electricity supply reliability in terms of the absolute and weighted deficit in energy supplied, and the number of months in which defined levels of restriction are imposed;

- user specification of methods for determining releases from individual reservoirs and allocating releases between multiple reservoirs;

It can be noted that the imbedded load dispatch simulation enables the contributions of existing or potential generating units to be assessed directly in terms of an integrated power system. By taking explicit account of temporal and spatial variations in stream flow, and the contributions of other generating plant in meeting electricity demands, SYSIM thus allows a clear distinction to be made between 'potential' and 'dispatchable' energy production. Where conflicts may arise as a result of reservoir releases made to satisfy power generation or water demand requirements, SYSIM can provide quantitative information necessary to establish the associated trade-off functions.

4.2 MOSPA Simulation Module (SIM)

Within Program MOSPA, the simulation module SIM provides a variable time-step model for simulating the operation of multiple-resource systems used for water supply. Generalised subroutines are called in a sequence, and with a frequency, that are data-defined, thus enabling the simulation of different system configurations at varying levels of detail without the need for code modifications.

Specific water supply system components that can be modelled include storage reservoirs and lakes, river and groundwater abstractions, pumping stations, treatment works, aqueducts and terminal storage. Multiple demand areas can be accommodated, with demands subject to seasonal variation profiles or as given by daily time series.

Source outputs can be governed by : individual rules and constraints e.g. reservoir control curves, statutory and flow related abstraction licences, maximum and minimum rates; joint procedures and constraints, e.g. reservoir balancing rules, combined abstraction licences, aqueduct capacity limits; system level operating policies which specify target takes from one or more sources, alternative abstraction limits and supply restrictions, all as a function of storage conditions and calendar month.

These outputs are routed through a data-defined system of aqueducts, pumping stations, treatment works and terminal storages to demand areas. The module includes routines for calculating electricity costs incurred at pumping stations and treatment works subject to supply tariffs featuring hourly, daily and monthly variations in unit prices and maximum demand charges, and annual availability charges.

Routines are also incorporated for : stream flow generation from base records; flow routing through storage; calculation of treatment costs using input chemical dosage rates and unit prices. The modular structure facilitates the incorporation of additional routines to model other types of system component or physical process. Separate data files are used to input : the system configuration; physical, cost and operating data e.g. capacities, tariffs, licence constraints, rule curves; the frequency with which each component is to be simulated i.e. hourly, daily or monthly; stream flow and demand series; system operating policies; and data output requirements e.g. monthly and/or daily by component, abstraction schedules.

The sub-program SIM comprises a number of subroutine elements which are used in the order defined by the user's description of the water supply system being modelled. The user can also specify the frequency with which each relevant attribute (inflow, spill, cost etc.) for each component (reservoir, treatment works etc. as appropriate) is to be simulated. In this way pumping to meet demand can, for example, be considered on an hourly basis, while the cost associated with that pumping can be evaluated on a monthly basis and hence correctly account for maximum demand charges.

4.3 Stochastic Dynamic Programming Algorithm

Programs MOSPS and MOSPA share a common stochastic dynamic programming module for optimising multiple-regime system operating policies of the type described earlier in this paper.

Dynamic Programming can be used for solving planning, design and operational problems that may be treated as multi-stage sequential decision processes. In most cases, a **stage** takes the form of a discrete time interval.

In analysing a process using dynamic programming it is conventional to refer to a system as being in a certain **state**. Such states may be characterised by the system configuration or some measures of system status. A system changes its state between stages as the result of inputs and outputs that may or may not be controllable.

At each stage of the process there are typically a number of **decision variables** which will effect future behaviour of the system. The role of a dynamic programming algorithm is to determine the decision variable values for each stage that optimise an **objective function**, while satisfying any imposed **constraints**. The combination of these optimal decision variable values constitutes the **optimal policy**.

Dynamic programming is based on the 'Principle of Optimality' which states that : 'An optimal policy has the property that whatever the initial state and initial decisions, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision' [4]. This may be expressed more simply as 'The optimum set of decisions to be used for future states is independent of the decisions used to reach the current state'.

Major advantages attributable to dynamic programming are that :

(i) computational effort increases approximately linearly with the number of **stages**, whereas most other methods display a geometric increase;

(ii) it is particularly well suited to solving problems where the decision variables are discrete or take integer values;

(iii) functional relationships within the objective function and constraints can be highly non-linear, non-convex and even discontinuous.

The major disadvantage of Dynamic Programming is the so-called 'Curse of Dimensionality' (4), which refers to the rapid rise in computational requirements as the number of **decision variables** to be optimised is increased. This has led to various algorithms being developed that limit the number of stage, state and decision variable combinations to be evaluated. Even so, when analysing water resource systems with more than two or three storage reservoirs, computational requirements can usually be contained only by severely limiting the number of storage states employed.

The number of stage, state and decision variable combinations to be evaluated also limit the amount of detail that can be included when modelling system behaviour. Transformation of the system from one state to another is normally determined by a number of factors, only some of which may be subject to control via the decision variables. For example, certain combinations of decision variable values may not be feasible due to physical operating constraints or may be incompatible with satisfying demand.

The dynamic programming algorithm used in the MOSPS and MOSPA programs incorporates minimum modelling of the water resource system being analysed and uses the simulation module to take account of such complexities and their effect on system state transitions and operating costs.

Dynamic programming algorithms can be classified as being either **deterministic** or **stochastic** (probabilistic). Since a crucial factor in deriving operating policies for water resource systems is the variability of hydrological inputs, the algorithm which MOSPS and MOSPA employ for optimising long-term policies falls into the latter category. When deterministic formulations are used it should be noted that, since perfect knowledge of future hydrological events is implied, a non-stationary operating policy will normally result i.e. one that may specify the adoption of different operating regimes for the same calendar month within the hydrological sequence, even though the system state is identical.

In the same way as the WRA approach described in Reference 3, the algorithm overcomes this problem by using VALUE ITERATION over a twelve (calendar) month cycle to obtain the optimal stationary policy. Within the algorithm :

- **stages** are separated by a time interval of one month;

- the system **state** is described by the volume of water held in reservoir storage;

- the **decision variables** are the operating regimes to be adopted in each (calendar) month and each storage state;

- the **objective function** is the sum of all operating costs;

- the **constraints** imposed are that a cost penalty is added to the objective function if the system enters certain states;

- the **optimum policy** is that set of decision variable values which minimises the objective function

The stochastic policy iteration dynamic programming algorithm is a development of that described by Mawer and Thorn [3], and the reader is referred to this paper for a more detailed description of the procedure. A theoretical justification for policy and value iteration is contained in the work of Howard [5].

Within MOSPS and MOSPA, input to the procedure includes four data streams which are produced by simulating performance of the system over the available hydrological sequence, and when operated in accordance with each of a defined set of alternative operating regimes. For these simulation runs, the reservoir contents are re-set at the start of each month to a user specified value.

The four data streams contain the following information for each month of the simulation sequence :

- the total operating cost;

- the gross change in total reservoir storage i.e. including any spill;

- the shortfall (deficit) in meeting the demand (if any), including any part of the demand not met due to the imposition of supply restrictions;

- the potential excess, or spill.

Within MOSPS and MOSPA it is assumed that system demands will always be met unless a restriction regime is being followed i.e. one that includes the imposition of demand management measures. Accordingly, the deficit data is used only to identify non-feasible regimes, it being noted that such feasibility may be a function of the calendar month due to variations in the demand profile.

Within the dynamic programming algorithm, costs are divided into two categories :

(i) the 'immediate' cost incurred by adopting a given operating regime in a given year and calendar month;

and

(ii) the 'future' cost of being in a certain system (storage) state.

The system storage is normally set to the total active reservoir storage and is discretised into a number of equal state intervals.

The algorithm identifies which of the alternative operating regimes should be adopted in each storage state and each calendar month so that the total future operating cost will be minimised. A penalty factor is used to penalise state/regime combinations which could lead to unacceptably low storage states in the future, and to obtain a policy which conforms with user defined supply reliability criteria in terms of maximum reservoir draw-down or an acceptable incidence of supply restrictions.

It should be noted that at the start of the process the correct value for the penalty factor is unknown, and hence the dynamic programming algorithm is embedded within a search procedure. Normally the appropriate penalty factor will be greater than the most expensive source of water, and for a new system it may be necessary to start with a wide range of uncertainty. As experienced is gained in how the system responds this range can be reduced.

4.4 Module Interaction

The MOSPS and MOSPA programs are comprised of three basic modules; the simulation and long term operating policy optimisation modules described above and a search procedure which enables the maximum sustainable demand (system yield) that can be supplied system at a defined level of security.

The way in these three modules interact are shown in FIGURE 4, and it can be noted how the simulation module can be used independently e.g. to test heuristically derived operating policies.

5. HISTORIC DEVELOPMENT AND APPLICATIONS

In Section 2 it was shown how alternative operating regimes can be defined for a conjunctive use system featuring river abstraction, groundwater and reservoir sources. For hydro/thermal power generation and irrigation systems a similar approach can be used, the objective of operating policy optimisation being to minimise the use of (expensive) thermal plant subject to meeting electricity and water demands with a defined level of security. A typical set of alternative operating regimes for such a system, and associated operating policy, is shown in FIGURE 5.

The MOSPS program and its simulation module SYSIM were originally developed in 1981 to model the Uruguayan hydro-thermal power generation system [6]. In 1986/87 improvements were made in the detailed modelling of hydro plant operation and MOSPS was applied to the hydro-thermal system in Burma [6].

In 1986/88 the SYSIM module was applied to the complex existing and potential hydro-thermal generation and irrigation systems in Sri Lanka. This required enhanced modelling capabilities of water (irrigation) demands and the conjunctive operation of reservoirs operating in series and parallel. In 1989/90 it was used to model operational performance of the integrated Centro-Norte hydro-thermal system in Peru and hence plan the development of that system. In 1991 SYSIM was used to optimise principal parameters of the Kukule hydroelectric project in Sri Lanka and in 1991/92 to study the conjunctive operation of hydro plants within the interconnected hydro-thermal power systems of the SADCC countries of Southern Africa. Between 1993 and 1996 SYSIM has been used to plan the development of the Tanzania hydro-thermal power generation system and is now installed in the offices of the state power company, TANESCO.

The MOSPA program was originally developed for application to the Lake District (LD) water supply system in the North West of England in 1986, and the optimised operating policies indicated that average savings of some 5% of average operating costs could be achieved when compared with those then applied [7].

The program was subsequently used to model, and derive optimised operating policies for, the Lancashire Conjunctive Use Scheme (LCUS), the Northern Command Zone System (NCZ : LD+LCUS) and the Southern Command Zone (SCZ) systems of North West Water [8]. In all cases it was possible to demonstrate that substantial costs savings could be made by optimising multiple-regime operating policies.

As a result of these applications the capabilities of the generalised simulation module have been steadily enhanced, particularly in terms of the modelling of complex electricity tariffs (including 'pool prices'), river regulation schemes, and demand management practises. A system yield determination module was developed in 1993 and medium-term operating policy optimisation/resource scheduling capabilities were added in 1994.

A model of the Lancaster water supply system was constructed in 1994 and work is currently being undertaken to expand the scope of the SCZ model to include the River Dee system and integrate the NCZ and SCZ models.

During 1995/96 a graphical user interface (MOSES) has been developed for the MOSPA package. This includes for the template editing of input files, the graphical and tabular display and plotting of results, and the database storage and retrieval of all input data.

6. EXAMPLE OF APPLICATION TO A MAJOR WATER SUPPLY SYSTEM

FIGURE 6 provides a schematic representation of the way in which the MOSPA program has been used to model the Northern Command Zone water resource and supply system operated by North West Water Ltd. (UK).

Within this system the major operating decisions to be made at any particular time are :

- the pumped transfer to be made from Lake Ullswater to the Haweswater Reservoir;

- the pumped abstraction to be made from Lake Windermere (taken into supply via the Watchgate treatment works);

- the pumped abstractions to be made from the rivers Lune and Wyre (taken into supply via the Franklaw treatment works);

- the quantity of water to be pumped from the Fylde aquifer via the Franklaw and Broughton borehole groups.

In this application a total of 50 alternative operating regimes have been defined and the MOSPA program used to derive optimised operating policies for a variety of demand and supply reliability levels. FIGURE 7 shows a set of typical alternative operating regimes and a MOSPA optimised operating policy.

7. CONCLUSIONS

Numerous applications of the MOSPS and MOSPA computer programs have demonstrated that there is often considerable scope for operating cost savings and/or improving the reliability of energy and water supplies from conjunctive use systems. However, there are a number of difficulties that must be overcome to convince system operators of the merits of such modelling and optimisation. These include :

- establishing, in advance, the potential cost savings and hence the cost benefits of applying the software;

- obtaining information on current operating procedures so as to establish a 'base case' against which to compare optimised policies; in many countries the state of major storage reservoirs is highly political and far too often short-term economic considerations lead to excessive risks being taken in their management e.g. overdrawing reservoirs rather than using thermal plants;

- obtaining the requisite data for constructing the simulation model of the system, particularly in developing countries and with respect to adequate hydrological (flow) series.

To achieve the on-going benefits of modelling and optimisation it is obviously desirable that system operators should have constant access to such software and personnel adequately trained in its use. Again, however, there are difficulties involved, which include :

- convincing potential users to pay realistic costs for complex software which represents many man-years of development time;

- expectations that all software must be as 'user-friendly' as commercial programs which are sold in millions of copies e.g. word processing and spreadsheet packages.

Finally, it must be emphasised that, even with a generalised simulation module, constructing models of complex systems requires familiarity with the modelling 'tools' available and knowledge of water resource system characteristics and operational principles. Similarly, as such models become more detailed, so too do data requirements.

Due to population growth, improving standards of living, ecological concerns and, possibly, climatic change, the pressure to use finite water resources with greater efficiency is constantly increasing. As a result, the management of conjunctive use water resource systems grows ever more complex and decision makers will increasingly need access to mathematical models with which to simulate system performance and optimise their operation. The unrelenting development of low cost PC's in terms of computing power and storage capabilities means that the integrated simulation/optimisation approach described in this paper has become increasingly feasible for large and complex systems.

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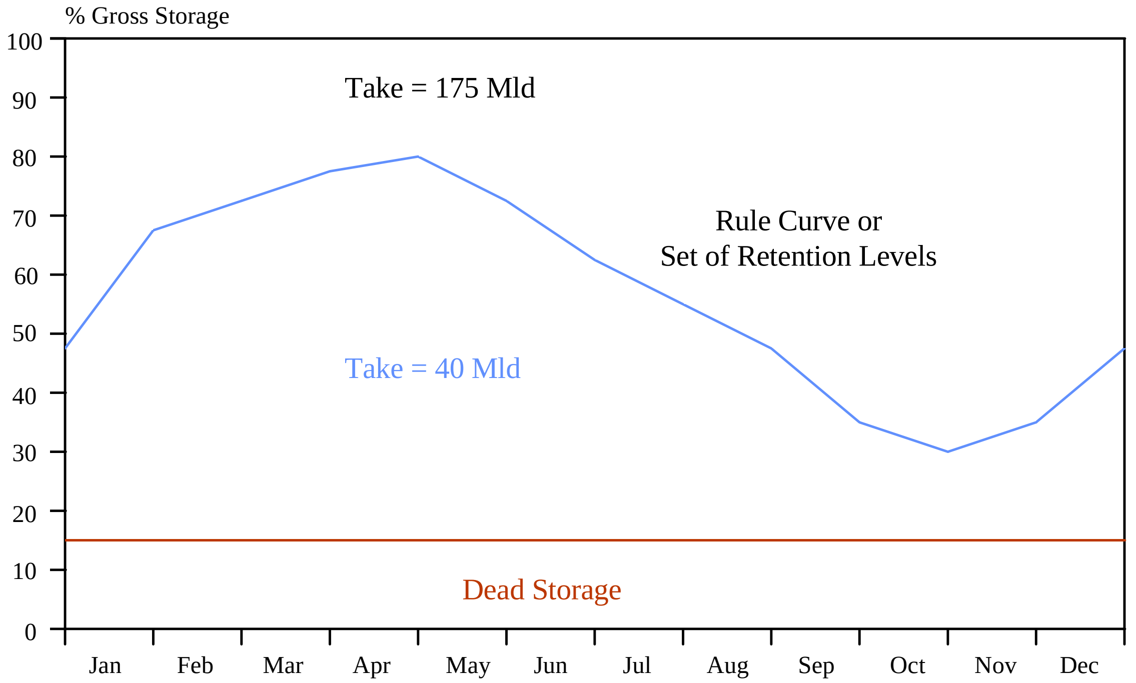
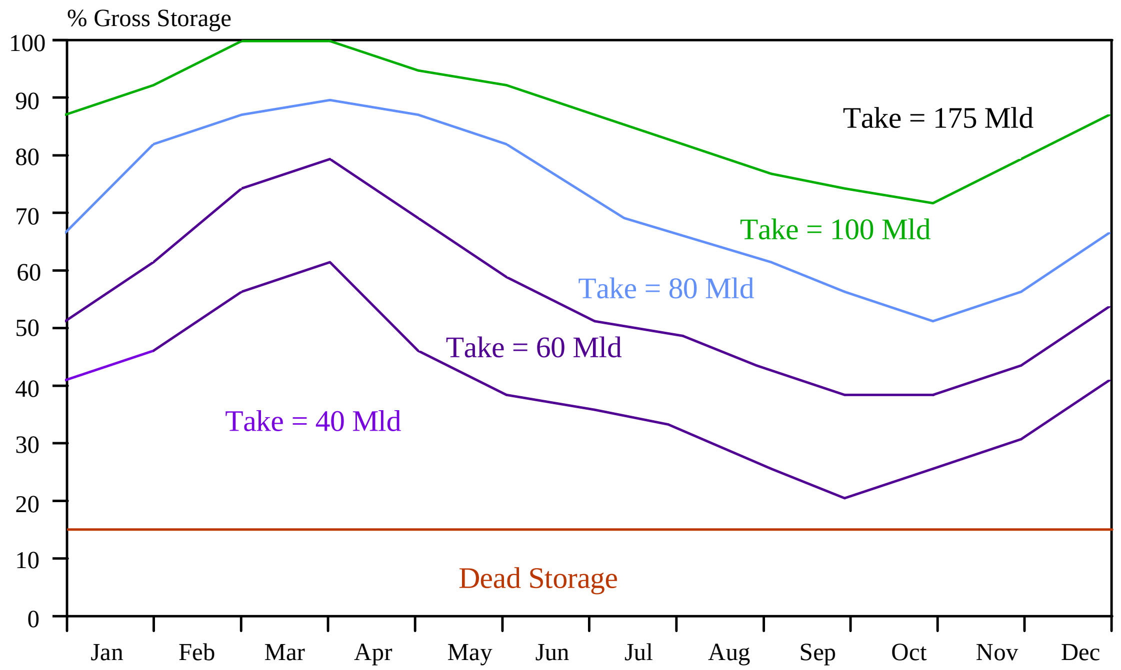
Derivation and Application of Medium-Term Operating Policies for the Northern Command Zone System of North West Water (UK)
Paper presented at the IAHS Baltimore Symposium, May 1989

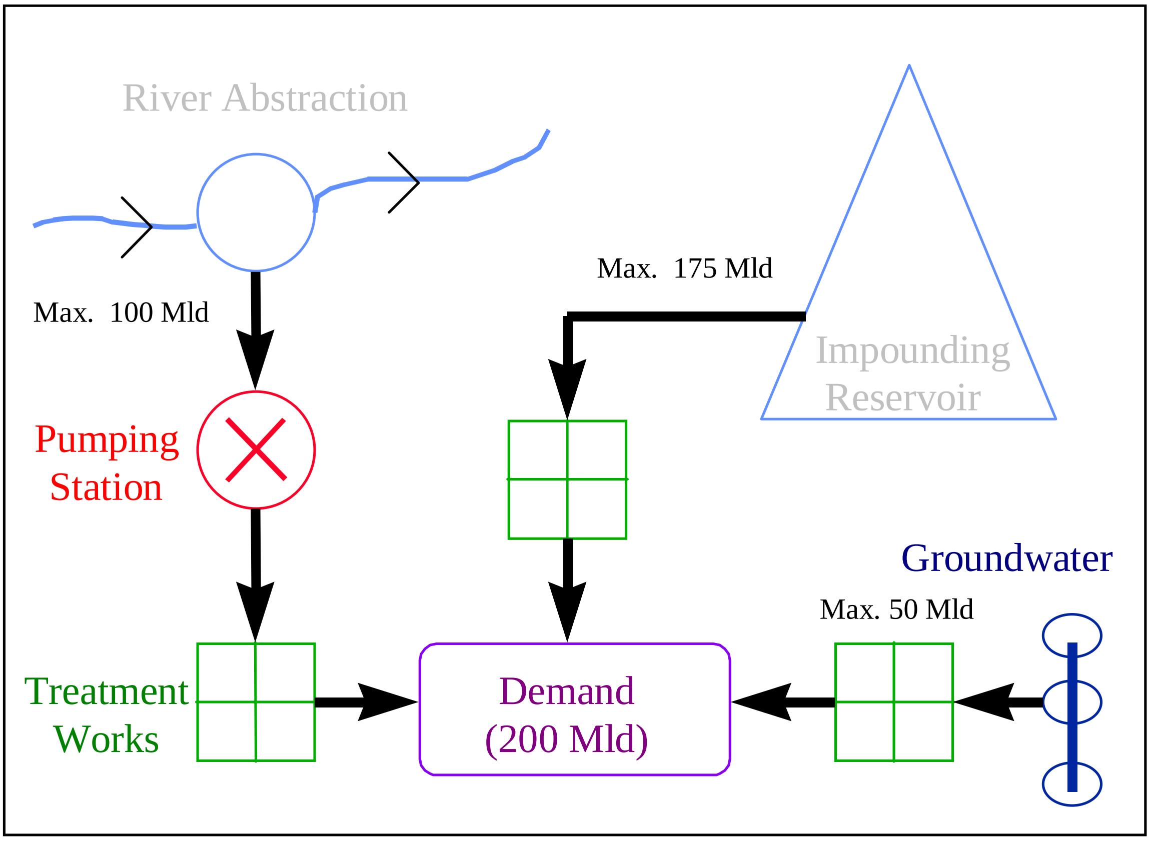


a) 2 Regime Reservoir Operating Policy



b) 5 Regime Reservoir Operating Policy

FIGURE 1 : Rule Curve and Multiple-Regime Operating Policies for a Direct Supply Reservoir



Example Conjunctive Use System

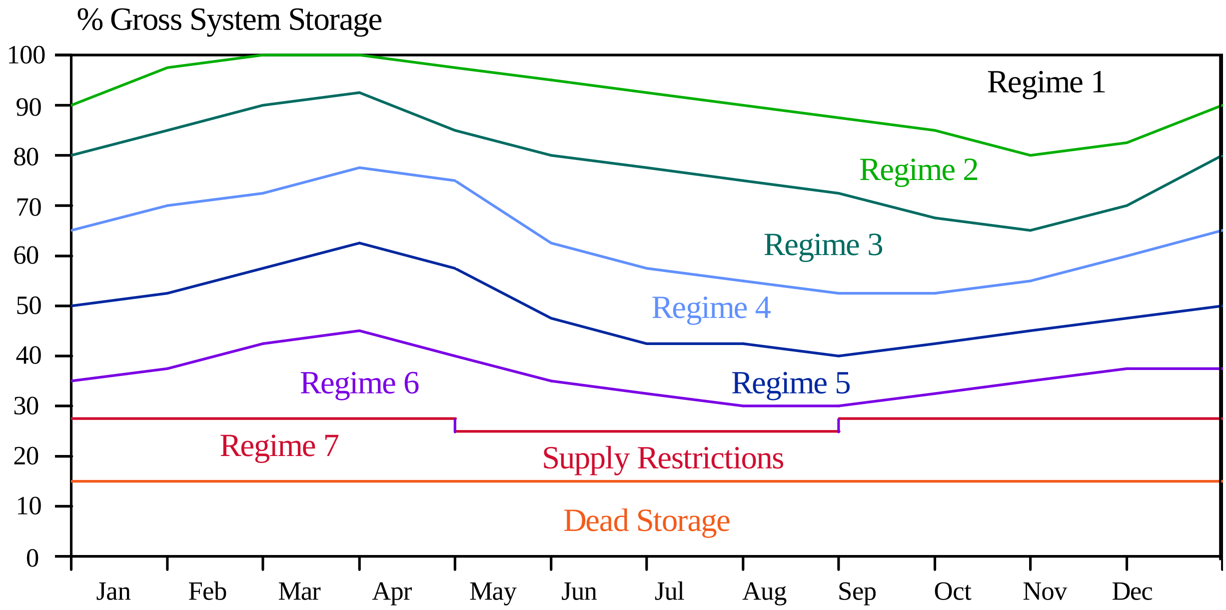
	Target Abstraction Rates (Mld)			Demand
	River	Groundwater	Reservoir	(Mld)
Regime 1	25	0	175	200
Regime 2	50	0	150	200
Regime 3	75	0	125	200
Regime 4	100	0	100	200
Regime 5	100	25	75	200
Regime 6	100	50	50	200
Regime 7	100	50	30	180

Alternative Operating Regimes

FIGURE 2 : Example Conjunctive Use Water Supply System and Alternative Operating Regimes

Alternative Operating Regime	Target Abstraction Rates (Mld)			Demand (Mld)
	River	Groundwater	Reservoir	
Regime 1	25	0	175	200
Regime 2	50	0	150	200
Regime 3	75	0	125	200
Regime 4	100	0	100	200
Regime 5	100	25	75	200
Regime 6	100	50	50	200
Regime 7	100	50	30	190

Alternative Operating Regimes



Optimised System Operating Policy

FIGURE 3 : System Operating Policy for Example Conjunctive Use System

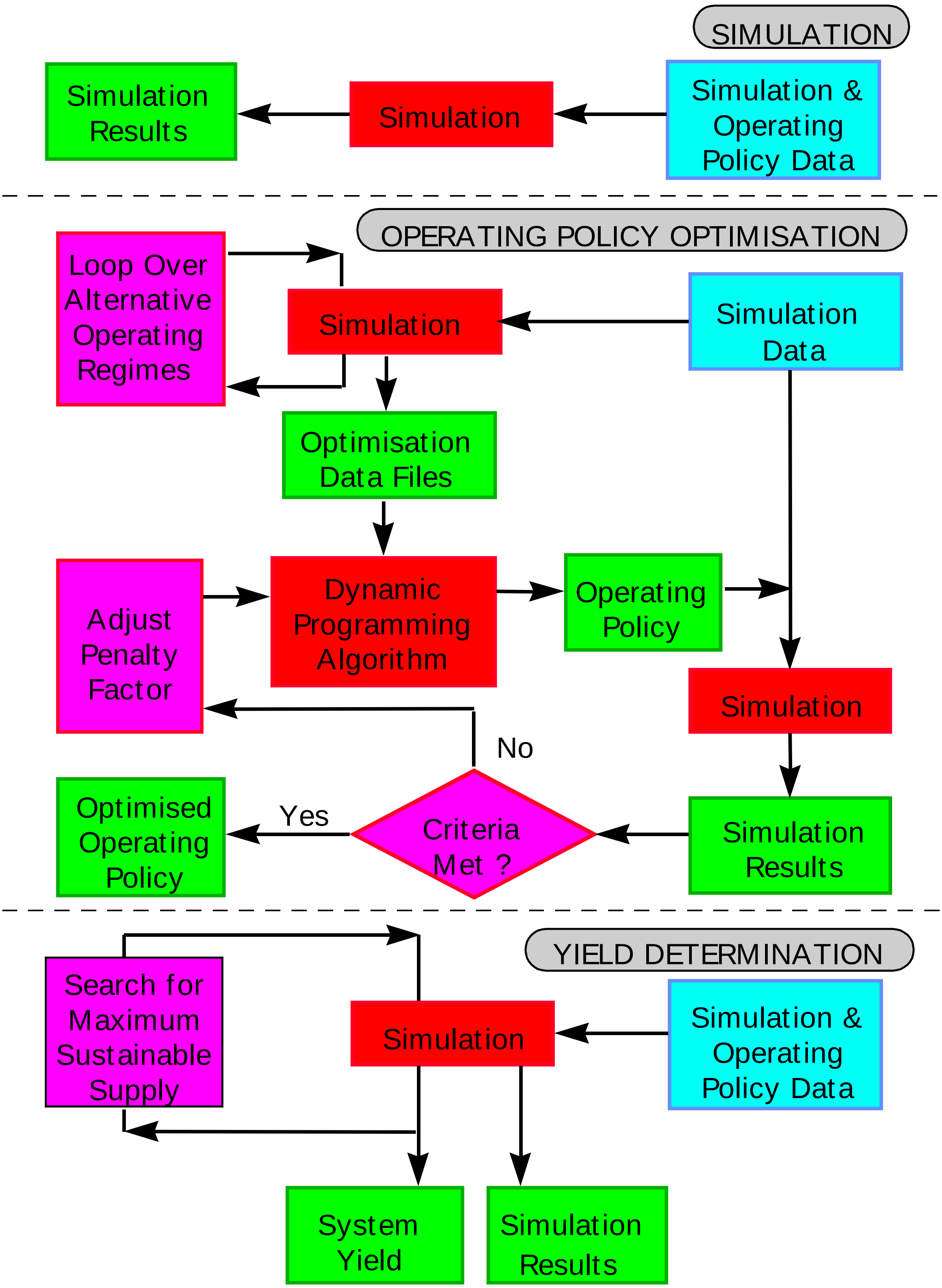
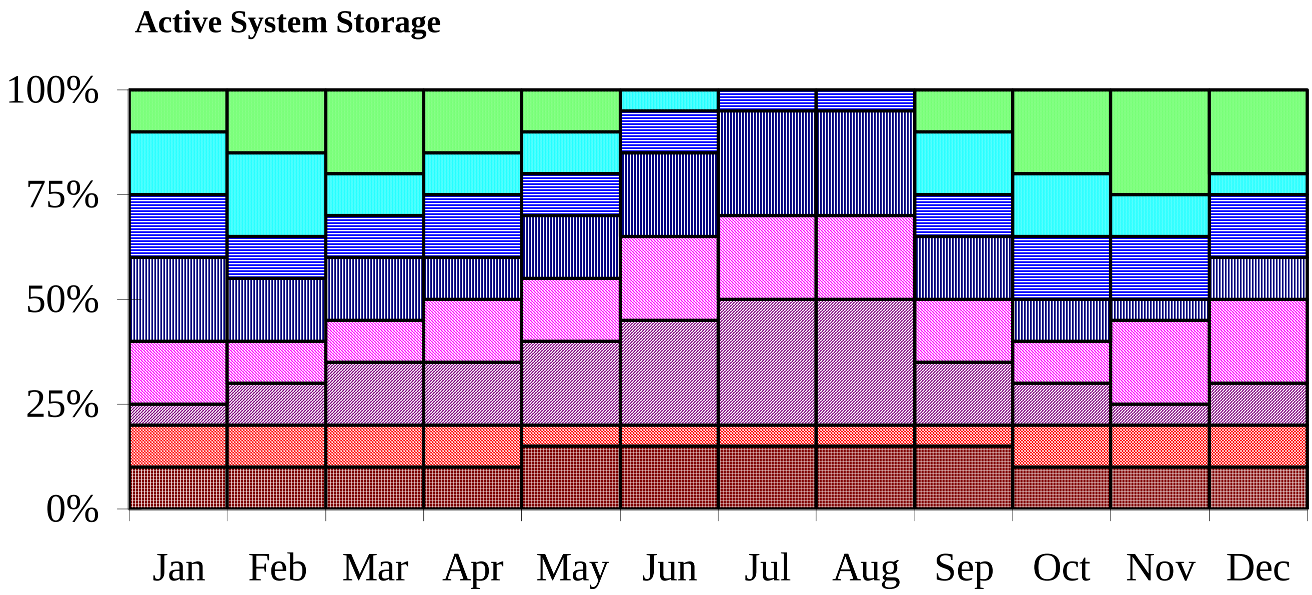


FIGURE 4 : Program MOSPA - Module Interaction

Operating	Regime	Scheduled Capacity (MW)						Restrictions	
Key	Number	Coal	Oil	Gas	Diesel	Import	Export	Water	Power
	1	60	-	-	-	-	Yes	No	No
	2	150	-	-	-	-	Yes	No	No
	3	150	100	-	-	-	No	No	No
	4	150	100	50	-	-	No	No	No
	5	150	100	50	30	-	No	No	No
	6	150	100	50	30	20	No	No	No
	7	150	100	50	30	20	No	Yes	No
	8	150	100	50	30	20	No	Yes	Yes

Alternative Operating Regimes



Optimised Multiple-Regime System Operating Policy

FIGURE 5 : Example Multiple-Regime Operating Policy for Hydro/Thermal Generation & Irrigation System

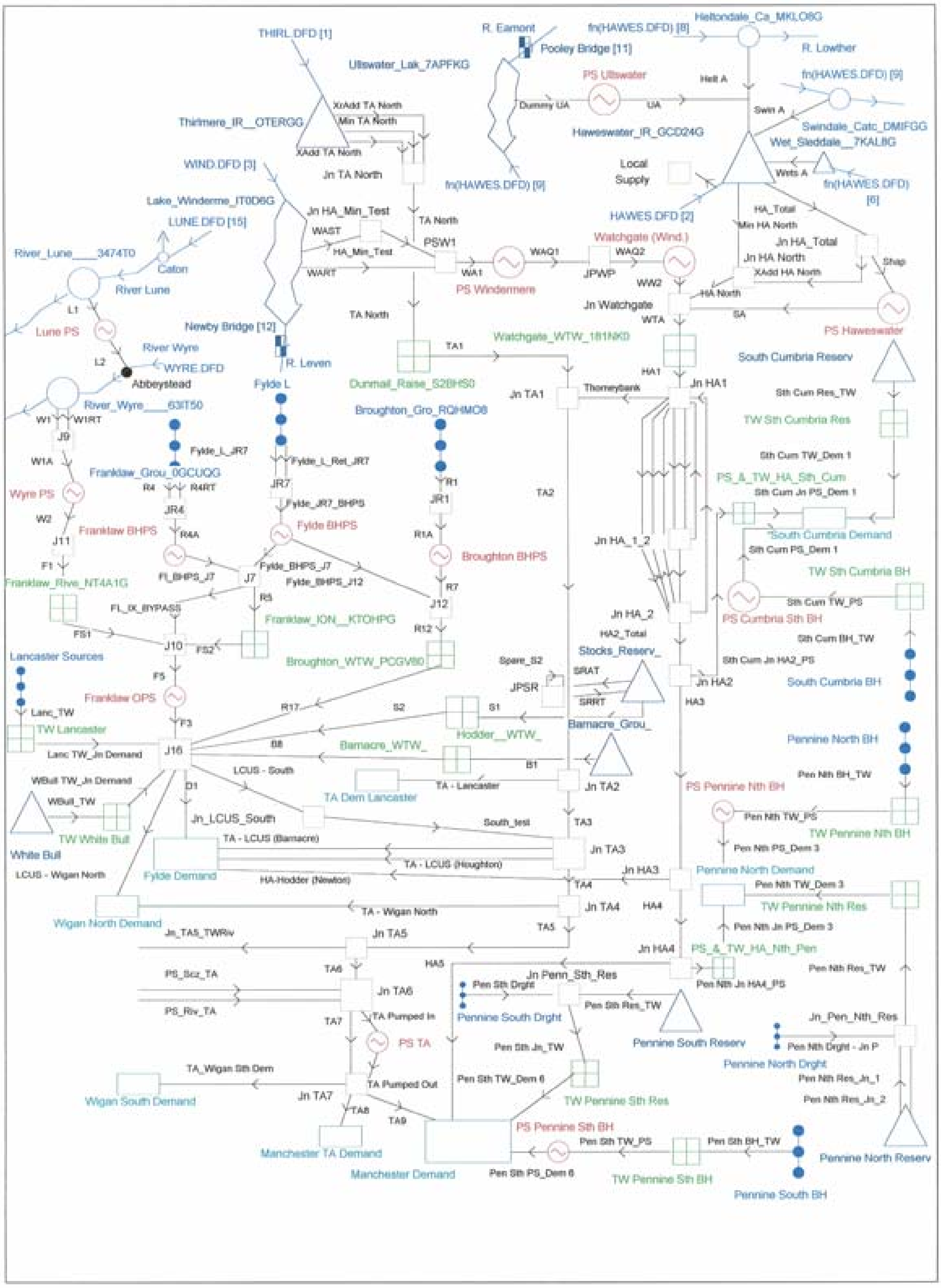
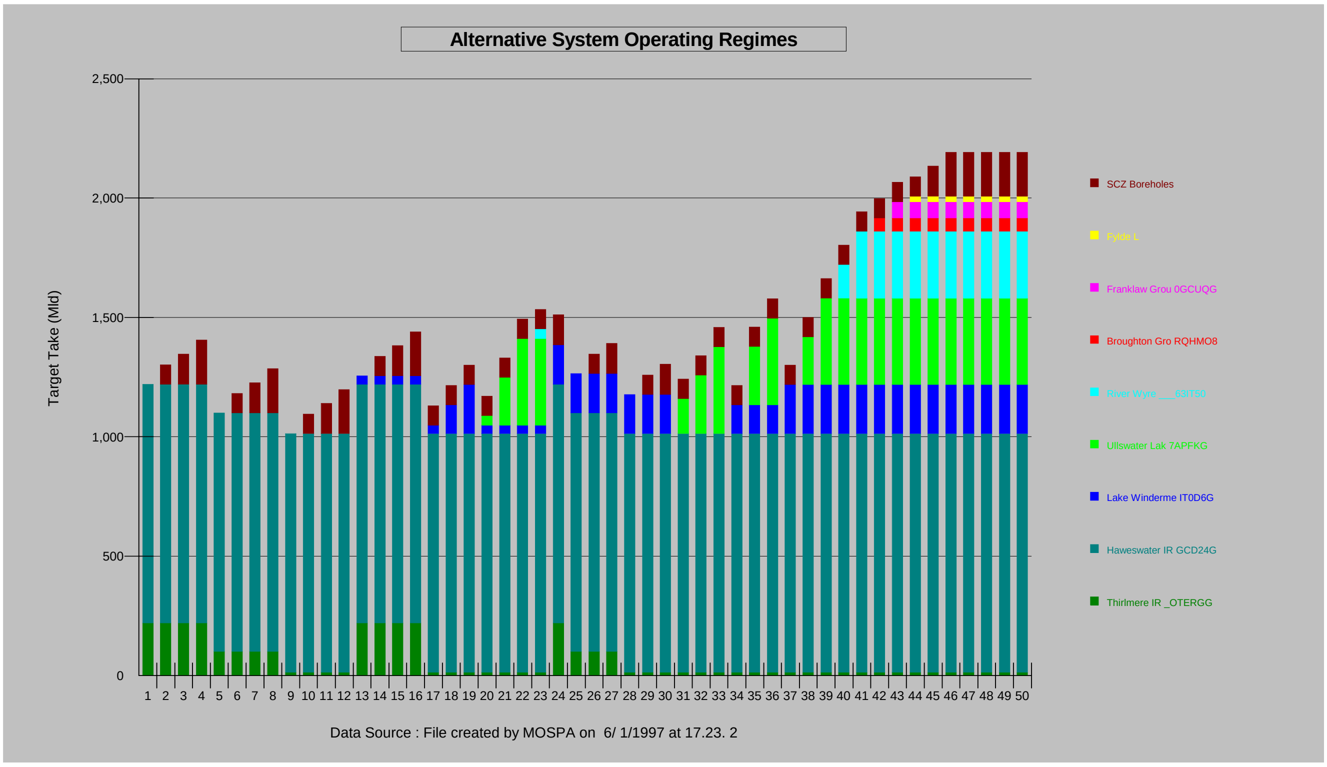


FIGURE 6 : MOSPA Model of NWW's Northern Command Zone System



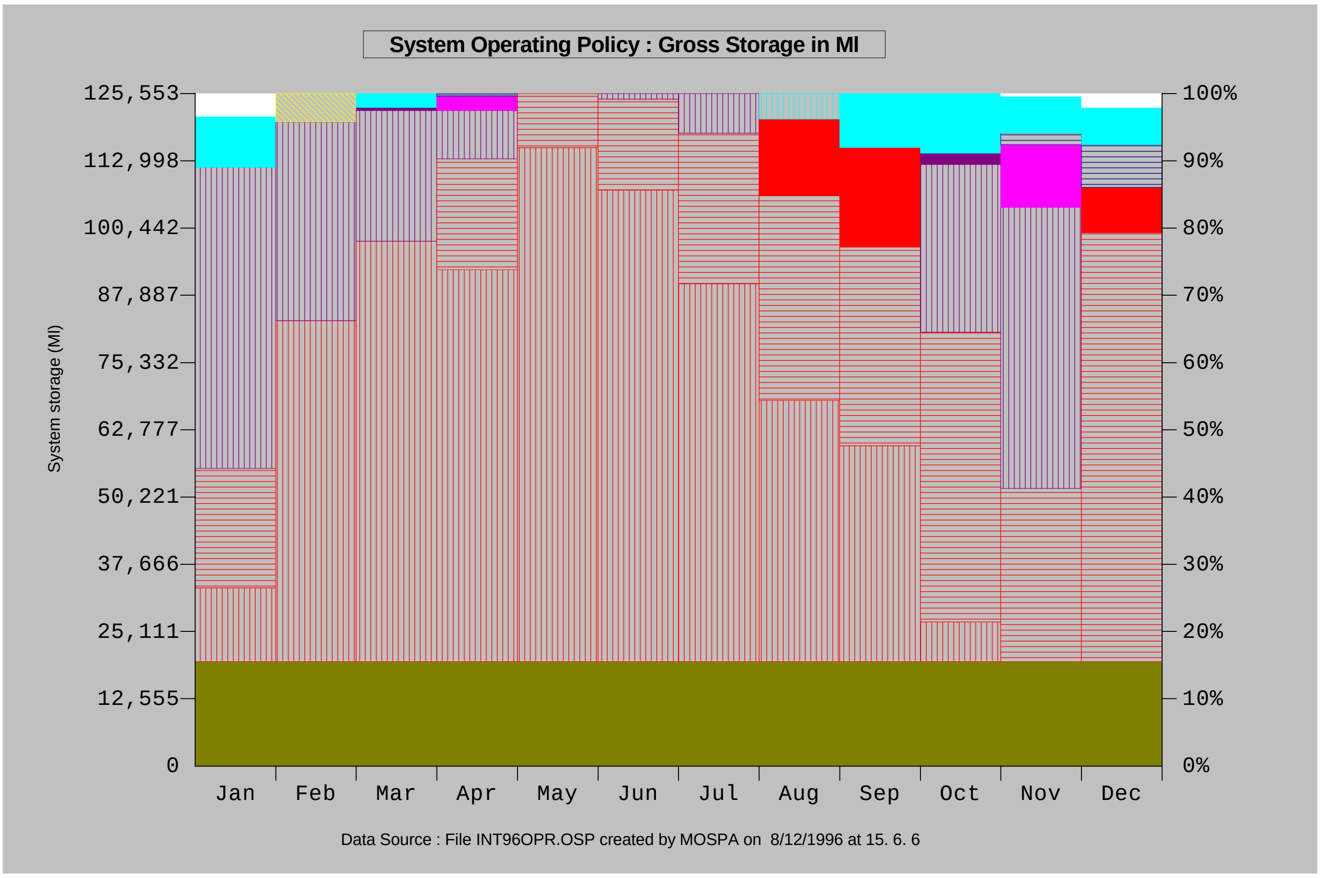


FIGURE 7 :Alternative Operating Regimes & MOSPA Optimised Operating Policy for the NWW's Northern Command Zone System