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Operation Models for Single and Multipurpose Reservoirs—A Review

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Abstract : *Reservoir management especially long term planning models for reservoir systems have attracted the attention of many researchers in the water resources management field. In comparison, less effort has been devoted to the development of operational (real time) models and their actual implementation in real life scenario. Some complexities associated with short term or real time operation models may include : smaller time steps, increased uncertainties due to lack of aggregation or lumping effects that is possible for larger time steps, and nonlinearities due to actual operational conditions like water level variations which affect short term benefits and losses more significantly. Some of these associated issues, the importance of real time forecasts, and the criteria for performance evaluation of an operational model are discussed. In this process, models already developed, some of which are being actually used for operation are briefly described.*

Introduction

Management of a single reservoir or a system of reservoirs has proved to be a popular topic to those researchers who were able to identify the analogy between general inventory management and water reservoir management (Datta and Houck, 1985). The primary reason why this particular area has attracted the widespread application of operations research techniques is this analogy and similarity. However, the management of reservoirs on streams is a very challenging problem because, here we have to deal with a natural system with all the associated uncertainties. That is why a universally accepted or uniquely defined solution methodology for this problem is not available till today. Here I intend to present a brief review of the models, methods and approaches for efficient and 'optimal' operation of single or multiple reservoirs. Such a discussion should help interested readers to evaluate what has been done in this area and what remains to be accomplished.

Distinction Between Planning and Operation Models

Before plunging into a discussion of operation models it is appropriate to distinguish between 'operation' models and planning models. The main purpose of a planning model is the design of the reservoir system in terms of sizing (capacity). location and numbers. No doubt the planning models do have to incorporate a long-term operation policy in order to decide on the size, location and number of reservoirs. This long term operation policy is essentially used for planning purposes and designing some other components of the system. Actual operation of reservoirs is made according to a short term or real-time operation policy that evolves from an operational model only.

There is a fundamental difference between planning or design models and operational models. The long term operation policy that has to be incorporated in a planning model does consider historical inflow records and other projected quantities such as demands for water for various purposes. Short-term operation models on the other hand must incorporate short-term or real-time forecasts of inflows and possibly of demands also. In an operational model, these quantities once forecasted, may be treated as a deterministic variable, for optimization purpose.

More over, the long-term and short-term benefits or loss functions are not identical. Real-time operation must consider deviation from a planning target to find the short term losses. The time step considered in operational model is also much smaller than the time step considered in a planning model. For example, operational models incorporate time steps which may range between an hour to few weeks, the time steps considered in a planning model may lie usually in the range of a month to a year. Planning models generally consider seasonal inflows and releases.

There are other issues which are equally important for operational as well as planning models. These are : conflicting objectives or purposes of operation and uncertainties in modeling. The first issue of conflicting objectives is addressed by multiple objective optimization models. The second issue of uncertainties in modeling is very wide in scope and can be addressed partially by improving hydrological forecasting capabilities.

Finally, reservoir operation objectives may include such objectives as : hydropower generation, irrigation and municipal water supply, low flow augmentation for water quality improvement, and flood control. Apparently these are surface water related problems. In reality, water supply problems are usually linked with surface and groundwater availability. Also, in many cases both the groundwater and surface water systems are hydraulically and hydrologically connected. Therefore, it becomes imperative to consider the conjunctive use of surface and groundwater, even when considering optimal operation of reservoirs.

The significance of optimal reservoir operation to mitigate the effects of natural calamities like climatological droughts and floods cannot be over emphasized. Therefore, the identification of approaching drought conditions or flood causing hydrological conditions remain an important part of evolving an optimal reservoir operation strategy. It is in this content that the rapid assimilation of large amounts of spatial and temporal information becomes very important. In order to be able to gather, process present, and analyse these necessary climatoological, geographical and economic information, computational tools such as the Spatial Decision Support Systems (SDSS) and knowledge based Expert Systems have been proposed. Use of these tools can no doubt enhance the basic information content of any decision model for operation.

In the simplest terms, operation of surface water reservoir is a basic inventory management problem. However, the complexity of this problem lies in the fact that the input i.e., streamflow is a weather related natural process. Therefore, operational models for reservoirs must emphasise on forecasting hydrological phenomena with poor long - term prodictibility. Also, unlike other commodities, surface or subsurface water avilability is largely independent of demand for water or its products. Keeping in view these important issues and conditions, a number of operations research tools such as stochastic and deterministic optimization, reliability analysis, multiobjective programing etc. have been applied widely to evolve an optimal water reservoir operation policy.

Multiple Objectives and Hydrologic Uncertainties

Most work reported in the literature concerning short term reservoir operation has used deterministic forecasts or has involved schemes for developing operating rules that are based on a single historical streamflow record. This means that the adopted policies are for a perfect flow forecast situation; however, operation policies should be developed on the basis of system operation being subject to uncertain forecasts of future inputs and demands. Consideration of a second objective, the actual storage state; as well as noisy forecasts of future streamflows are important issues that substantially influence mathematically derived reservoir operation policies.

Multiple objectives of operation may include other more detailed objectives of meeting various conflicting demands like water supply, irrigation, flood control, low flow augmentation, hydroelectric power generation, recreation, or navigation. As some of these conflicting goals or objectives are to be included often in a multiple reservoir system scenario, the problem of reservoir operation becomes one of multiple objectives, multiple decision makers and uncertain hydrologic forecasts. A simpler objective set containing storage and release targets as two conflicting goals of operation can simplify the problem to a two objective optimization problem. However, even if the uncertainties are ignored, or over looked in modeling, the fact remains that a vector optimization problem cannot be fully solved without the preference ordering by the decision makers collectively. Hydrologic forecasting errors of course further complicate the decision making process.

To illustrate the incorporation of a second objective and noisy forecasts into the problem of operating even the simplest possible single reservoir, it is necessary to discuss multiple objectives, economic loss functions, the expected value decision making criterion, the nature of decision variable targets, decision model structures, and aspects of short-term streamflow forecasts.

The objectives of operation are of prime importance in developing an operation policy, whether they are stated explicitly in the objective function or incorporated implicitly as binding constraints in the model. All models have to satisfy some implicit objectives, for example, meeting minimum and maximum storage and release bounds with specified reliabilities. These multiple implicit objectives stated in the form of constraints are, in addition to the objectives, stated explicitly in the objective function. When only a single value of streamflow for a given period (which may be the actual value or a forecast) is used as an input to the model, the multiplicity of these implicit objectives is reduced. The optimum solution obtained by using such limited streamflow information may be far from satisfactory. When such models utilise externally forecasted streamflow value, their performance depends on the quality of the forecast as characterized by the forecast error distribution.

Application of Systems Approach to Reservoir Operation

Application of systems approach to modelling and solving the single or multiple reservoir operation problem can be classified into four categories : simulation, optimization, multiobjective analysis and combinations of these techniques. An excellent review of reservoir management and operation models is given in Yeh (1985). Much of the discussion in the following section is based on this state of the art review, with proper updating where applicable.

Simulation Models

Simulation models are better suited to the modeling of a physical system for decision making as some of the approximations essential in an optimiziation model may not be necessary in a simulation model. However, simulation models are not able to directly generate optimal solutions except by exhaustive search of all possible alternative scenarios.

Simulation models for reservoir operation include mass balance conditions, computation of inflows, outflows and storage. It may also consider economic evaluations of various operation purposes.

Some of the simulation models utilize the concepts of target storage and release volumes, multiple storage allocation zones, and operating rule curves generally conditioned on the existing volumes, and expected natural stream flows.

Some examples of simulation models for reservoir operation are found in Hall and Dracup (1970) dealing with the operational study of six reservoirs on the Missouri River. The use of simulation models for evaluating the economic performanae of a river basin is described in Maass et. al. (1962). Thomas and Fiering (1962), Burges (1979) and Hufschmidt and Fiering (1966) discuss the utility of using synthetic streamflows for enhancing model reliability.

Examples of recent applications of simulation include the HEC-3 model developed by the Hydrologic Engineering Center (1971). the simulation models (SIM I and II) for the Texas Water System (Evanson and Mosely, 1970), the simulation of New York's Oswego Basin (Liu et al., 1972), the Upper Wabash studies at Indiana (Toebes and Chang, 1972), HEC-5 model (Hydrologic Engineering Centre, 1979), Arkansas River Basin model (Coomes, 1979), TVA model (Shelton, 1979), Hydro System Seasonal Simulator developed by the North Pacific Division, the Corps of Engineers (Jones, 1979), Lower Colorado River System (Freeney, 1979), Duke Power Hydro System (Sledge, 1979), the Acres model (Sigraldason, 1976), and Simonovic (1992).

Optimization Models

Optimization models are useful for generting solutions that are optimal within the given scope of the model assumptions and criterion for evaluation of a decision of (objective functions). Most of the optimization models use some kind of mathematical techniques like Limar Programing (LP), Dynamic Programing (DP); Non Linear Programing (NLP); or that variations. Also, each of these techniques can be applied under deterministic assumed conditions or stochastic and uncertain conditions. Often the expected value of the benefits or losses are used as the objective function of the models when stochastic conditions are incorporated. However, as noted in Datta and Burges (1984), the expected value criteria may lead to inefficient "optimal" decisions, and therefore should be used with caution. A typical set of constraints of the optimization model may include mass balance equation, maximum and minimum permissible releases and storage as function of time, penstock or canal system capacity, plant capacity, legal and institutional constraints, and other physical bounds such as demands. The objective function value represents the level of performance of the system for assigned values of the decision variables, often in terms of economic units.

No doubt, of all the optimization methods LP has found the maximum acceptance due to the associated ease in solution, capacity to solve large scale problems and easily available computer codes. However, LP models are limited to solving models with limar objective function and constraints.

Application of LP to reservoir operation problems in a deterministic environment is suggested in Dorfman (1962). Application of recursive LP to the same problem is described in Windsor (1974) with particular emphasis on flood control. Becker and Yeh (1973) suggest the combined use of LP and Dynamic Programing (DP) for optimum real time operation of reservoirs in the California Central Valley

Project. Takeuchi and Moreau (1974) developed a combined LP and stochastic DP model for operation of reservoirs based on economic losses and expected future value of future losses. Other examples of LP application in reservoir planning and operation are given in Loucks (1981), Houck (1982). Grygier and Stedinger (1985) present the application of Sequential Linear Programing technique for optimization of reservoir operation for hydropower generation. Other variation of LP techniques incorporating uncertainties in the modeling process are : chance constrained LP (Datta and Houck, 1984), Stochastic LP and reliability programing (Houck, 1979; Simonovic and Marino, 1980). Other modifications include a combination of Linear Programing and Dynamic Programing (Becker and Yeh. 1974). Chance constrained LP models incorporating real-time streamflow forecasts and the reliability of operation policies were first introduced for real time cperation of reservoir systems by Datta and Houck (1984).

Dynamic programing based on sequential sub-optimal decisions to obtain an optimal decision is capable of efficiently solving reservoir operation problems with linear or nonlinear seperable objective functions, and constraints. Applications of DP to reservoir operation problems have been investigated by a number of researchers (Yakowitz, 1982). One particular restriction that has discouraged wide spread application of DP techniques to reservoir systems operation is the "curse of dimensionality" associated with a large and multivariable decision space. In discrete DPs, the curse of dimensionality also comes from the large number of state variables.

Many modification of the discrete DP concept has been proposed to make this technique more efficient. Such modifications include : Differencfial DP, constrained Differential DP, reliability constrained DP, and stochastic DP. It should be noted that stochastic DPs, are more suited to longterm planning problems. Application of DP for operation of reservoir systems are described in Arunkumar and Yeh (1973), Loucks are Falkson (1970) and Turgeon (1980, 1981). An excellent review of DP techniques and its applications is given in Yakowitz (1982).

Nonlinear optimization techniques have not been applied extensively to solving water resources systems optimization problems in general, and reservoir operation problems in particular. One particular reason for this may be the relative difficulty in writing a Nonlinear Programing (NLP) computer code and certain limitations of NLP in ensuring that a global optimum solution has been found. However, in almost all cases some of the constraints or objective functions are actually nonlinear and therefore, NLP offers more general and accurate formulation of the problem. Nonlinearities are inherent in modeling hydropower generation. Some examples of applying NLP to reservoir operation problems are : Hicks et al. (1974) quoted in Yeh (1984) for maximizing the system hydropower generation capability of the Pacific Northwest Hydroelectric System in U.S.A., Chu and Yeh (1978) for Shastha Reservoir in Northern California, and TVA (1976) for the Tennessee Valley Authority.

As most other water resources systems problems, planning, management, and operation of reservoir systems are for multiple purposes and therefore are multiple objective in nature. As mentioned earlier, it is not possible to find an optimal solution to a vector optimization problem with conflicting objectives. However, with the preference ordering of the decision makers it is possible to identify a compromise optimal solution based on the non-inferior region of the trade off function.

Application of multiobjective analysis to reservoir management problems are presented and discussed in Cohon and Marks (1975), Haimes (1977), Duckstein and Opricovic (1980)

Can and Houck (1984), Reznieck et al (1991), and Datta and Burges (1984).

Simulation - Optimization Models

Some researchers have suggested that optimization models for reservoir operation and planning should be used only as a screening model due to the limitations in the optimality of the optimum solution. It has been further suggested that optimization and simulation models should be linked together to evolve an efficient operation policy.

Especially for real time (short term) operation of reservoir systems, it is necessary to include real time inflow forecasts (demands can be treated as more or less deterministic). Any real time model must incorporate inflow forecasts for future streamflows and then correct the system status for actual streamflows occurring during the first time period of operation; again re-solve the optimization model starting from the next time period. This approach needs the implementation of an optimization - simulation model as propesed in Datta and Houck (1984). In order to avoid myopic nature of operation it is imperative that forecasts of streamflows beyond the actual time period of operation be included in such operation models (Datta and Houck, 1984).

SOME EXAMPLE MODELS OF RESERVOIR OPERATION

In some ways real time operation models are more complicated than long term planning models. The time increments or intervals permissible may vary from a single hour to a number of weeks. If hydropower, water quality down stream, etc. are considered, not only the model becomes nonlinear, the time interval considered in the model also needs to be as small as possible. The objective function depends on the purposes of operation. These short term purposes, targets etc. are again based on long term contracts and long term targets or long term benefit and loss functions (Datta and Burges, 1985). Some examples of real time operation models actually applied to various reservoir system are briefly mentioned here.

Incremental Dynamic Programing with Successive Approximations (IDPSA) was applied to a sytem of 9 reservoirs, 9 power plants, 3 canals, and 4 pumping plants in the California Central Valley Project (Yeh, 1979). The optimization model used an hourly time step, and links up with a long term monthly operation model. The optimization procedure uses Integer Programing with IDPSA. The objective includes maximization of weighted summation of generated power over a 24-hour period subject to specified plant releases from a longer term model, and other equipment and managerial constraints.

Some of the success stories associated with the actual application of system management models to reservoir system applications are from the Tennessee Valley Authority (TVA). These models form a part of a comprehensive water resources management method for the multipurpose management method. These set of models can be subdivided into four categories : weekly planning, weekly scheduling, daily planning and daily scheduling. The scheduling models are used for actual operation. The main purposes of operation are : flood control, navigation and hydroelectric power generation. The TVA reservoir systems management models contains simulation, optimization and forecasting models. In addition it has data management components. Both LP and DP are used for optimization. Discussion on these models are given in Shane and Gilbert (1982). Gilbert and Shane (1982) and Wunderrlich (1985).

Another example applying systems models for operation of reservoir systems is Hydro Quebee in Canada. Linear separable programing model wes developed for control of floods and generation of hydroelectric power in the Ottawa River Basin (Bechard et. al. 1981). Multiobjective optimization was used to analyze the tradeoff between these two objectives. Other examples are reservoirs managed by Pacific Gas and Electric Company of San Francisco, Manitoba Hydro of Canada, Swedish State Power Board, French Electricity Department and Yugoslavia's Djerdep Hydro-Power Project (Simonovic, 1992).

ROLE OF FORECASTS IN REAL TIME OPERATION

As mentioned in Datta and Burges (1984) and Datta and Houck (1984), real time forecasts and the associated inaccureies and uncertainties are most important for operation of reservoir systems. The probability of errors in forecasts also provide a framework for reliability based operation of reservoirs. No doubt, improvement in real time forecasting capabilities are key to improving real time operation of reservoir systems. Adoptive forecasting techniques like Kalman Filters can make full use of enormously advancing computer capabilities. Tracking of storms. rainfall cells etc. linked to on-line adaptive forecasting models can certainly improve the benefits from integrated management of reservoir systems. No operational model irrespective of its sophistication, can perform satisfactorily without the maximum utilization of online adaptive forecasting capabilities.

EXPERT DECISION SUPPORT SYSTEMS

Expert Intelligent Decision Support Systems (EDSS) and Expert Spatial Decision Support Systems are the latest computer related buzz word in the water resources management scenario. No doubt Expert Systems (knowledge based) are useful in finding solution to messy and difficult real world problems. EDSS are being touted as the application of AI in water resources management. Unfortunately, some researchers have tended to follow the path of an interactive program with modules for different functions and some if-then-else rules as an AI application. Therefore, caution is necessary before models based on Expert System concepts are utilized for actual operation.

Geographical Information Systems (GIS) and ES - GIS combinations known as Intelligent Geographic Information Systems (IGIS) (Arnold et. al., 1989) are also potentially applicable for management, especially planning of reservoir systems. Operation of reservoirs may be made more efficient by a judicious combination of EDSS, GIS and proper optimization-simulation tools that supplement the existing knowledge base of the EDSS.

Some examples of applying Expert System concepts to reservoir operations and management are : RESER applicable to every day reservoir design practice (Simonovic, 1992) and an Expert System model for drought management in the Seattle Water District (Palmer and Tull, 1987).

One particular advantage of using knowledge based ES could be the possibility of incorporating the heuristic reasoning and inference skills of a knowledgeable experienced operator. One word of caution again : advanced search algorithms for structured problems already exists in the form of optimization techniques. These capabilities must be preserved in a knowledge based ES. The role that ES (or EDSS), together with GIS etc. can play in reservoir management is in terms of diagonistics and inferences in an risky, fuzzy and uncertain environment, ubiquitous in water resources management. Finally. many EDSSs have been built and suggested but few have been actually applied. The potential still remains.

SOME CRITERIA FOR EVALUATION OF SYSTEM PERFORMANCE

Risk and reliability has become almost synonymous with water resources management. But these measures of operational performance is not adequate. Hashimoto et. al. (1982), Fiering (1982), Datta and Burges (1984) suggest and evaluate these criteria for reservoir operation policy. In addition to the commonly accepted measure of reliability as a system performance criterion for evaluating an operation policy, other criteria, including resiliency and vulnerability of operation policies are necessary. Reliability of a system performance is defined as the probability that the state of the system is in a satisfactory state 'S'.

$$\alpha = \text{Prob } [X_t \in S]$$

The resiliency of system operation may be defined as the probability of a system's recovery to a satisfactory state 'S' in time period (t+1), given that the system was in a failure state 'F' at time period 't'. Therefore, the resiliency of system operation may be defined as :

$$\text{Prob } [X_{t+1} \in S / X_t \in F]$$

Vulnerability may be defined as the expected severity of a failure when in a failure state 'F'.

Robustness of an operation policy can be described as a measure of overall economic performance. It can be related to the concept of economic regret which is more appropriate for evaluating operation policies (Datta and Burges 1984). All these criteria must be judiciously used in evolving an operational policy for reservoir systems.

BENEFIT LOSS AND PENALTY FUNCTIONS

Long-term reservoir operation policy is derived typically from an optimization model with an objective of maximizing long-term benefits or minimizing long-term losses. For short-term operations the objective is to maximize short-term benefits or minimize the opportunity cost of a decision.

Losses are negative benefits : actual loss or benefit functions are assessed or specified objectively and reflect the actual benefits or extent of damages corresponding to a given state. On the other hand, penalty functions reflect opportunity costs. Any decision that causes a decrease from the maximum possible benefit (or any increase from the minimum possible loss) incurs a penalty.

While it is quite difficult to construct an accurate benefit or loss function, it is more difficult to assess the opportunity cost of a decision. In many cases the shape of the penalty function is imposed by the decision makers to reflect a policy designed deliberately to achieve specific results. In short-term reservoir operation the penalty function is obtained from the long-term benefit function, the short-term benefit function, a planning target (a release guaranteed with high reliability), and an operational target (corresponding to the maximum of short-term benefits for a planned release).

If the only objective of operating a multiplereservoir or reservoir system is to ensure a dependable flow during dry periods, and other objectives are ignored, it is possible to adopt a loss function that constitutes only the dry branch of a two-sided generalized loss function. A two-sided loss function may be necessary when multiple objectives, e.g., recreation, flood damage mitigation, navigation, water supply, and hydropower are important (Datta and Burges, 1984).

EXPECTED VALUE OF LOSSES

One of the drawbacks of justifying any result according to the expectation criterion is that actual values and expected values differ. In the past, many arguments have been made for and against using expected returns from a particular policy as the sole criterion for decision making. The objection generally cited is that the expected value criterion does not take into consideration the variations in return.

The above reasoning for not using expected returns as the sole decision making criterion is only superficially valid. When utility measures (according to the Von Neumann-morgenstern Cardinal Utility Theory), not monetary values, are considered, the criterion of maximizing expected utilities accounts for the risk associated with probable returns and the decision maker's preferences for a combination of values. In practice the major difficulty is in constructing a proper utility function. Even with proper measures for returns, an expected utility criterion is impractical for water resource or other socioeconomic systems because usually more than one decision maker (representing different constituents) is involed. A single many-to-one mapping that relates all measures of importance to a utility scale is not obtainable in such cases. Therefore, expected return as a criterion for decision making may be unsuitable for water resources systems optimization problems.

GAP BETWEEN MODEL DEVELOPMENT AND ACTUAL USE

The numerous academic exercises aimed at formulating systems operation models and their actual application to operation of reservoir systems are not correlated. One of the main concerns of system modelers today is the lack of proper acceptability of systems analysis and management tools in actual operation. A few plausible reasons for this may be listed as : (i) lack of willingness of actual operators and decision makers to adopt these sophisticated mathematical tools for operational purposes, (ii) a gap between the model proposed by researchers and the form of the modal actually applicable to a real system of reservoirs, mainly due to the additional fine tunings necessary to adopt the developed model to the system, (iii) lack of interaction between model developers and actual users.

Not withstanding these drawbacks, a large number of instances are there, showing the successful and beneficial adoptation of optimization-simulation models for large reservoir system operation. Knowledge based Expert Systems, if cautiously and properly used, can have a beneficial impact on the actual implementation of systems analysis tools and mathematical models for reservoir operation.

SUMMARY

A very superficial attempt has been made to discuss some of the issues relevant to reservoir system operation models. The literature on this subject is vast, and a number of excellent review papers exist in this area. Therefore, an indepth discussion of available models was avoided. None the less some important issues that interested readers may find useful were raised and discussed. It is also hoped that these discussions will help future researchers, actual operators, and decision makers.

The ubiquitues uncertainties in the decision making environment for water resources management always makes the subject exciting, challenging and interesting. With the tremendous advancements in the computer field, it is a certainty that computers will play most significant role in the day to day operation of water reservoir systems. Therefore, the scope for further improvement in optimizing algorithms. large scale simulations, geographical information processing and machinised inference mechanisms relevant to AI techniques will remain.

Particularly for India, where a new outlook is growing in terms of new approaches for the management of natural resources like water, and greater emphasis is placed on mitigation of natural disasters like floods, the economics of multipurpose water resources management will gain more and more importance. The economic benefits of using properly formulated mathematical models for synergistic operation of reservoir systems cannot be over emphasised. The future is bright, but caution must be exercised in selecting right models, right approaches and right assumptions. Scope for some degree of subjective judgement in formulating an 'optimal' operation policy will remain. However, we should try to find proper techniques to solve challenging problems, not search for problems that suit the techniques we desire to utilize.

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