OPTIMAL OPERATIONAL RULES FOR RESERVOIRS: USE OF STOCHASTIC DYNAMIC PROGRAMMING AND GENETIC ALGORITHMS

by

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Abstract

Stochastic dynamic programming technique has been very widely used in optimal management of water resource schemes compared with genetic algorithms. This may be due to the comparatively recent development of genetic algorithm technique. The paper shows the applicability of both techniques in the derivation of optimum operating policies for a reservoir in a multi-purpose water resource system. The system comprises two reservoirs, viz., Samanalawewa reservoir and Udawalawe reservoir, built to harness the hydropower and irrigation potentials of the Walawe River in Sri Lanka. The recently completed Samanalawewa reservoir primarily generates hydropower while the Udawalawe reservoir, which was built in 1960s, supplies water mainly for irrigation. The objective function adopted in the derivation of operation rules is to minimize squared deviation of total system hydro-energy generation from a target. Irrigation demands are treated as constraints. The system was simulated with the developed operation rules by both methods for a period of six years for which actual operational pattern is available. The comparison of the performance indicates that the operation rules obtained from above two methods perform better than the actual operation, while GA based rules are the best.

Introduction

Reservoir system operations are complex and often offer substantial increases in benefits for relatively small improvements in operating efficiency. Reservoir operation involves determining decision policies, which will optimize certain objectives subject to various constraints. During the last several decades many attempts have been made towards determining optimum reservoir operating policies by various mathematical methods such as Linear Programming, Non-Linear Programming, Dynamic Programming techniques and simulation technique (Wurbs, 1993).

Samanalawewa and Udawalawe are two reservoirs built along the Walawe River in Sri Lanka to harness its hydropower and irrigation potentials. The Samanalawewa reservoir was built mainly for hydropower generation while the Udawalawe reservoir supplies water for the Walawe irrigation scheme. The Udawalawe reservoir commenced operation in 1967 while the Samanalawewa reservoir, which is situated upstream of the Udawalawe reservoir, started functioning in 1998. The Samanalawewa reservoir can provide additional storage for the Walawe irrigation scheme, potentially increasing the irrigable area.

An effective strategy for analyzing many reservoir operation problems will involve a combination of both optimization and simulation techniques. Stochastic dynamic programming (SDP) has been accepted as a suitable optimization technique in such studies and its applications are numerous. This paper initially presents the derivation of optimum operating policies for the reservoirs built along the Walawe River using a model developed based on SDP and simulation techniques.

Genetic Algorithms (GAs) introduced by Holland, (1975), and developed by Goldberg (1989), is a powerful optimization approach, which has a potential in water resources system analysis. McKinney and Lin, (1994), applied GAs in the management of groundwater models. Simpson et al, (1994), used GAs in optimization of pipe networks. Savic and Walters, (1997), developed a computer model for least cost design of water distribution networks. However, GAs have very little application in reservoir system optimization. East and Hall, (1994), Kumari, (1995), Oliveira and Loucks, (1997), are a few applications of GA in reservoir operational problems reported in literature.

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Secondly, this paper presents an application of GAs in the derivation of optimum operating rules for reservoirs built along the Walawe River. Finally, it compares the performance of the system obtained by operating the reservoir according to the SDP based operational policies and GA based operational policies with the actual (historical) operation.

Stochastic Dynamic Programming Based Model

A model called "ShellDP" (Bogardi et al, 1995), which was developed based on SDP and simulation techniques for analyzing multiunit reservoir systems, is used in the study. Nandalal and Ampitiya, (1997), and Nandalal, (1998), used this model to derive operation policies for reservoirs in two different water resources development schemes in Sri Lanka.

The direct application of SDP for two reservoirs is limited by dimensionality of the problem. Therefore, a sequential decomposition method is employed in the model. The algorithm employed decomposes the system into single reservoir sub-systems and subsequently, each subsystem's operation is individually optimized using a SDP based optimization model and then simulated using a reservoir operation simulation model. The algorithm is essentially an iterative procedure. One iteration cycle comprises optimization and simulation of operation of each reservoir within the system. These iterations are repeated until the solution converges to a stable optimal solution.

The procedure starts by optimizing the performance of the upper reservoir of the system. The operation policy derived for that reservoir is then used to simulate its performance over the period for which hydrological data are available. The sequence of releases from the reservoir is one of the results from this simulation. These releases represent the volume of water available for downstream after supplying all the demands. These volumes of water released (defined as free downstream releases) are added to the inflows (inflow from the catchment lying in between reservoirs to the downstream reservoir) to estimate the total inflow to the downstream reservoir.

Then the optimization and simulation of the downstream reservoir are carried out similar to the previous one, which concludes one iteration. Data transfer between two consecutive iterations consists of sets of reservoir water shortages obtained by simulation in the preceding computational step.

Optimization

The core of the method is the SDP-based optimization algorithm. The SDP algorithm employed is a variation of the one given by Loucks et al, (1981). The procedure derives the optimal, expectation oriented, long-term operational strategy for a single reservoir. Due to the nature of dynamic programming, (DP), all state and decision variables are represented in their respective discrete domains. A month is considered as one stage in the present study. The state of the system (reservoir) is the volume of water stored at the beginning of a stage. Uncertainty in inflow is explicitly incorporated into the optimization procedure with inflow to a reservoir being represented by a set of class intervals with their respective independent or transitional probabilities being considered as an additional state variable in the SDP-based optimization procedure. Thus, whether the inflows are considered to be random or Markovian, the system's state is described by two state variables, reservoir storage at the beginning of the month, and the inflow to the reservoir during the month.

Objective Function

The objective function is to minimize the expected value of annual sum of squared deviation between a targeted energy and the energy generated (single sided), with the constraint of satisfying the irrigation demand. This objective function can be mathematically formulated as:

$$OF = Minimize\ \xi\left[\sum_{j=1}^{N}\left(Eng_{trg,j} - Eng_{gen,j}\right)^2\right]$$

where,

$Eng_{gen,j}$ = system energy generation during time period j,

$Eng_{trg,j}$ = system energy target during time period j,

j = time period, and

N = total number of time periods.

The optimisations are subjected to constraints in reservoir storage volume and release. The state transformation equation is based on the principle of continuity of the reservoir. The system energy generation is the total hydro energy generated at the power plant at the Samanalawewa and two power plants at the Udawalawe reservoir.

Operational Policy for the Reservoirs

The decision to be taken at each stage within one annual cycle is the storage volume of the reservoir at the end of the time interval. Thus, the operating policy is defined for each month and is expressed in terms of the optimal decision to be taken as a function of system states.

Simulation

Once an operational strategy is defined, simulation is carried out to assess and to incorporate the effects of the reservoir's performance into the operation of the system as a whole. The simulation is carried out over the total historical record of inflow. The role of simulation in the approach is two fold:

i) It is used to evaluate the effectiveness of a reservoir's operating policy.

ii) In conjunction with release allocation algorithm, simulation provides necessary information on the interaction among reservoirs (i.e., expected levels of each individual demand fulfilment and deficit, additional flows available to reservoir situated downstream on the river course and shortages in supply that a reservoir is going to encounter by following the derived operating policy).

Genetic Algorithm Based Model

Genetic Algorithms, (GA), can be viewed as search techniques. These algorithms are based on the processes of natural selection (survival of fittest) that have been theorized as the primary rule of Darwinian evolution. GAs reflect this basis both by their method of operation and by the terminology that has been associated with the procedures used by the algorithm itself. GAs rely on randomness or probabilistic rules to transform solution states. They operate on solution sets, not individual solutions themselves. They utilize evolution functions (or objective functions) to rate the "survivability" or goodness of sets of solutions. Also, GAs do not perform calculations with the parameters of a solution directly, they work with symbolic representations or encoding of these parameters called strings. Simple GAs are based on three operators and an evaluation function. The three operators are commonly referred to as the reproduction operator, the crossover operator and the mutation operator.

Working Principle of Genetic Algorithms

A nonlinear optimization problem is solved using GAs involving basically three tasks viz., coding, fitness evaluation and genetic operation. Initially, decision variables are identified from a given optimization problem. These decision variables are coded into some string like structures. For coding the decision variables binary coding is used. This coded string is called Chromosome. The length of the chromosome depends on the desired accuracy of the solution.

Generally, the fitness function is first derived from objective function and is used in successive genetic operations. The fitness function value of a string is known as the string's fitness. Once the fitness of each string is evaluated, the population is operated by three common operators for creating new population of points. They are reproduction, crossover and mutation. Reproduction selects good strings in a population and forms a mating pool. In this work Roulette wheel simulation is used for the selection of good strings. In crossover operation, two strings are picked from the mating pool at random and some portions of the strings are exchanged between the strings. A single point cross over operation is performed by randomly choosing a crossing site along the string and by exchanging all bits on the right side of the crossing site. The mutation operator changes 1 to 0 and 0 to 1 with a small mutation probability within the string. Mutation creates points in the neighbourhood of the current point, which helps in local search around the current solution. It is also used to maintain diversity in the population.

The newly created population using the above operators is further evaluated and tested for termination. If the termination criterion is not met, the population is iteratively operated by the above mentioned three GA operators and evaluated. This process is continued until termination criterion is met. One cycle of these operations and the subsequent evaluation procedure is known as a generation.

Objective Function

The objective of the system operation is to minimize the squared deviation between the hydro-energy generation and an energy generation target during the whole operational period with the constraint of satisfying the irrigation demands. It is expressed in mathematical terms as,

$$O.F. = Mininize \sum_{j=1}^{N} \left(Eng_{irg,j} - Eng_{gen,j}\right)^2$$

The optimization is subjected to the principle of continuity of the system and the constraints on allowable discharges and reservoir storages for both reservoirs.

Operational rules for the Samanalawewa reservoir

The decision variables are the monthly releases from the Samanalawewa reservoir. The release from the reservoir at month j (Relj) is considered as a function of the reservoir storage at the beginning of the month (S,j) and the inflow to the reservoir during the month (Ij) as shown below. The parameters (1,j, (2,j, (1,j and (2,j in the release equations are determined by the GA model.

$$Rel_j = \alpha_{1,j} S_j^{\beta_{1,j}} + \alpha_{2,j} I_j^{\beta_{2,j}} \quad ; \qquad for\ j=1,2,3,....,12$$

In the GA model, there are forty-eight variables (4(12 months) or genes (each variable is called a gene) and a gene is represented by a 6-bit binary number. Therefore, the chromosome in the GA, which contains forty-eight genes, consists of 288 binary digits. The fitness function in the GA model is the objective function mentioned earlier. The GA makes selection according to the fitness of each individual with a probability proportional to its fitness. The combined evaluation and selection process, which is called the reproduction phase of the GA, individuals are selected from the population and recombined producing offspring. These will comprise the next generation. Having selected two parents, their chromosomes are recombined typically using the mechanisms of "crossover" and "mutation". A gene converges when 95% of the population share the same value. The population is said to have converged when all of the genes have converged. As the population converges, the average fitness will approach that of the best individual.

Operation of the Udawalawe reservoir

In the GA model, the Udawalawe reservoir operation was assumed as follows: The reservoir supplies irrigation demand fully if water is available in the reservoir. If the amount of water available in the reservoir is less than the demand, the amount that could be supplied is released subject to the constraint on minimum operating level. If the reservoir is full after supplying the demand water is further released upto the outlet capacity. If the storage exceeds the full capacity level after doing so, the excess will spill.

Reservoir System

The Walawe River basin is located in the south of Sri Lanka and has a drainage area of about 2,442 km2. Average rainfall over the catchment is about 1750 mm/year. This river drains to the sea close to the town of Ambalantota.

The top most Samanalawewa reservoir on the Walawe River supplies irrigation water to the Kaltota irrigation scheme of an area about 870 ha located just downstream of it, in addition to generating hydropower. The Udawalawe reservoir supplies irrigation water to downstream lands located on both banks of the river through right and left bank canals. This water passes through two small hydropower plants built at the Udawalawe dam. The total land area irrigated on the right bank is about 11,400 ha. while that on the left bank is about 6,110 ha. Development of additional land for irrigation of about 5,340 ha. has been commenced on the left bank. Liyangastota diversion weir is the most downstream water resource development scheme on the Walawe River. It diverts Walawe River water for irrigation supply to the Ridiyagama irrigation scheme. Figure 1 presents the schematic diagram of the system while Table 1 gives the features of the reservoirs in the system.

Table 1 Salient features of the reservoirs in the system

Samanalawewa Reservoir	
Full supply level (FSL)	460.0 m MSL
Minimum operating level (MOL)	424.0 m MSL
Storage at FSL	298.0x106 m³
Storage at MOL	60.0 $\times 10^6$ m³
Tailwater level - unit 1	116.4 m MSL
Tailwater level - unit 2	117.2 m MSL
Samanalawewa Power House	
Number of turbine units	2 Francis
Maximum flow	40.20 m3/s
Maximum head loss	8.90 m
Maximum power supply	120 MW (60 MW x 2)
Udawalawe Reservoir	
High flood level	90.21 m MSL
Full supply level (FSL)	88.39 m MSL
Minimum operating level (MOL)	74.98 m MSL
Storage at FSL	268.76 $\times 10^6$ m³
Storage at MOL	28.26 $\times 10^6$ m³
Udawalawe Power House - Right Bank	
Type	Kaplan vertical
Installed capacity	1.8 MW
Minimum operating elevation	79.4 m MSL
Udawalawe Power House - Left Bank	
Type	Kaplan vertical
Installed capacity	3.6 MW
Minimum operating elevation	79.4 m MSL

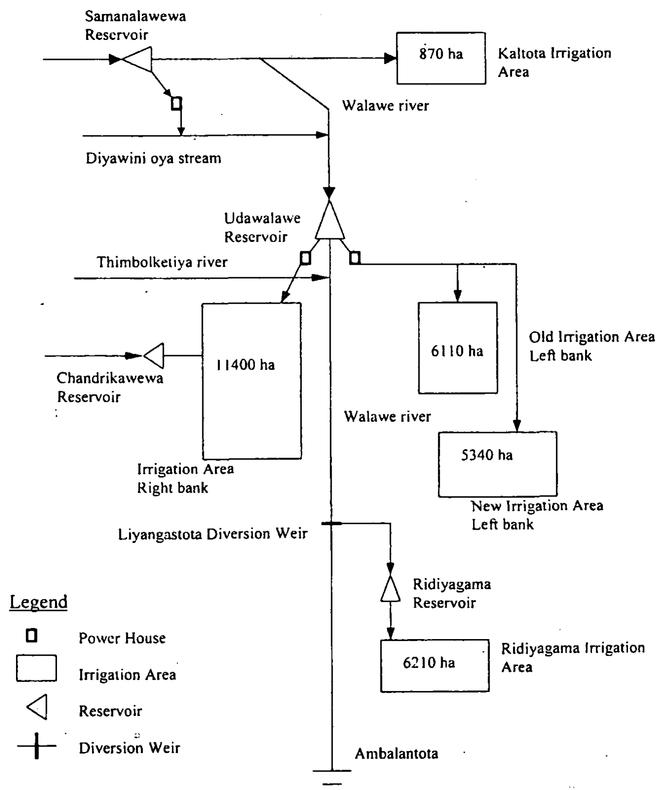

Figure 1 Schematic diagram of the system

Analysis and Results

SDP based operation policies

The model ShellDP was used to derive operation policies for the Samanalawewa and Udawalawe reservoirs based on a 37-year long record of monthly streamflow data (1950-1986).

The irrigation demands estimated for the Feasibility Study on Walawe Irrigation Upgrading and Extension Project (JICA, 1992), presented in Table 2 are used in the derivation of operational policies. The demands are treated as deterministic. Since considerable amounts of water supplied to the right and left bank contour canals enter the Walawe River as return flow, the study assumes that the return flow from the Walawe Scheme along with the Thimbolketiya river flow, which enters the Walawe River downstream of the Udawalawe reservoir, satisfy the Liyangastota irrigation demands. This assumption is in line with the present operational practices of the Walawe reservoir system. Therefore, the Liyangastota demands are not added to the water demand to be supplied by the Udawalawe reservoir. The model, which considers the stochasticity of the inflows, computes their probability distributions by employing monthly inflow data series.

The operation policy designated for a reservoir by the model is a set of rules specifying the storage level at the beginning of the next month for each combination of storage levels at the beginning of the current month and the inflow during the current month. This results in a policy matrix for each month specifying storage level in terms of stage of storage and inflow. For the two reservoirs studied, the optimal operational policy prescriptions resulted in 24 tables in matrix form. As such, they are not presented in this paper.

GA based operation policies

Initially, the GA model was run for a period of one year for different values of crossover and mutation probability to fix the GA parameters, crossover probability and mutation probability.

Sensitivity of crossover probability was studied using a population size of 100 and a mutation probability of 0.05. Crossover probabilities from 0.5 to 0.95 were considered through runs with a fixed length of 2000 generations and the value of 0.85 was observed as the best. To determine the sensitivity of mutation probability, a crossover probability of 0.85 was used with all other parameters and run controls as given before. The model was run varying mutation probability in the range from 0.001 to 0.06 and the value 0.05 was chosen since it gave the best results.

Once the GA parameters were fixed, the GA model was run for a period of 10 years from 1976 to 1985 to obtain the optimum parameters in the release equation for the Samanalawewa reservoir. In the run the population size was 10 while the number of generations were 2000. The crossover probability and mutation probability were 0.85 and 0.05, respectively. The optimum was reached after six cycles and at that time 98% of the population shared the same value. Table 3 presents the optimum values of the parameters obtained from the GA model.

Table 2 Irrigation demands of the system in 106m³

Month	Kaltota Scheme	Walawe Right Bank	Walawe Left Bank
January	5.14	49.60	37.75
February	0.46	54.20	26.29
March	4.27	23.00	29.44
April	8.90	19.50	46.46
May	5.02	48.80	32.81
June	6.23	50.10	38.75
July	4.17	59.80	37.36
August	0.00	34.80	17.23
September	0.00	4.10	11.16
October	7.66	22.70	35.71
November	6.23	34.20	24.31
December	4.19	34.40	18.89
Total	52.27	435.20	356.17

Table 3 Parameters in the release equation obtained from the GA model

Coeff.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\alpha1,j$	0.476	0.603	0.492	0.254	0.333	0.016	0.111	0.714	0.460	0.921	0.905	0.667
$\alpha2,j$	0.683	0.587	0.651	0.952	0.762	0.683	0.349	0.730	0.857	0.143	0.810	0.762
$\alpha1,j$	0.683	0.857	0.968	0.508	0.238	0.825	0.413	0.714	0.032	0.746	0.349	0.381
$\alpha2,j$	0.730	0.429	0.349	0.460	0.063	0.683	0.206	0.317	0.206	1.000	0.333	0.730

Comparison of the SDP based and GA based operations with the actual operation

The system operation was simulated from 1994 to 1999 using the developed monthly release rules for the Samanalawewa reservoir by both methods. The operation policy adopted for the Udawalawe reservoir was the same as that used in the GA model.

The resulting operations were compared with the actual system operation during the same period based on hydro-energy generation. Figure 2 compares the total annual hydro-energy generations from the Samanalawewa hydropower plant. Though the hydro-energy generations obtained from the GA based operation are lower than actual generations in 1994 and 1997, the total generation during the whole period of six years is the highest with the GA based operation. The total actual energy generation during the six years period is about 1667GWh while it is 1744GWh with the GA based operation. This is an increase of about 5%. The total energy generation with SDP based operation during this period is 1715GWh.

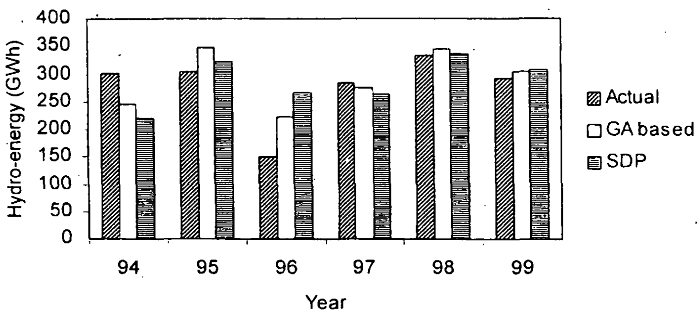

Figure 2 Comparison of hydro-energy generations - Samanalawewa reservoir

The comparison of the reservoir behaviour is presented in Figure 3. GA based operation keeps the Samanalawewa reservoir level higher compared to the actual operation. The SDP based operation and GA based operation are close to each other most of the time. There was no spill observed during this period from the Samanalawewa reservoir with all the different operations. Further, the Samanalawewa reservoir satisfies the Kaltota irrigation demand totally during the whole period.

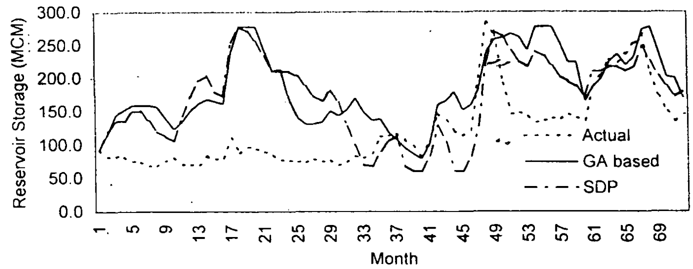

Figure 3 Variation of the Samanalawewa reservoir storage

The results indicated that the Udawalawe reservoir could supply the Walawe left bank and right bank irrigation demands without any failure throughout the total period of six years. The total water spilled from the Udawalawe reservoir during the whole period is about $2085x10^6m^3$ in the actual operation, while it has reduced to $657x10^6m^3$ with the GA based operation. The spill from the Udawalawe reservoir is only $413x10^6m^3$ with the SDP operation.

Conclusions

The operational behaviour of a water resources system that consists of two reservoirs in series, the Samanalawewa reservoir and the Udawalawe reservoir were analyzed in this study. The first model applied is based on SDP and simulation techniques. To handle the two-reservoir system, a decomposition approach was employed. The operational policy developed for each reservoir is a set of rules specifying the storage at the beginning of the next month for each combination of storage levels at the beginning of the current month and the inflow during the current month. As such the total optimal operational policy prescriptions for the year resulted in 12 tables in matrix form for a reservoir.

The second model developed based on GA shows its applicability in the derivation of operation rules for a reservoir in a water resources system. A reservoir operator could very conveniently use the resulting simple operational rules, which are in equation format expressing release during a month as a function of reservoir storage at the beginning of the month and the inflow during the month. Further, the performance of the system has been a little improved, with respect to energy generation from the reservoir, when it is operated according to the GA based operation rules.

The development of the GA based model needed less effort compared to the development of the SDP based model, which is a combination of SDP, simulation and a decomposition approach. Besides, the operation rules obtained from the GA model are easy to use. Thus, the relatively recent GA technique seems to be a very efficient technique to be used in reservoir system optimisation analysis.

Since both models use inflow to the reservoir during the month, which is an unknown at the beginning of the month, the models need a forecasting of inflows. Coupling an inflow forecasting module to both models would be necessary to use them in real applications.

The irrigation demand, which includes the new area to be extended to irrigation in the left bank canal of the Udawalawe reservoir could be supplied totally during the simulation period of six years with both optimum operations. Although the performances of the system obtained by the two methods do not differ very much, the study has brought out an important aspect that with even after supplying water to the extended irrigated area in the left bank, there is still more flow in the Udawalawe, which can be used for further increasing irrigated area downstream of the Udawalawe reservoir.

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