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Estimation of Optimal Storage of a Multi-Reservoir System Using Simulation Linked Genetic Algorithm

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ABSTRACT: In this paper the cost of a multiple reservoir system is minimized using simulation linked Genetic Algorithm (GA). Simulation is used to determine preliminary storages of reservoirs at potential sites which satisfied a given set of targets. Thereafter, GA is applied on yield-cost functions of reservoirs to get the optimal (minimum) cost of the system. The model is applied to a real multiple reservoir system in India i.e., the Damodar Valley System of Reservoirs. The result obtained from GA is found to be very close to that obtained from dynamic programming method.

INTRODUCTION

For a planner/designer of a water resources scheme, it is important to provide storages at sites which augument sufficient water to meet multiple demands of different users at the minimum cost. Releases through reservoirs have to satisfy reliability criteria. Simulation and optimization are two modeling approaches which help us achieve this objective. Simulation, based on mass balance accounting procedure, is essentially a screening method which is widely used for evaluating alternate water resources schemes as it offers a rapid means of evaluating expected performance of the system for given inputs. If inputs are fed carefully, simulation can give very good solutions that are close to the optimal solution. The technique is also popular among designers as it is easy to comprehend and mathematically less daunting. Yeh (1985) and Wurbs (1991) have given excellent review of the use of simulation method in design of water resources schemes.

Designers find it useful to link simulation with an optimization technique for arriving at an optimal reservoir configuration. Simulation would fetch them 4–5 good candidate solutions for use as initial values for optimization. This way search space and thereby computational burden is lessened. Linear Programming (LP) and Dynamic Programming (DP) find maximum use as optimization method in design of water resources schemes. Yeh (1985), and Wurbs (1993) provide excellent review of application of optimization methods in water schemes.

In recent times, Genetic Algorithm (GA) which works on the principle of natural evolution of genes, have developed into a powerful optimization tool. Though user is doubtful if indeed this search technique has arrived at the optimal solution, yet he finds GA useful as he is confident it would give some solutions which should be very close to the optimal solution. GAs score over other algorithms because they can be easily applied on a non-convex, discontinuous and highly nonlinear functions which traditional methods find difficult to solve. GAs have been utilized in wide spectrum of problems in science and engineering since theie invention by Holland (1975). A review of GA applications to water resources problems can be seen in the works of Wardlaw and Sharif (1999).

OBJECTIVE OF THE PRESENT STUDY AND ADOPTED METHODOLOGY

The objective of the present study is to estimate the total storage of a multiple reservoir system which satisfied a set of demands (irrigation, hydropower, flood control, and municipal and industrial) at the minimum cost. This simply means arriving at best strategy of providing more storages at the economical sites. The objective is achieved employing the following two methods:

1. Simulation is employed to determine the relationships between storages and yields at different potential sites. The reservoirs, yields are to satisfy a predefined reliability criteria. From given elevation-area-storage relationships, storage-yield-cost functions are obtained. Reservoirs' costs include construction and submerged area costs.

2. Genetic algorithm is employed on storage-yield-cost functions at potential sites obtained from simulation to get the minimum cost of the reservoir system.

SIMULATION

Individual Reservoir Simulation Equations

The method employed here is essentially a screening method, which gives preliminary best sizes of different reservoirs for specified targets. The first step in the analysis is to identify the potential storage sites in a basin and independently analyze them to determine their water yield as a function of reservoir storage. The storage-yield relationship thus developed is combined with the estimated cost of storage to derive a yield-cost relationship at each potential site. The storage-yield-cost relationships is then used in the optimization of reservoirs in series and in parallel. Yields from individual potential sites are done using the following equations and constraints:

1. The volume of water released during any period cann't exceed the net content of reservoir at the beginning plus the net flow into the reservoir during that period,

$$O_t \le S_{t-1} + I_t + P_t + \bar{I}_t - El_t - Y_{\min,t} \text{ for all } t \quad \dots (1)$$

2. The continuity equation must be observed,

$$S_t = S_{t-1} + I_t + P_t + \bar{I}_t - O_t - El_t \text{ for all } t \quad \dots (2)$$

3. Storage at time must lie between upper and lower bounds,

$$Y_{\min,t} \le S_{t-1} \le Y_{\max,t} \quad \dots (3)$$

Where for any time t, $Y_{\min}$ = gross storage upto minimum pool level, $Y_{\max}$ = gross storage upto maximum pool level, S_{t-1}= initial gross reservoir content, S_t = gross reservoir content after time t, P_t = Precipitation directly upon reservoir O_t = total reservoir release, I_t = river inflow to reservoir, $\bar{I}_t$ = local inflow to reservoir, and El_t = evaporation from reservoir.

Simulation of Reservoir in a Multi-reservoir System

The reservoir operation policy has been prepared for the operation of different reservoirs in the following manner:

1. The operation starts from the uppermost to the next reservoir. The starting month being June.
2. The individual reservoir operation policy takes place as described above.
3. Water uses of same priority are initially clubbed for computation purposes and later distributed into unclubbed water uses in the ratio of their amount. Deficits are also distributed in the same ratio.
4. Water can be diverted into one reservoir to another reservoir in terms of priority of water uses.
5. The return flows from upstream schemes or spills from upstream reservoirs add to the inflow of downstream reservoir.

GENETIC ALGORITHM (GA)

The Genetic Algorithm (GA), invented by Holland (1975) works on the principle of natural evolution of genes. The working principle of GA can be referred in the books of Goldberg (1989), Michalewicz (1996) and Deb (2001). Rather than starting from one initial guess, GA starts from a population of randomly generated guesses (chromosomes or strings) which represent variables or components. In turn, these chromosomes are made up of gènes or substrings. Each string, a candidate solution, has its own fitness value based on objective fitness value. The entire population of strings form a generation. A set of genetic operators (selection, crossover and mutation) are employed on chromosomes of this generation to create chromosomes for next generation. This operation is repeated till stopping criterion is reached. The criterion may be either number of generations or change in fitness value of chromosomes between two consecutive generations. Generally, the fitness values of the later generations should improve though we cann't expect the best solution in the final generation.

CASE STUDY AND MODEL APPLICATION

The developed simulation-linked GA optimization model is applied to an existing Indian hydroelectric system namely Damodar Valley Corporation (DVC) Reservoir System. The DVC is an integrated multiple reservoir multi-purpose water resources system with four reservoirs, on two almost parallel streams-Damodar and Barakar. The reservoirs are located at Konar, Panchet, Tilaiya, and Maithon with a barrage at Durgapur. Konar is in series with Panchet and Tilaiya with Maithon. The catchment area of the system upto Durgapur is 22015 sq.km (Voorduin, 1945). A schematic layout map of the system is given in Figure 1. The system serves primarily the need of flood control, irrigation, hydropower and water supply for industrial and domestic use. The navigation canal is also a part of the system but it is inoperative at present. The salient features of the dams are given in Table 1.

Table 1: Salient Features of DVC Reservoirs

Reservoir *Stream*	*Konar* *Konar*	*Panchet* *Damodar*	*Tilaiya* *Barakar*	*Maithon* *Barakar*
Purpose	I + M + F	I + M + H + F	I + M + H + F	I + M + H + F
Drainage Area (km^2)	996.7	10691	983.8	11694
Avg. rainfall (mm)	1321	1141	1118	1192
Avg.ann. runoff (Mcm)	555.1	4539	432	4861
Dead storage (Mcm)	62	183	72	206
Conservation storage (Mcm)	221	228	142	612
Flood storage (Mcm)	54	666	178	609
Dead storage Lvl (msl)	410.5	119.5	363.3	132.6
Conservation Lvl (msl)	425.8	125	368.81	146.3
Flood Control Lvl (msl)	428	132	372.5	150.9

Mcm = Million cubic meter; I = irrigation, M = municipal and industrial; H = hydropower; and F = flood control.

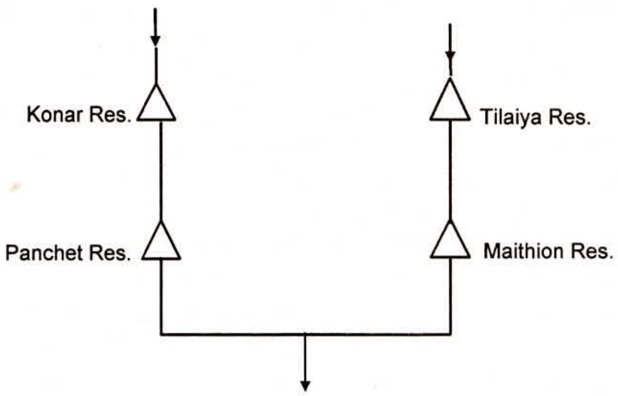

Fig. 1: Schematic Representation of Damodar Valley Reservoirs

SIMULATION STUDY COMPUTATION AND RESULTS

A computer program in FORTRAN is developed for simulation of an individual reservoir and its performance (yield) is evaluated for different reservoir sizes giving the same inflow input. The simulation starts from uppermost reservoir (Konar/Tilaiya) and continues to the next downstream one (Panchet/ Maithon). Water is shared among different uses based on pre-defined priorities. Water uses of same priority are initially clubbed for computational purposes. After computation of unit time period (here a month), the deficits in clubbed uses are distributed into unclubbed water uses in the ratio of their amounts. Here, the priorities are for municipal and industrial, hydropower, and irrigation uses in that order. The simulation is done for years 1956–80 for which inflows at the potential sites are available. The monthly water requirement for different uses is specified fraction of annual requirements. The evaporation loss is calculated based on average water spread in the month. The inflow includes the spill contribution from the upper reservoir, if any. The target annual yield from the system is taken as 3716 Mcm. The simulation run showed monthly releases for irrigation, hydropower, municipal & industrial uses, spills, deficit months (where yield<target), minimum and maximum active content of reservoir, number of times reservoir is empty/full in a calendar year, average monthly deficits, average annual deficits, number of annual deficits for various uses and final content at the end of the analysis period. The year is considered a deficit year for a use when present is a single deficit month for that use. For irrigation the reliability considered is 75% (number of deficit year should not be more than 8 in 32 year simulation run), 90% for hydropower and 100% for municipal and industrial use. Yields thus evaluated from simulation are given in Figure 2. Costs of reservoirs given in the project report of the DVC, are converted at year 2005 cost level assuming 6% constant inflation rate. With the help of storaage-yield curves (Figure 3), yield-cost curves are drawn (Figure 4).

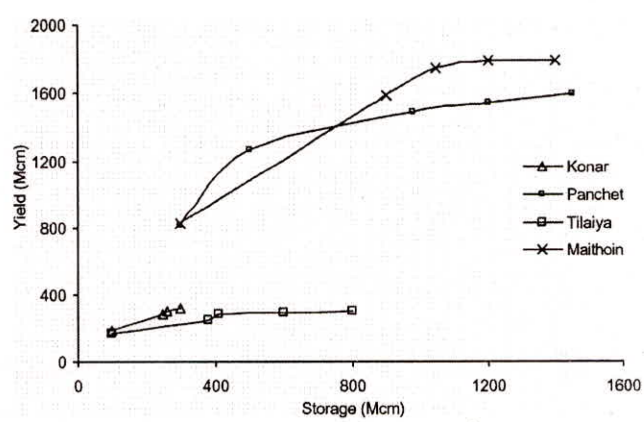

Fig. 2: Storage-yield curves for reservoirs

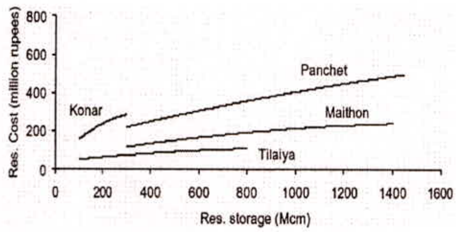

Fig. 3: Reservoir storage cost curves

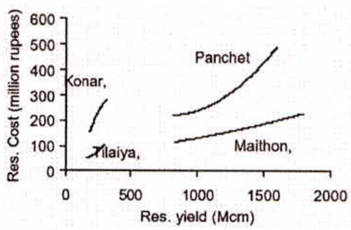

Fig. 4: Reservoir yield cost curves

FORMULATION OF GA AND RESULT

The objective of the study is to obtain optimal sizes of reservoirs which produced a definite yield to satisfy demands. Mathematically, the objective function is expressed as,

$$\text{Min} \sum_{i=1}^{N} C_i(X_i) \text{ subject to } \sum_{i=1}^{N} X_i \geq X_T \qquad \ldots (4)$$

Where, X_i = annual yield from reservoir i, $i = 1, N$, $C_i(X_i)$ = cost of reservoir i corresponding to yield X_i, X_T = total yield to be provided from the set of all reservoirs, and N = total number of reservoirs considered.

To solve the four-reservoir problem of Damodar Reservoir System using GA, it is necessary to construct a chromosome representing a decision variables which are reservoir yields. Each yield can be considered to a be gene, and in binary representation is encoded as binary number. In binary coding, ten digits are sufficient to represent yields for the range of releases defined and thus total length of each chromosomes in the population is 40.

The GA run is carried out with initial population of 100, tournament selection approach, uniform crossover probability 0.8 and uniform mutation probability 0.02.

The cost obtained by GA is given in Table 2.

Table 2: Optimal Storages of Reservoirs

Total Reservoir Yield (Mcm)	*System Cost (million rupees)*	*Storage at Different Sites (Mcm)*			
		Konar	*Panchet*	*Tilaiya*	*Maithon*
3716 (GA)	9840	465	1105	355	1117
3716 (designed)	9650	368	1231	398	978

DISCUSSION AND CONCLUSIONS

Optimization and simulation are two basic approaches for identifying economical sites for reservoir construction. GA has emerged as a popular optimization tool as it can be applied on almost any type of function. In this study, the applicability of GA in arriving at optimal sizes of reservoirs so that the cost of the multi-reservoir system is minimized is investigated. From Table 2, it is apparent that the result obtained is very near to that obtained from dynamic programming. It is also clear that Konar, Panchet, Tilaiya sites are more economical, so larger sizes of reservoirs can be provided than proposed in the project report, but opposite is true for Tilaiya site. It should be mentioned again that cost function assumed is approximate, nevertheless, the procedure of optimization should remain same. Simulation study suggests that the annual municipal & industrial supply, irrigation, and navigation requirements below Maithon and Panchet Reservoirs are 541 Mcm, 2792 Mcm and 239 Mcm respectively. As navigation is presently not operative, the allocated water for this can be diverted to municipal use. The average annual spill through Maithon is 1750 Mcm. This water can be utilized either by increasing the size of the Maithon of constructing an upstream reservoir as is proposed in the project report of DVC. Table 2 illustrates that for a total water yield requirement of 3716 Mcm, the storage to be provided at individual sites deviates from designed values between –10.84% to 26.5%.

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