

An Overview of Reservoir Systems Operation Techniques

Azhar Husain

Assistant Professor, Department of Civil Engineering, Jamia Millia Islamia (Central University), New Delhi

Abstract:-A review of application of various optimization techniques to operation of multi-reservoir systems has been presented. Operation of reservoirs, often for conflicting purposes, is a daunting task. The solution to the problem is difficult because of the large number of variables involved, the non-linearity of system dynamics, the stochastic nature of future inflows, and other uncertainties of the system. The uncertainty associated with reservoir operations is further increased due to the ongoing hydrological impacts of climate change. Traditionally, reservoir systems operation has been carried out using optimization techniques such as linear programming and dynamic programming. Linear programming cannot be applied when either the objective function or the constraints become non-linear. Dynamic programming, however, becomes computationally bounded on problems of moderate size and complexity. Therefore, various artificial intelligence techniques such as genetic algorithms, ant-colony optimization, and fuzzy logic are increasingly being employed to solve multi-reservoir operation problems. A large number of application of traditional as well as artificial intelligence techniques have been described in the present paper.

Keywords: - Reservoir, Optimization, Optimal, Linear, Review, Dynamic

I. INTRODUCTION

India has several reservoirs that play a significant role in the progress and development of the country. Most of the reservoirs serve multiple purposes such as flood control, hydropower generation, water supply, navigation, and restoration. In recent years, the problem of ineffective operation of existing reservoirs using outdated technology and highly subjective management practices has been repeatedly indicated by many specialists (e.g. Guariso et al., 1986; Oliveira and Loucks, 1997; Chen, 2003; John, 2004). The situation of excess water in the rainy season and scarcity in the dry season poses significant challenges to effective reservoir operation. Many reservoirs in India are water-deficient in the dry season, but are threatened by dam-break disasters in the flood season. Additional uncertainty in reservoir operations is introduced due to global climate change as well as economic activities in the river basin. Due to changes of hydro-meteorological conditions and shifting goals of water requirements from one region to the other, each reservoir has a different set of operation rules. Operation of reservoirs is a complex problem that involves many decision variables, multiple objectives as well as considerable risk and uncertainty (Oliveira and Loucks, 1997).

Reservoirs are often required to be operated for conflicting objectives thereby leading to significant challenges for operators when making operational decisions. Traditionally, reservoir operation is based on heuristic procedures, embracing rule curves and subjective judgements by the operator. This provides general operation strategies for reservoir releases according to the current reservoir level, hydrological conditions, water demands and the time of the year. Established rule curves, however, do not allow a fine-tuning (and hence optimisation) of the operations in response to changes in the prevailing conditions. Therefore, it would-be valuable to establish an analytic and more systematic approach to reservoir operation, based not only on traditional probabilistic/stochastic analysis, but also on the information and prediction of extreme hydrologic events and advanced computational technology in order to increase the reservoir's efficiency for balancing the demands from the different users.

II. MATHEMATICAL PROGRAMMING TECHNIQUES

Optimising the economic benefits of water resource systems is a classical and persistent problem. The solution to the problem is difficult because of the large number of variables involved, the non-linearity of system dynamics, the stochastic nature of future inflows, and other uncertainties of the system. Nevertheless, a number of mathematical programming techniques have been developed to aid derivation of optimal operating strategies for water resource systems. Most of these techniques perform satisfactorily for the problems they are developed for. A generic methodology that can handle problems in their general form has not yet been identified, however. During the last three decades, one of the most important advances made in the field of water resources engineering has been the development of optimisation techniques for planning, design and management of complex water resource systems. The recent rapid increase in computer technology has made the development of sophisticated mathematical models for the analysis of water resource systems possible. These models are increasingly being used by system managers to determine decision alternatives which are optimal in some defined sense. The optimisation of reservoir systems operation usually involves the search through large decision spaces for optimal parameter sets. Often, the decision space is too large for a complete search. This has motivated the development of various optimisation procedures. However, despite the extensive research carried out in the last three decades, reservoir control still remains an active research field.

Most optimisation models are based on some type of mathematical programming technique. Many successful applications of these techniques to reservoir operation studies have been reported in the literature, but no universally proven technique exists. Excellent treatment of these techniques can be found in the works by Loucks et al. (1981) and Mays and

Tung (1992). A survey of dynamic programming (DP) models applied to water resources planning problems was presented by Yakowitz (1982). The application of various optimisation models to reservoir operation problems has been reviewed by Simonovic (1992) and Wurbs (1993). Yeh (1985) provides an excellent state-of-the-art review of reservoir management and operation models. According to Yeh (1985), the techniques being commonly used by the researchers can be broadly classified as follows:

1. Linear programming (LP)
2. Non-linear programming (NLP)
3. Dynamic programming (DP) including
4. Discrete differential DP (DDDP), differential DP (DDP), successive approximation DP (SADP), and stochastic DP (SDP)
5. Genetic algorithms
6. Simulation

1. Linear Programming

In a problem where all the objective and constraint functions are linear, LP can be used in the optimisation of reservoir systems. It has been one of the most widely used techniques in water resources management due to its simplicity and adaptability.

A typical LP model is Minimize or maximize $Z = C^T X$

Subject to $AX \geq b$

where $X \geq 0$ is a n dimensional vector of decision variables, C is a n dimensional vector of objective function coefficients; b is a m dimensional vector of right hand side of above equation; A is a $m \times n$ matrix of constraint coefficients; and T represents the matrix transpose operation.

Dorfman (1962) demonstrated the application of LP to a water resource problem with three versions of a model, each with increasing complexity. The objective was to maximise the economic benefits of water use while satisfying the constraints of the problem. In all the three versions, both storage capacities and target releases were treated as decision variables. The first version of model involved a simple LP application to a simplified river basin planning problem. In the second version, critical period hydrology was used. In the third version, the model treats inflows stochastically. Gilbert and Shane (1982) describe a model called HYDROSIM used to simulate the Tennessee Valley Authority reservoir system based on established operating strategies. The model employed LP to compute reservoir storages, and hydropower generation for each period of operating horizon. Palmer and Holmes (1988) incorporated a LP model in the Seattle Water Department integrated drought-management expert system. The model was used to determine optimal operating policies and system yield based upon the objectives of maximising the yield, and minimising the economic losses associated with deficits from a specified target.

Randall et al. (1990) used LP to study the operation, during drought, of a water resource system consisting of multiple reservoirs, groundwater, treatment plants, and distribution facilities. The objectives was to maximise the net revenues, which were the difference between the cost of production and the selling price of water; maximise reliability, expressed as the minimum of the ratios of consumption to demand for each water use deficit; maximise reservoir storage at the end of the operating horizon; and maximise the minimum flows in the streams. Crawley and Dandy (1993) used LP to develop a planning and operational model for the Adelaide headworks system in South Australia. The objective was to determine optimal sequences of pumping and transfers for the system so as to minimise pumping cost while maintaining a satisfactory level of reliability within the system. Martin (1995) describe an optimisation procedure based on LP to maximise the power generation over a 24-hr period from the Highland Lakes of Lower Colorado river in Texas. The application of LP requires the linearization of constraints and of the objective function, which for most of the practical reservoir systems are non-linear functions. This limits the application of LP to problems with linear functions. Non-linear functions can be approximated by linear functions, and successive LP (SLP) can be used to approximate the solutions. Grygier and Stedinger (1985) and Hiew (1987) describe the application of SLP, among many other techniques, to multi reservoir optimisation problems. Reznicek and Simonovic (1990) describes the application of SLP to Manitoba Hydro system in Canada. The objective was to maximise the power production from the system. Since the power was not linearly related to the release, Taylors series expansion was used to linearise the power function. Such simplification may, however, lead to reduction in the value of the optimisation results.

2. Non-linear Programming

NLP technique can be applied where either the objective function or constraints are non-linear. NLP can effectively handle a non-separable objective function and non-linear constraints. A general NLP problem can be expressed in the form

$$\text{Minimise } F = f(x_1, x_2, \dots, x_n)$$

$$\text{subject to } g_i(x) = 0 \quad i = 1, m$$

$$\text{where } \underline{x}_j \leq x_j \leq \bar{x}_j \quad j = 1, n$$

in which F is to be minimised subject to m constraints expressed by function $g(x)$, n is the number of decision variables, and equation **Error! Reference source not found.** is a bound constraint for the j th decision variable x_j with \underline{x}_j and \bar{x}_j being the lower and upper bounds, respectively.

NLP has not been very popular due to the computational complexity of the approach for multi reservoir systems optimisation. Lee and Waziruddin (1970) applied NLP to a theoretical system of three reservoirs in series with the objective of maximising a non-linear function of irrigation releases and storages in the reservoirs. Applications of NLP have also been reported by Simonovic and Marino (1980), Rosenthal (1981), and Guibert et al. (1990). A special case of NLP is quadratic programming (QP) where the degree of various terms in the objective function is 2, 1, or 0. A quadratic optimisation model for the California Central Valley Project (CCVP) has been presented by Marino and Loaiciga (1985). The model was compared with an LP model, and it was found that a significant increase in the total energy production could be obtained using the QP model. Diaz and Fontane (1989) applied sequential QP (SQP) to determine optimal economic returns from hydropower generation for a multi reservoir system in Argentina. The SQP approach was found to be superior to SLP in terms of the execution time and the value of the objection function achieved. Wardlaw et al. (1997) used QP to solve water allocation problem to the Lower Ayung irrigation system on the island of Bali in Indonesia. The objective was to maximise crop production while maintaining equity in water supply between irrigation schemes and the irrigation blocks within the schemes.

A large number of NLP software packages are commercially available. Most commonly used packages include GAMS, INRIA, LINDO, LINGO, Mathworks, NAG and OSL. For multiple reservoir systems, the number of constraints is large because they deal with similar subsystems repeated in time or location. Therefore, NLP requires large amount of storage and execution time when compared to other methods limiting its applicability to large systems (Yeh 1985). The use of NLP is further limited to problems that are smooth and continuous because it requires the calculation of derivatives for its search procedure.

3. Dynamic Programming

DP (Bellman 1957) is the most commonly used method for the optimisation of reservoir systems as these are characterised by large number of non-linear and stochastic features that can be translated into a DP formulation. DP is an enumeration procedure used to determine the combinations of decisions that optimises overall system effectiveness as measured by a criterion function. It is capable of treating non-convex, non-linear and discontinuous objective and constraint functions, and this is the greatest advantage of DP. Constraints on both decision and state variables introduce no difficulties. In fact, the constraints speed up the computational procedure. The key feature of DP application is that it is usually identified as serially or progressively directed for operational or planning problems, respectively. The operation of reservoirs is a multistage decision process and DP is particularly suited to such problems. The problem is divided into stages with a decision required at each stage. The stages usually represent different points in time and each stage should have a finite number of states associated with it. In reservoir operation studies, the state usually represents the amount of water in the reservoir at a given stage. If DP is used for determination of reservoir releases, these form the decision variables. The stage to stage transformation is carried out by the continuity equation subject to constraints on storages and releases. The recursive equation of DP can be written as

$$F_n(s_n) = \max[V_n(s_n, d_n) + F_{n-1}(s_{n-1})]$$

where s_n is the state variable, d_n is the decision variable, $V_n(s_n, d_n)$ is the objective function value, $F_n(s_n)$ is the cumulative return at stage n with $F_0(s_0)$ known, and $s_{n+1} = g(s_n, d_n)$ is the stage to stage transformation function.

DP has been successfully used by many researchers for optimisation of water resource systems. Hall and Buras (1961) were the first to propose the application of DP to determine optimal returns from reservoir systems. Young (1967) developed optimal operating rules for a single reservoir using DP. A series of synthetically generated inflow sequences were used to derive a set of optimal release trajectories. These trajectories were then related to various system variables through regression analysis. As a result, an operating rule expressed as a function of a set of system variables was obtained. Allen and Bridgeman (1986) used DP for optimal scheduling of hydroelectric power. Applications of DP to reservoir operation problems have also been reported by Opricovic and Djordjevic (1976) and Collins (1977). Extensive review of DP applications to reservoir systems can be found in the works by Yakowitz (1982) and Yeh (1985).

The disadvantages associated with DP are the huge requirements in terms of computer memory and execution time. The approach breaks down on the problems of moderate size and complexity, suffering from a malady labelled the 'curse of dimensionality' by its creator Bellman (1957). For a system with n state variables and k levels of discretization, there exists k^n combinations that need to be evaluated at each stage of analysis. The usefulness of DP when applied to multiple reservoir systems is therefore limited by the "curse of dimensionality" which is a strong function of the number of state variables and the levels of discretization used. The application of DP to problems with more than two or three state variables still remains a challenging task on present day computers. A traditional and simplistic procedure for reducing computational effort in DP is the iterative coarse grid method. The problem is first solved using a coarser discretization of the state variables. Based upon the resulting solution, revised bounds on the state variables are defined and the grid size is then reduced. The iterative procedure is repeated until the grid size has been reduced to a desired precision. The algorithm is stopped when no further improvement in the value of the objective function can be obtained. This procedure, however, cannot guarantee a global optimum. Besides, it also does not resolve the dimensionality problem.

To overcome the dimensionality problem imposed by DP to some extent, use of LP in combination with DP has been reported by many researchers. In a combined LP-DP procedure, the stage to stage optimisation is carried out by LP, and DP is used for determining optimal policy over a number of stages. Becker and Yeh (1974) applied a combined LP-DP approach to optimal real time operations associated with CCVP. The LP minimised the loss in potential energy of the stored water in the reservoirs resulting from any release policy in each period. The multiperiod optimisation was carried out by embedding the LP solutions in a deterministic forward DP. The LP-DP combination has also been used by Takeuchi and Moreau (1974), Becker et al. (1976), Yeh et al. (1979), Yeh and Becker (1982), and Marino and Mohammadi (1983). The

non-linearities are handled using an iterative technique, such as SLP. Grygier and Stedinger (1985) describe the application of SLP, an optimal control algorithm (Pontryagin et al. 1962), and a combined LP-DP algorithm to a multi reservoir system. The optimal control algorithm is based on Pontryagin's maximum principle (Pontryagin et al. 1962) and involves the solution of Kuhn-Tucker necessary conditions of optimality. The optimal control algorithm for the problem solved by Grygier and Stedinger (1985) executed five times faster than the SLP. The LP-DP algorithm took longer to execute and produced comparatively inferior solutions.

4. Discrete Differential Dynamic Programming

Many variants of DP have been developed over time to alleviate the problems of dimensionality. Notable among these are incremental dynamic programming (IDP), DPSA and DDDP. These are iterative techniques and start with the assumption of a trial trajectory. DDDP is specifically designed to overcome the dimensionality problem posed by DP. The technique uses the same recursive equation as DP to search among the discrete states in the state-stage domain. Instead of searching over the entire state-stage domain for the optimum, the optimisation is constrained only to a part of the state-stage domain saving computer time and memory. The method starts with the selection of a trial state trajectory satisfying the boundary conditions. Several states, located in the neighbourhood of a trial trajectory can be introduced to form a band called a corridor around the trial trajectory. The traditional DP approach is applied to optimise within the defined corridor. Consequently, an improved trajectory is obtained which is adopted as the new trajectory to form a new corridor. This process of corridor formation, optimisation with respect to the states within the corridor and trace back to obtain an improved trajectory for the system is called an iteration. The procedure is repeated for a number of iterations until no further improvement in the value of the objective function can be obtained. Larson (1968) obtained the solution to the four reservoir problem using IDP. Hall et al. (1969) used a different version of IDP and solved a two reservoir system. The major difference between the two versions is that the time interval used in the computation is variable in the former and fixed in the latter. Another version called DDDP was developed by Heidari et al. (1971) which could be seen as a generalisation of IDP. They solved the four reservoir problem formulated by Larson (1968). The terms IDP and DDDP have been used interchangeably in water resources applications. In the standard IDP of Larson (1968), the number of discretizations is limited to three per state variable. The computational burden and memory requirements for such an approach is a function 3^n , where n is the number of state variables. IDP does overcome the dimensionality problem to a large extent but requires stringent conditions to be satisfied for implementing the procedure. The IDP method require that there must exist a function $g_t(s_t, s_{t+1})$ such that for every pair of states s_t and s_{t+1} ,

$$g_t(s_t, s_{t+1}) = r_t$$

where r_t is the release in time step t such that $s_{t+1} = f_t(s_t, r_t)$

In IDP, an optimal solution can only be obtained if all the states in the corridor are accessible from one stage to another. When the optimisation is restricted to three states in each stage, the above condition may not be satisfied and IDP may converge to a non-optimal solution. When the optimisation is carried out over the entire decision space, the method becomes time consuming and memory requirements are also high but the likelihood of locating the optimum is increased. Turgeon (1982) demonstrated that IDP may lead to non optimal solutions. Suggestions were then made to adjust the increment sizes in each stage to obtain the desired results. The choice of initial trial trajectory is vital for good convergence in all iterative algorithms. For complex systems, the determination of feasible trial state trajectories is not a trivial task.

Another approach which overcomes the dimensionality problem is the DP successive approximation technique (DPSA). The technique was first proposed by Larson (1968). Trott and Yeh (1973) used successive approximation technique in combination with IDP. The original multiple state variable DP problem was decomposed in a series of sub-problems of one state variable. To demonstrate the technique, a six reservoir problem was solved. The optimisations were carried out with respect to a single reservoir while keeping the states in the other reservoirs fixed. The procedure is repeated for other reservoirs until the convergence criteria is satisfied. Successive approximation is one-at-a-time optimisation technique and its common drawback is convergence to a local optimum. Extension to successive approximation technique has been reported by Nopmongcol and Askew (1976), who suggested higher level combinations, such as two or three-at-a-time combinations. The technique was demonstrated through application to the four reservoir problem. The requirement that the state variables be discretized is a major cause of computational complexity. Jacobson and Mayne (1970) developed differential DP (DDP) for multi state problems. Murray and Yakowitz (1979) applied DDP to multi reservoir control problems. The important feature of the technique is that discretization of state and decision space is not required. The method requires a quadratic approximation of the objective function. Application of the method to a ten reservoir problem by Murray and Yakowitz (1979) has demonstrated its effectiveness. Murray and Yakowitz (1979) also solved the four reservoir problem using DDP and showed that the global optimum was obtained in much lesser number of iterations than in DDDP. Application of DDP to estuary management has been reported by Li and Mays (1995). However, the technique requires that the objective function is differentiable and that constraints are linear. Howson and Sancho (1975) developed a progressive optimality algorithm (POA) for multistate problems. Turgeon (1981b) applied the algorithm to an example system consisting of four reservoirs in series. The most promising aspect of the approach is that the state variables do not have to be discretized. The algorithm, however, required 823 iterations to converge to an optimal solution for the simple example considered. The approach has merit in that it overcomes the dimensionality problem. A binary state DP algorithm has been developed by Ozden (1984) in which the optimisation is constrained within a subset consisting of only two states at each stage. One of the states is the component of the optimal trajectory found in the previous iteration. The second value is defined according to the shifting direction of the optimal trajectory in the state space at previous iteration. This procedure differs from DDDP in the manner in which the states are chosen for next iteration.

5. Genetic Algorithms

Despite intensive research carried out during the last three decades, a generic technique for the optimisation of complex systems is yet to be identified. In recent years, genetic algorithms (GAs) have gained growing popularity among researchers as a robust and general optimisation technique. A genetic algorithm is a technique in which a population of abstract representations of candidate solutions to an optimisation problem are stochastically selected, recombined, mutated, and then either eliminated or retained, based on their relative fitness. The approach has been successfully applied to a wide variety of problems from diverse fields. The results of employment of GAs to various difficult optimisation problems have indicated considerable potential. In the "Origin of Species", Darwin (1859) stated the theory of natural evolution. Over many generations, biological organisms evolve according to the principles of natural selection like the "survival of the fittest" to reach some remarkable forms of accomplishment. In nature, individuals in a population have to compete with each other for vital resources such as food and shelter. Because of this, the least adaptable individuals are eliminated from the population while the fittest or the most adaptable individuals reproduce a larger number of offsprings. During reproduction, a recombination of the good characteristics of each parent can produce offsprings whose fitness is greater than either of the parents. After a number of generations, the species evolve spontaneously to become more and more adapted to their environment. Holland (1975) developed this idea in "Adaptation in Natural and Artificial Systems" and laid down the first GA. Since then, GAs have developed into a powerful technique for identifying optimal solutions to complex problems. Excellent introductions to GAs are given by Goldberg (1989) and by Michalewicz (1992). Application of GAs to many complex real problems can be found in the works by Davis (1991), Michalewicz (1992), and Dasgupta and Michalewicz (1997). GAs are a class of artificial intelligence techniques based on the mechanics of natural selection and natural genetics directly derived from the theory of natural evolution. GAs simulate mechanisms of population genetics and natural rules of survival in pursuit of the ideas of adaptation and use a vocabulary borrowed from natural genetics. To surpass the traditional methods, GAs must differ in some very fundamental ways. Goldberg (1989) identifies the following as the significant differences between GAs and more traditional optimisation methods. GAs

- work with a coding of the parameter set, not the parameter themselves;
- search from a population of points, not a single point;
- use objective function information, not derivatives or other auxiliary knowledge;
- use probabilistic transition rules, not deterministic rules.

A GA is a robust method of searching for the optimum solution to a complex problem. It is basically an automated intelligent approach to find a solution to a problem, although it may not necessarily lead to the best possible one. Consider an optimisation problem with 100 parameters with each parameter taking on 100 values. The number of possible combinations of parameters would be 100^{100} . Since the search space is huge, it is not possible to quickly enumerate all the possible solutions. In the past, such problems were tackled by making intelligent guesses about the values of the parameters and a solution obtained by trial and error procedure. But with the advent of GAs, a fairly good solution to such problems can be found within an affordable computing time. A GA represents a solution using strings of variables that represent the problem. In biological terminology such strings are also known as chromosomes or individuals. Coding components of possible solutions into a chromosome is the first part of a GA formulation. Each chromosome is a potential solution and comprises of sub-strings or genes representing decision variables which can be used to evaluate the objective function of the problem. The fitness of a chromosome as a candidate solution to a problem is an expression of the value of the objective function represented by it. It is obtained using an evaluation function, which is a link between the GA and the problem to be solved. The fitness is also a function of problem constraints and may be modified through the introduction of penalties when constraints are not satisfied. A GA starts with a set of chromosomes representing potential solutions to the problem. These chromosomes are combined through genetic operators to produce successively fitter chromosomes. The genetic operators used in the reproductive process are selection, crossover, and mutation. Combination is achieved through the crossover of pieces of genetic material between selected chromosomes. Chromosomes in the population with high fitness values have high probability of being selected for combination with other chromosomes of high fitness. Mutation allows for the random mutations of bits of information in individual genes. The fitness of chromosomes should progressively improve over the generations. The whole GA procedure is allowed to evolve for a sufficient number of generations, and at the end of the evolution process a chromosome representing an optimal (or a near optimal) solution to the problem should be obtained.

6. Simulation

Simulation is a modelling technique used to approximate the behaviour of a system on a computer, representing all the characteristics of the system largely by a mathematical or algebraic description. Simulation models provide the response of the system to certain inputs, which include decision rules that allow the decision makers to test the performance of existing systems or a new system without actually building it. A typical simulation model for a water resources system is simply a model that simulates the interval-by-interval operation of the system with specified inflows at all locations during each interval, specified system characteristics and specified operating rules. Optimisation models aim to identify optimum decisions for system operation that maximises certain given objectives while satisfying the system constraints. On the other hand, simulation models are used to explore only a finite number of decision alternatives so that the optimum solution may not necessarily be achieved. However, many simulation models now involve a certain degree of optimisation and the difference between the optimisation and simulation models is becoming less distinct. For a given operating criteria, the performance of a reservoir system may be evaluated by analysing the computed time sequence of levels, storage, discharges, hydropower etc. The procedure can be repeated for a number of inflow sequences to arrive at a statistical measure of the system. Simulation models have been routinely applied for many years by water resource development agencies. Yeh (1985) and Wurb (1993) present reviews of a number of such models. An excellent treatment of the subject of computer simulation in hydrology has been provided by Fleming (1975). A total of 19 simulation models have been presented in the text. The

background and structure of each model is discussed, and the functions used to represent the major processes involved are described. The input/output requirements and the range of application of models are also discussed. Simulation models have also been extensively used in combination with optimisation models. Karamouz and Houck (1982) describe an algorithm that cycles through an optimisation model, a regression analysis and a simulation model to develop reservoir operating rules. Labadie et al. (1987) presents an application of a simulation model in estimating the reliable power capacity of a reservoir system. Recently, researchers have tried to incorporate optimisation methods within the simulation models. Wardlaw (1993) has developed a simulation model which incorporates economic functions for hydropower, agriculture and fisheries production. The model was used to assess the economics of alternative strategies for water resources development in the Brantas Basin in Indonesia. Jain et al. (1998) describe the application of a simulation model to reservoir operation studies of Sabarmati system in India. Operating procedures were derived for all the four reservoirs of the system.

III. RESERVOIR OPERATIONS UNDER CLIMATE CHANGE

Due to changes in spatial and temporal availability of water at reservoir sites, reservoir management is likely to be influenced. Several studies have been conducted to evaluate hydrological impacts of climate change on watersheds in different parts of the world. Applications of optimization techniques to derive reservoir operating rules have been described by many researchers (e.g., Oliveira and Loucks 1997; Sharif and Wardlaw, 2000; Tu et al. 2003). Applications describing the impacts of climate change on reservoir operations are, however, very few. Klemes (1985) performed an assessment of the anticipated sensitivity of water resource systems to climatic variations, and found that (a) decrease in reliability might occur much faster than any decrease in precipitation or increase in evaporation losses; (b) the impact of drier climate would be more severe where the present level of development is high than where it is low; and (c) the relative effect of the precipitation change would probably be greater than that of the evapo-transpiration change. Burn and Simonovic (1996) investigated the potential impacts of changing climatic conditions on the operational performance of water resource systems. Reservoir operation was carried out for two potential monthly flow sequences reflecting two different sets of climatic conditions. Reliability (the probability of success) and resilience (a measure of how quickly the reservoir will recover from a failure) criteria were used to show that, despite moderate changes in inflow characteristics, the values of the performance criteria are substantially impacted. It was concluded that the reservoir performance was sensitive to the inflow data. More recently, Minville et al. (2010) evaluated the impacts of climate change on medium-term reservoir operations for the Peribonka water resource system. The results of simulations clearly indicated the tendency for reduction in mean annual hydropower production and an increase in spills, despite an increase in the annual average inflow to the reservoirs. This reduction was partly attributed to the impacts of climate change. Whitfield and Cannon (2000) analyzed recent (1976-1995) climatic and hydrological variations in Canada and found that even small changes in precipitation and temperature considerably affect river discharges. Christensen et al. (2004) claimed that statistically insignificant changes in the inflows would have large impacts on reservoir storage. Consequently, reservoir operation procedures are likely to be impacted.

REFERENCES

- [1]. Allen, R. B., and Bridgeman, S. G. (1986). "Dynamic programming in hydropower scheduling." *Journal of Water Resour. Plang. and Mgmt.*, ASCE, 112(3), 339-353.
- [2]. Becker, L., and Yeh, W-G. W. (1974). "Optimization of real time operation of multiple-reservoir system." *Water Resour. Res.*, 10(6), 1107-1112.
- [3]. Becker, L., Yeh, W-G. W., Fults, D., and Sparks, D. (1976). "Operations models for the Central Valley Project." *Journal of Water Resour. Plang. and Mgmt.*, ASCE, 102(WR1), 101-115.
- [4]. Bellman, R. (1957). "Dynamic programming". Princeton University Press, Princeton, New Jersey.
- [5]. Burn, D. H., and Simonovic, S. P. (1996). "Sensitivity of reservoir operations performance to climatic change". *J. Water Resource Management*, 10,463-478.
- [6]. Chen, L., (2003), Real time genetic algorithm optimization of long term reservoir operation. *Journal of the American Water Resources Association* 39(5): 1157-1165.
- [7]. Christensen, N. S., Wood, A. W., Voisin, N., Lettenmaier, D. P., and Palmer, R. N. (2004). "The effects of climate change on the hydrology and water resources of the Colorado River basin". *J. Climate Change*, 62, 337-363.
- [8]. Collins, M. A. (1977). "Implementation of an optimization model for operation of a metropolitan reservoir system." *Water Resour. Bull.*, 13(1), 57-70.
- [9]. Crawley, P. D., and Dandy, G. C. (1993). "Optimal operations of multiple-reservoir systems." *J. Water Resour. Plang. and Mgmt.*, ASCE, 119(1), 1-17.
- [10]. Darwin, C. (1859). "Origin of species".
- [11]. Dasgupta. and Michalewicz, Z. (1997). *Evolutionary algorithms in engineering applications*. Springer- Verlag, Berlin, Germany.
- [12]. Davis, L. (1991). *Handbook of genetic algorithms*. Van Nostrand, Reinhold.
- [13]. Diaz, G. E., and Fontane, D. G. (1989). "Hydropower optimization via sequential quadratic programming." *J. Water Resour. Plang. and Mgmt.*, ASCE, 115(6), 715-733.
- [14]. Dorfman, R. (1962). *Mathematical models: The multistructure approach*, in *Design of water resources systems*, A. Maass, ed., Harward University Press, Cambridge, Mass.
- [15]. Fleming, G. (1975). *Computer simulation techniques in hydrology*. Elsevier, New York.
- [16]. Gilbert K. G. and Shane, R. M. (1982). "TVA Hydro Scheduling Model: Theoretical Aspects". *Journal of Water Resources Planning and Management*, ASCE, Vol. 108, No. 1, pp. 1-20.
- [17]. Goldberg, D. E. (1989). *Genetic algorithms in search, optimization and machine learning*. Addison-Wesley, Reading, Mass.

- [18]. Grygier, J. C., and Stedinger, J. R. (1985). "Algorithms for optimizing hydropower system operation." *Water Resour. Res.*, 21(1), 1-10.
- [19]. Guariso, G., Rinaldi, S. and Soncini-Sessa, R., (1986), The management of Lake Como: A multiobjective analysis. *Water Resources Research* 22(2): 109-120.
- [20]. Guibert, J. A. T., Stedinger, J. R., and Staschus, K. (1990). "Optimization of value of CVP's hydropower production." *J. Water Resour. Plang. and Mgmt.*, ASCE, 116(1), 52-70.
- [21]. Hall, W. A., and Buras, N. (1961). "The dynamic programming approach to water resources development." *J. Geophys. Res.*, 66(2), 510-520.
- [22]. Hall, W. A., Harboe, W., Yeh, W. W-G., and Askew, A. J. (1969). "Optimum firm power output from a two reservoir system by incremental dynamic programming." *Water Resour. Center Contrib.*, University of Calif., 130, 273-282.
- [23]. Heidari, M., Chow, V. T., Kokotovic, P. V., and Meredith, D. D. (1971). "Discrete differential dynamic programming approach to water resources systems optimization." *Water Resour. Res.*, 7(2), 273-283.
- [24]. Hiew, K.L. (1987). "Optimization algorithms for large scale multireservoir hydropower systems." Ph.D thesis, Colorado State Univ., Fort Collins, Colo.
- [25]. Holland, J. H. (1975). *Adaptation in natural and artificial systems*. MIT Press, Cambridge, Mass.
- [26]. Howson, H. R., and Sancho, N. G. F. (1975). "A new algorithm for the solution of multistate dynamic programming problems." *Math. Programming*, 8(1), 104-116..
- [27]. Jain, S. K., Goel, M. K., and Agarwal, P. K. (1998). "Reservoir operation studies of Sabarmati system, India." *J. Water Resour. Plang. and Mgmt.*, ASCE, 124(1), 31-38.
- [28]. Jacobson, D. H. and D. Q. Mayne. (1970). *Differential dynamic programming. Modern analytic and computational methods in Science and Mathematics*, No. 24. American Elsevier Publ. Co., Inc., New York. XVI, 208 S., 17 Abb., Dfl. 51.50.
- [29]. Karamouz, M., and Houcks, M. H. (1982). "Annual and monthly reservoir operating rules." *Water Resour. Res.*, 18(5), 1333-1344.
- [30]. Klemes, V. (1985). Sensitivity of water resource systems to climatic variations, World Climate Program Report, WCP-98, WMO, 115 pp.
- [31]. Labadie, J. W., Fontane, D. G., Tabios, G. Q., and Chou, N. F. (1987). "Stochastic analysis of dependable hydropower capacity." *J. Water Resour. Plang. and Mgmt.*, ASCE, 113(3), 422-437.
- [32]. Larson, R. E. (1968). *State increment dynamic programming*, American Elsevier, New York.
- [33]. Lee, E. S., Waziruddin, S. (1970). "Applying gradient projection and conjugate gradient to the optimum operation of reservoirs." *Water Resour. Bull.*, 6(5), 713-724.
- [34]. Li, G., and Mays, L. W. (1995). "Differential dynamic programming for estuarine management." *J. Water Resour. Plang. and Mgmt.*, ASCE, 121(6), 455-462.
- [35]. Loucks, D. P., Stedinger, J. R., and Haith, D. (1981). *Water resources systems planning and analysis*, Prentice Hall, Englewood Cliffs, N. J.
- [36]. Marino, M. A., and Mohammadi, B. (1983). "Reservoir operation by linear and dynamic programming." *J. Water Resour. Plang. and Mgmt.*, ASCE, 109(4), 303-319.
- [37]. Marino, M. A., and Loaiciga, H. A. (1985a). "Dynamic model for multireservoir operation." *Water Resour. Res.*, 21(5), 619-630.
- [38]. Marino, M. A., and Loaiciga, H. A. (1985b). "Quadratic model for reservoir management: application to the Central Valley Project." *Water Resour. Res.*, 21(5), 631-641.
- [39]. Martin, Q. W. (1995). "Optimal reservoir control for hydropower on Colorado River, Texas." *J. Water Resour. Plang. and Mgmt.*, ASCE, 121(6), 438-446.
- [40]. Mays, L. W., and Tung, Y. K. (1992). *Hydrosystems engineering and management*. McGraw-Hill Book Co., Inc., New York.
- [41]. Michalewicz, Z. (1992). *Genetic Algorithms + data Structures = evolution programs*, Springer-Verlag, New York, Inc., New York.
- [42]. Minville, M., Brissette, F., Leconte, R. (2010). "Impacts and uncertainty of climate change on water resource management of the Peribonka River System (Canada) ". *J. Water Resource Planning and Management*, 136(3), 376-385.
- [43]. Murray, D. M., and Yakowitz, S. (1979). "Constrained differential dynamic programming and its application to multireservoir control." *Water Resour. Res.*, 15(5), 1017-1027.
- [44]. Nopmongcol, P., and Askew, A. J. (1976). "Multilevel incremental dynamic programming." *Water Resour. Res.*, 12(6), 1291-1297.
- [45]. Oliveira, R., and Loucks, D. P. (1997). "Operating rules for multireservoir systems." *Water Resour. Res.*, 33(4), 839-852.
- [46]. Ozden, M. (1984). "A binary state DP algorithm for operation problems of multireservoir systems." *Water Resour. Res.*, 20(1), 9-14.
- [47]. Palmer, R. N., and Holmes, K. J. (1988). "Operational guidance during droughts: Expert system approach." *J. Water Resour. Plang. and Mgmt.*, ASCE, 114(6), 647-666.
- [48]. Pontryagin, L. S., Boltyanskii, V., Gamkrelidze, R., and Mishchenko, E. (1962). *The mathematical theory of optimal processes*. Wiley-Interscience, New York.
- [49]. Randall, D., Houck, M. H., and Wright, J. R. (1990). "Drought management of existing water supply system." *J. Water Resour. Plang. and Mgmt.*, ASCE, 116(1), 1-20.

- [50]. Reznicek, K. K., and Simonovic, S. P. (1990). "An improved algorithm for hydropower optimization." *Water Resour. Res.*, 26(2), 189-198.
- [51]. Rosenthal, R. E. (1981). "A nonlinear flow algorithm for maximization of benefits in a hydroelectric power system." *Oper. Res.*, 29(4), 763-786.
- [52]. Sharif, M., and Wardlaw, R. (2000). "Multi reservoir systems optimization using genetic algorithms". *J. Computing in Civil Engineering*, 14(4), 255-263.
- [53]. Shane, R. M., and Gilbert, K. C. (1982). "TVA hydro scheduling model: Practical aspects." *J. Water Resour. Plang. and Mgmt.*, ASCE, 108(1), 21-36.
- [54]. Simonovic, S. P. (1992). "Reservoir systems analysis: Closing gap between theory and practice." *J. Water Resour. Plang. and Mgmt.*, ASCE, 118(3), 262-280.
- [55]. Simonovic, S. P., and Marino, M. A. (1980). "Reliability programming in reservoir management, 1. Single multipurpose reservoir." *Water Resour. Res.*, 16(5), 844-848.
- [56]. Takeuchi, K., and Moreau, D. H. (1974). "Optimal control of multiunit interbasin water resource system." *Water Resour. Res.*, 10(3), 407-414.
- [57]. Trott, W. J., and Yeh, W. W.G. (1973). "Optimization of multiple reservoir system." *J. Hydraul. Div.*, ASCE, 99(HY10), 1865-1884.
- [58]. Tu, M.-Y., Hsu, N. S., and Yeh, W. W. G. (2003). "Optimization of reservoir management and operation with hedging rules". *J. Water Resource Planning and Management*, 129(2), 86-97.
- [59]. Turgeon, A. (1981b). "A decomposition method for the long-term scheduling of reservoirs in series." *Water Resour. Res.*, 17(6), 1565-1570.
- [60]. Turgeon, A. (1982). "Incremental dynamic programming may yield nonoptimal solutions." *Water Resour. Res.*, 18(6), 1599-1604.
- [61]. Wardlaw, R. B. (1993). "Water resources systems modelling for the Brantas Basin in East Java." *Proc.*, 4th National Hydrology Symposium, Univ. of Wales, Wales, United Kingdom.
- [62]. Wardlaw, R. B., Moore, D. N., and Barnes, J. M. (1997). *An assessment of the potential of optimisation in real time irrigation management, in Water: Economics, management and Demand*, M. Kay, T. Franks, and L. Smith, eds., Chapman and Hall, London.
- [63]. Wardlaw and Sharif (1999), "Evaluation of genetic algorithms for optimal reservoir system operation", *J. water resource planning management*. 125(1), 25-33.
- [64]. Whitfield, P.H., and Cannon. A.J. (2000). "Recent variation in climate and hydrology in Canada" *.Can. Water Resour. J.*, 25(1), 19-65.
- [65]. Wurbs, R. A. (1993). "Reservoir-system simulation and optimization models." *J. Water Resour. Plang. and Mgmt.*, ASCE, 119(4), 455-472.
- [66]. Xu, C. Y., and Singh, V. P. (2004). "Review on regional water resources assessment models under stationary and changing climate". *J. Water Resource Management*, 18, 591-612.
- [67]. Yakowitz, S. (1982). "Dynamic programming applications in water resources." *Water Resour. Res.*, 18(4), 673-696.
- [68]. Yeh, W. W.G., Becker, L., and Chu, W. S. (1979). "Real time hourly reservoir operation." *J. Water Resour. Plang. and Mgmt.*, ASCE, 105(WR2), 187-203.
- [69]. Yeh, W. W.G., and Becker, L. (1982). "Multiobjective analysis of multireservoir operations." *Water Resour. Res.*, 18(5), 1326-1336.
- [70]. Yeh, W. W.G. (1985). "Reservoir management and operation models: A state-of-the-art review." *Water Resour. Res.*, 21(12), 1797-1818.
- [71]. Young, G. K. (1967). "Finding reservoir operating rules." *J. Hydr. Div.*, ASCE, 93(HY6), 297-321.