Reservoir operation
- the case for water value based policies

Conventional reservoir operation is typically based on defining the maximum amount of water to be abstracted as a function of storage content and time of year. In simple cases, this needs the specification of ‘above’ and ‘below’ curve quantities and the derivation of the storage contents below which the lower rate should be adopted if a prescribed level of supply reliability is to be maintained over a given inflow sequence (Fig. 1).

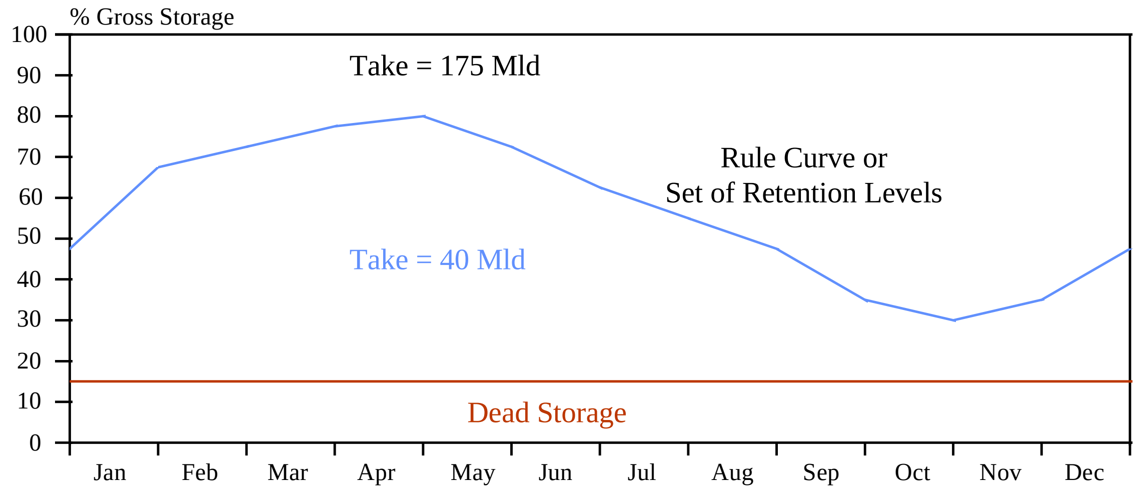

Fig. 1 : Conventional Reservoir Operating Policy

For isolated direct supply reservoirs the ‘above curve’ rate may be limited by a maximum aqueduct capacity and the ‘below curve’ rate is often set equal to the so-called ‘firm yield’. Deriving the associated ‘critical storage volumes’ or ‘retention levels’ is relatively straightforward using some form of critical period analysis, and such control rules are efficient in terms of minimising spill and maximising total average abstractions.

However, few reservoirs now operate in isolation and, once they form part of an integrated or ‘conjunctive use’ supply system, the optimum ‘below curve’ rate is no longer obvious. For example, when a reservoir is operated in conjunction with a costlier source, it makes economic sense to set the ‘below curve’ abstraction rate to the difference between the demand and the maximum output of the alternative source. This is because a lesser ‘below curve’ value means that the critical storage volumes can be set lower than for the ‘firm yield’ situation, with a consequent reduction in spill and increase in total reservoir take.

Other examples of conjunctive use involve the combined operation of two or more reservoirs where potential benefits, in terms of increased ‘yield’ and/or reduced operating costs, can arise from exploiting spatial and temporal variations in their respective inflow sequences and differences in the degrees of regulation afforded. To realise such benefits, individual reservoir operating policies need to be replaced or augmented by ‘balancing rules’ to maintain reservoirs at preferred states of relative fullness. While essentially heuristic, such rules can be effective in achieving the desirable situations when reservoirs spill and empty coincidentally.

Multiple Regime Operating Policies

As systems become more complex in terms of the number of reservoirs, alternative water sources, and operational constraints in the form of aqueduct, treatment works and pumping station capacities, the application of operating policies based on individual reservoir rule curves becomes increasingly difficult to justify in terms of operating cost minimisation, supply security maximisation and even deployable output determination (Fig. 2).

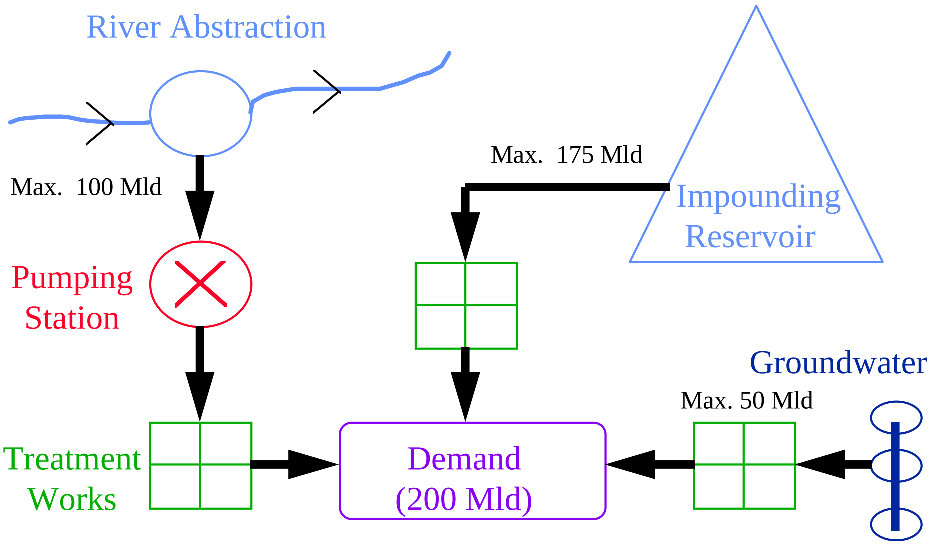

Fig. 2 : Example Conjunctive Use System

For such systems, ‘multiple regime operating policies’ (Fig. 3) can define target abstraction rates from different sources as a function of the quantity of water held in storage at a particular time of year. It can be noted that such rates represent 'target values', since availability at any particular time may be reduced by time and flow dependent licences, maintenance schedules and other operational constraints. Additional regimes can be incorporated for specifying the imposition of demand management measures, while individual reservoir operating rules may still be necessary to protect local compensation requirements or supplies.

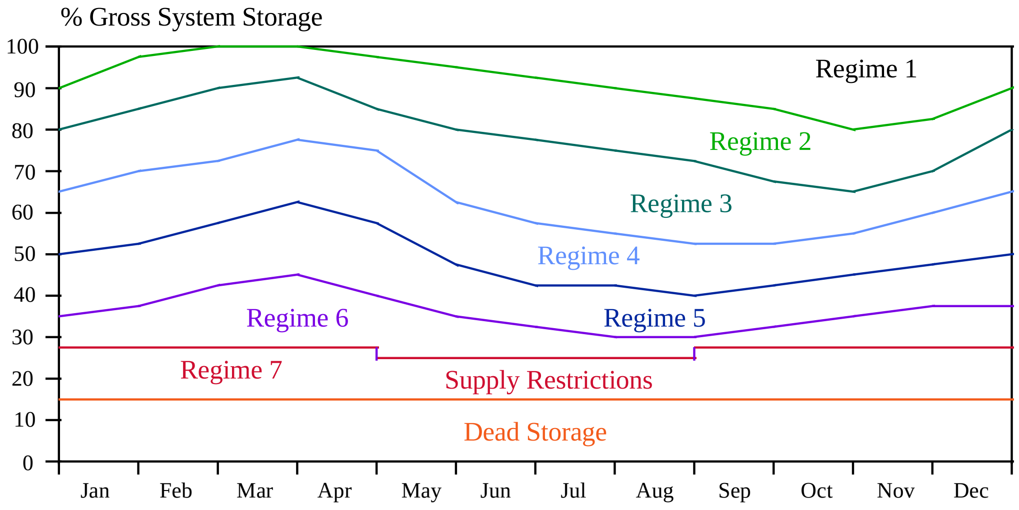

Fig. 3 : Multiple Regime Operating Policy for Conjunctive Use System

Determining the storage volumes below which a particular regime should be adopted does, however, present a significant optimisation problem, since they are not independent variables and it is not feasible to apply critical period methods. Integrated simulation and stochastic Dynamic Programming (DP) methods can be used to optimise such volumes, and demonstrate the scope for significant potential savings in operating costs when compared with more conventional policies. However, the limitations of ‘rule based’ simulation methods, where abstractions are made according to a defined order of preference, become increasingly apparent as more complex systems are modelled, and the optimum resource/demand allocation in each time step less obvious.

Water Value Based Operating Policies

Compared with individual reservoir and multiple regime rules, water value based policies can provide a more intuitive indication of when other sources of water or power generation within the system should be operated i.e. when the cost of doing so is less than that associated with releasing water from storage. However, within the allocation procedure, all associated ‘downstream’ costs need to be taken into account, and with hydroelectric plants relative generation efficiencies must be considered. Water values can also provide the logical basis for balancing releases from, and making transfers between, reservoirs.

Water value based reservoir operating policies are increasingly used to optimise hydro-thermal power system operation, with the application of mathematical programming techniques prompted by increased private sector investment. Since decisions on the levels at which generating plants should operate can have major financial implications for owners, it is vital that such decisions are transparent and based on clearly defined economic and technical criteria. Heuristic rules for individual reservoir operation or balancing are open to challenge, with power system regulators insisting that operational decisions be based on rigorous mathematical procedures.

Linear Programming Based Simulation & Time Steps

Advantages of using linear programming to optimize the resource/demand allocation within each time-step when simulating the operation of water resource, water supply or power supply systems, include:

- the Objective Function to be minimised can contain unit costs associated with the operation of treatment plant, pumping stations, river abstractions, aqueducts, transmission lines, hydro, thermal and wind power generation plant, as well as supply shortfall penalties and benefits;
- the optimal solution to a properly formulated problem is guaranteed;
- operational limits such as those represented by maximum and minimum outputs, time and flow dependent licences etc., can be formulated as ‘>=’, ‘<=’ and ‘=’ constraints;
- solutions can provide the ‘marginal costs’ for supplying extra units of water or power at demand centres and intermediate distribution system nodes, and thus form the basis for tariff setting, ‘spot market’ and inter-basin transfer pricing, and ‘indicative’ planning.

Disadvantages are that:

- the Objective Function and all constraints must be linear;
- solution times increase with both the number of objective function variables and the number of constraints.

Until recently, solving an LP problem for each time step of a water or power supply system simulation over long inflow sequences would have been computationally unrealistic. However, with modern computing power we can exploit the appreciable benefits of such formulations, and the effects of any linear approximations can be considerably reduced by using daily rather than weekly or even monthly time steps. Modelling a major water supply and power system will typically produce an LP matrix of some 500 columns (objective function variables) x 500 rows (constraints), a problem which the latest computers can solve in less than half a second. For simple systems solution times can be less than 0.01 of a second per time step.

Comparisons of Conventional, Multiple Regime and Water Value Based Operating Policies

Acceptance of new techniques for operating policy optimisation is always hindered by the impossibility of guaranteeing the magnitude of potential benefits that might accrue from application to a particular system, since the scope for optimisation depends on the demands and supply reliability criteria imposed and the ultimate supply capability or 'yield' of the system. The 'optimisation space' may be further reduced by capacity and licence constraints.

A recently developed computer program, AQUARIUS, combines LP-based daily, weekly or monthly time-step simulation with stochastic DP for weekly or monthly policy optimisation. It enables the modelling and optimisation of individual reservoir rules, as well as multiple-regime and water value based system operating policies, and can therefore be used to compare each approach. As part of the development process, AQUARIUS models have been built for a number of major water resource, water and power supply systems, and results indicate the potential for substantial improvements in operational efficiency using water value based operating policies. A major factor is the efficiency with which reservoirs with disparate characteristics are kept in balance during both drawdown and refill cycles. An optimised weekly time-step water value policy for one of these systems is shown in Fig. 4, it being noted that within the simulation water values can be interpolated between individual curve values.

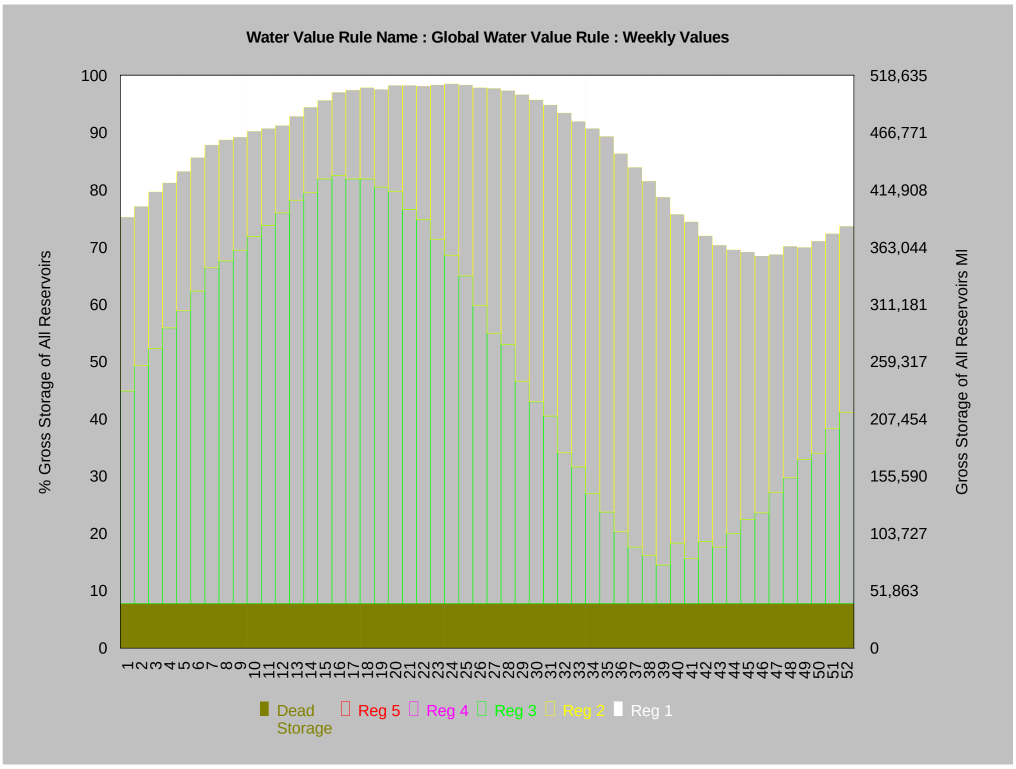

Fig. 4 : Optimised 3-Regime Water Value based Weekly Operating Policy

Increasing recognition of the true value and scarcity of water, the prospect of increasing flow variability as a result of climate change, and political and regulatory concerns are likely to increase the pressure on system operators to ensure and demonstrate that water resources under their control are used as efficiently and equitably as possible. This seems bound to result in demands for the increased application of robust mathematical optimisation techniques in place of more conventional ‘heuristic’ methods.

Comprehensive comparisons need to be made with existing methods of operation, although this process can be facilitated using generalised software incorporating ‘user friendly’ interactive techniques for model building and data entry. Further details of Program AQUARIUS can be found at www.pwsc.co.uk.

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