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OPTIMAL OPERATION OF A THREE-RESERVOIR SYSTEM - A CASE STUDY

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ABSTRACT

In this study, a heuristic approach was applied for the optimal operation of a three-reservoir system located in Mahanadi basin in Chhattisgarh, India. In Mahanadi basin, there are two parallel upstream reservoirs (Dudhawa and Murumsilli reservoirs) which are in a series with a downstream reservoir (Ravishankar reservoir). The approach initiated using historical inflow data for the downstream reservoir and the optimal policies for the downstream reservoir were used to provide targets for the upstream reservoirs. Revised input of inflow to the downstream reservoir was then obtained by running the historical inflow record through the optimal releases for the upstream reservoirs. These flows were then used to develop new operating policies for the downstream reservoir and new targets for upstream reservoirs. The process was continued until the same objective function value was obtained for two successive iterations. Results obtained from the procedure were compared to the results obtained by historical operation of the system in terms of releases, spills and demand deficit for the operation period. Results reveal that this heuristic approach with revised inflow performed better in all. Real coded and constraints genetic algorithms (GAs) technique was used for optimal operation of this multireservoir system.

Keywords: Optimal operation, multireservoir, genetic algorithm.

INTRODUCTION

Optimization in planning, design and implementation of complex water resources systems have always been intensive research activities. Literature review of the subject of optimization of reservoir operations reveals that no general algorithm is possible. Choice of the method depends on the characteristics of the reservoir considered, on the availability of data, the specified objectives and constraints (Yeh, 1985).

A genetic algorithm (GA) is a search algorithm originated in the mid-1970s (Holland, 1975; Goldberg, 1989) and has developed into an effective optimization approach. Fairly a large amount of research has been carried out in applying GAs for reservoir operating problems and watershed management. East and Hall (1994) applied a genetic algorithm to the four–reservoir problem. The objective was to maximize the benefits from power generation and irrigation water supply, subjected to constraints on storages and releases from the reservoirs. Fahmy et al. (1994) applied genetic algorithm to the reservoir system operation and compared the performance of the genetic algorithm approach with that of dynamic programming (DP). It was concluded that genetic algorithm performs better than the DP model. Oliveira and Loucks (1997) used GAs model to evaluate operating rules for multireservoir systems, demonstrating that GAs can be used to identify effective operating policies. Wardlaw and Sharif (1999) explored the potential of alternative GAs formulations in application to real-time reservoir operation. Sharif and Wardlaw (2000) applied genetic algorithms for the optimization of multireservoir system in Indonesia (Brantas Basin), by considering the existing development situation in the basin and two future water resource development scenarios and proved that the GAs was able to produce solutions very close to those produced by dynamic programming. Kim and Heo (2004) applied multi-objective GAs to optimize multireservoir system of the Han River basin in South Korea. It was reported that multi-objective GAs has limited application in multireservoir system optimization. Ahmed and Sarma (2005) developed genetic algorithm model for deriving the optimal operating policy and compared its performance with that of stochastic dynamic programming (SDP) for a multipurpose reservoir. It was concluded that GAs model was advantageous over SDP model in deriving the optimal operating policies. Jothiprakash and Shanthi (2006) developed GAs model to derive operational policies for a multipurpose reservoir. Chauhan and Shrivastava (2008) used Genetic Algorithm formulation with preference-based approach to derive optimal operating policies for a multipurpose reservoir. A comprehensive Genetic Algorithm (GA) model has been developed (Jothiprakash and Shanthi, 2009) and applied to derive optimal operational strategies of a multipurpose reservoir. It was concluded that the GAs model performs better than the SDP model. Garudkar et al. (2011) developed an optimization model for the reservoir releases based on elitist GA approach considering the heterogeneity of the command area. Hincal et al. (2011) explore the efficiency and effectiveness of genetic algorithm in optimization of multireservoir. The results obtained were compared to the real operational data and genetic algorithm was found to be effective and can be utilized as an alternative technique to other traditional optimization techniques. Ming et al. (2016) developed a real-coded genetic algorithm with self-adaptive crossover operators was employed to solve the environmental reservoir operation model for Three Gorges Reservoir. Tayebiyan et al. (2016) proposed release policies

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using new forms and to determine the optimal operation of each policy, real coded genetic algorithm was applied as an optimization technique. Literature review reveals that GA as an optimization technique can be used for obtaining the optimal operation policy of reservoir system.

This study presents a heuristic approach for the optimal operation of three-reservoirs in Mahanadi Reservoir basin. The approach utilizes the optimization formulation for a single reservoir problem. The linkage between the reservoirs within the system was provided using a 'desired target' approach. System performance generated by the model was compared to those obtained by historical operation of the system. An optimization technique genetic algorithm was used for optimal operation of this multireservoir system. Stochastic dynamic programming based approach to the operation of a multireservoir system was used by Tai and Goulter (1987).

SYSTEM DESCRIPTION

Mahanadi basin consists of three reservoirs as shown in Fig. 1. The system consists of two parallel upstream reservoirs (Murumsilli and Dudhawa reservoirs) in a series with a downstream reservoir (Ravishankar reservoir). The two upstream reservoirs Murumsilli and Dudhawa served as the feeder to the Ravishankar reservoir. These two upstream reservoirs do not have any demands and are only storage regulation structures. Ravishankar reservoir has irrigation and municipal & industrial (M&I) demands, which can be met through releases in Mahanadi Main Canal and Mahanadi Feeder Canal respectively. Salient features of three reservoirs, given in Table-1 and Table-2, show the detail of commanded area of canals of Ravishankar reservoir.

AVAILABLE DATA

Data pertaining to physical features have been collected from the Government of M. P., Irrigation Department Report (1990) on MRP system planning and operation. The rainfall data, data of inflow and outflow of the reservoirs were collected from the Office of the Superintending Engineer, Water Resources Department, Dhamtari (C. G.). Data regarding agricultural practices, crops and climatic parameters were collected from Indira Gandhi Agricultural University, Raipur (C. G.)

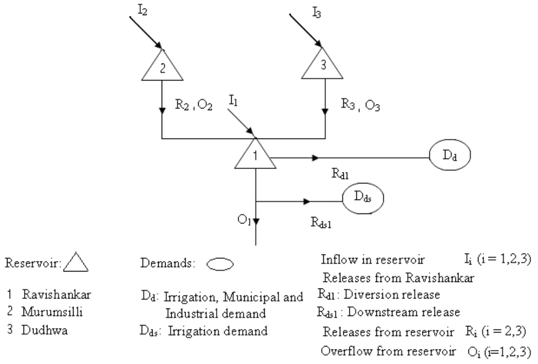

Fig. 1. Configuration of Reservoirs in Mahanadi Basin.

Table 1: Salient feature of Dams in Mahanadi basin

Description	Ravishankar	Murumsilli	Dudhawa
Catchment area	3670 Sq.Km	484 Sq.Km	621 Sq.Km
Gross Storage	910 Mm^3	165 Mm^3	288 Mm^3
Dead storage	143 Mm^3	3.40 Mm^3	4.50 Mm^3

METHODOLOGY

A heuristic procedure for the optimal operation of a three-reservoir system has been applied. The primary objective for the approach was the development of an operating policy for the upstream storage and downstream reservoir to minimize the demand deficit as objective function. It should be noted that the irrigation and M&I requirements are at the downstream reservoir. Hence, the two upstream storages both must respond to the requirements of the downstream reservoir. This principle was the fundamental to the approach as described in the following sections.

Table 2: Canals and Command Area of Ravishankar reservoir

S. No.	Canal	Discharge capacity (cumecs)	*Kharif* season		*Rabi* season	
			CCA (ha.)	100% Irr. intensity (ha.)	CCA (ha.)	35% Irr. intensity (ha.)
1.	Mahanadi Main Canal	98.32	249190	249190	249190	87216.5
2.	Mahanadi Feeder Canal	19.80	14810	14810	14810	5184

CCA: Culturable command area, Irr.: Irrigation, ha.: Hectares

The basic component in the model is the determination of the optimal policy for the Ravishankar reservoir. In initiating the procedure, the historic inflows into Ravishankar were taken as natural inflows. The optimal operating policy with these flows was then developed for the Ravishankar reservoir and the value of the release for each month or time *t* is determined. The value of release in each month is an indication of the release that is most beneficial to the system given overall operating conditions and was termed as the monthly 'target release'. These releases were used for the development of the operating policies for the upstream reservoirs as follows. The upstream reservoirs (Murumsilli and Dudhawa) have no demands. Hence, any release either of these two reservoirs only generates benefit when it passed through downstream reservoir i.e. Ravishankar reservoir. The requirement of Ravishankar reservoir as indicated by the 'target release' introduced above, therefore represent the best way of distributing the releases throughout the year to optimize the overall performance of the system. These releases were indicators of the best distribution of total input or inflow into Ravishankar reservoir. The total input was a combination of the outflows or releases from each of the two upstream reservoirs and the local inflows to Ravishankar reservoir. To determine the total release 'desired' from the two upstream reservoirs, the local inflow in each month was subtracted from the 'target release' for that month. The resulting target release was then divided into targets for each of the two reservoirs. This division can be done using the historical proportions of flow from each system. In this study, 40% of target release was decided for Murumsilli and 60% for Dudhawa. Setting of the targets for two reservoirs (Murumsilli and Dudhawa) permits the reservoirs to be operated in response to the need of the downstream reservoir (Ravishankar).

Using these target values to measure the value of the release in each month, the optimal operating policy for each of the upstream reservoir can be determined independently. Using the optimal policy defined for each upstream reservoir, the historic inflows were run through each reservoir and the resulting releases are determined. The resultant releases from each upstream reservoir and the historic local inflows of Ravishankar reservoir were then combined into a revised inflow record for the Ravishankar reservoir. New optimal operating policy was developed for the downstream reservoir. The new 'target releases' were then calculated for upstream reservoirs and the procedure was repeated. The process is continued until the overall system performances do not change within small tolerances from one iteration to another. Using the above described approach, GAs model was developed to derive operational policies for a multireservoir system.

RESERVOIR INFLOWS

Inflows into the three reservoirs are computed with the help of storage level records, elevation-capacity curves and various outflows made from the reservoir in accordance with mass balance equations. Inflows are computed for 20 years for the period from 1996-2015 for Murumsilli, Dudhawa and Ravishankar reservoirs. The entire inflow series has been utilized for developing the optimum operating policy for the reservoir in Mahanadi Basin.

IRRIGATION DEMAND

The irrigation demands for 20 years from January 1996 to December 2015 were estimated based on the methodology suggested by Doorenbos and Pruitt (1977) and the monthly reference crop evapotranspiration (ET_o) were estimated using FAO 56 Penman and Monteith method (Allen et al, 1998).

The other demands are the constant requirements of municipal and industrial demands for Ravishankar reservoir.

Genetic Algorithm Model Formulation

In the present study, the objective function of the GAs model (the fitness function) for the Ravishankar reservoir was minimizing the sum of squared deficit of monthly diversion irrigation demand and downstream irrigation and M&I demand. Mathematically the objective function is given by:

$$Z1 = Minimize \sum_{t=1}^{12} (R_{d1,t} - D_{d1,t})^2 + (R_{ds1,t} - D_{ds1,t})^2 \tag{1}$$

and for Murumsilli and Dudhawa reservoirs the objective functions are given by:

$$Z2 = Maximize \sum_{t=1}^{12} R_{2,t} \text{ for Murumsilli)} \tag{2}$$

$$Z3 = Maximize \sum_{t=1}^{12} R_{3,\,t} \text{ (for Dudhawa)} \tag{3}$$

where $D_{d1,t}$ = irrigation and M&I demand during the month '*t*' for Ravishankar reservoir, $R_{d1,t}$ = diversion release during the month '*t*' for Ravishankar reservoir $D_{ds1,t}$ = downstream irrigation demand during the month '*t*' for reservoir, and $R_{ds1,t}$ = downstream release during the month '*t*' for reservoir 1. $R_{2,t}$ and $R_{3,t}$ are the releases during the month '*t*' for Murumsilli and Dudhawa reservoirs respectively.

The above objective functions of the GA model are subjected to the following constraints,

1. Release constraint

The irrigation release during any month should be less than or equal to the irrigation demand in that month and this constraint is given by

$$R_{d1,\,t} \le D_{d1,t}, \quad t = 1, 2, \ldots, 12 \tag{4}$$

$$R_{ds1,t} \le D_{ds1,t} \quad t = 1, 2, \ldots, 12 \tag{5}$$

$R_{n,t} \leq T_{n,t}, \quad t = 1,2,...,12$ and $n = 2,3$ (6)

where $T_{2,t}$ and $T_{3,t}$ are the target releases obtained from the optimal operation of Ravishankar reservoir for Murumsilli and Dudhawa respectively.

2. Maximum and minimum storage constraints for each reservoir

The reservoir storage in any month should not be more than the capacity of the reservoir and should not be less than the dead storage. Mathematically this constraint is given as:

$$S_{n,\min} \leq S_{n,t} \leq S_{n,\max} \quad n = 1,2,3 \text{ and } t = 1,2\ldots12 \tag{7}$$

where $S_{n,min}$= minimum Storage in Mm^3 and $S_{n,max}$ = capacity of the reservoir in Mm^3 in t month for reservoir n.

3. Mass balance constraints

The mass-balance or continuity equations explicitly define storage volumes at the beginning of each period t. Let S_t be the storage volume in the reservoir at the beginning of period t. Continuity or conservation of flow required that the initial storage volume S_t plus any inflow Q_t less the release R_t and evaporation loss E_t must equal to the initial reservoir storage volume in the next period S_{t+1}

$$S_t + Q_t - R_t - E_t = S_{t+1} \tag{8}$$

Evaporation loss (in volume) in a period is given by the product of the evaporation rate (in depth units) and the average spread area (average of the water spread areas at the beginning and at the end of the period) of reservoir in that period. The water spread area is a function of the total storage (dead + active) in the reservoir. The reservoir level will always above the dead storage level. If the water spread area is plotted against reservoir storage the relation between the water spread area above the dead storage level and the active storage (storage above the dead storage) can in most cases, be approximate by a straight line (Loucks et al., 1981)

The evaporation loss E_t in each period t may be approximated by Loucks et al., 1981, as

$$E_t = A_a e_t \left(\frac{S_t + S_{t+1}}{2} \right) + A_o e_t \tag{9}$$

where A_o is water surface area at the top of the dead storage level, A_a is area per unit active storage volume above A_o and e_t evaporation rate in the period t . Let

$$a_t = 0.5 A_0 e_t \tag{10}$$

Then combining equations (8), (9) and (10) and rearranging terms so that equation (8) can be written as

$$(1 + a_t) S_{t+1} = (1 - a_t) S_t + Q_t - R_t - A_o e_t \tag{11}$$

On the basis of above equation, continuity constraints for Ravishankar reservoir

$$(1 + a_{1,t}) S_{1,t+1} = (1 - a_{1,t}) S_{1,t} + I_{1,t} - R_{d1,t} - R_{ds1,t} + R_{2,t} + R_{3,t} - A_{1,o} e_{1,t} - O_{1,t} + O_{2,t} + O_{3,t} \tag{12}$$

where t represents time period in month of the year, $S_{1,\,t+1}$ is the storage in the Ravishankar at the end of the period t, $S_{1,t}$ is the storage at the beginning of period t, $I_{1,t}$ is the inflow into Ravishankar reservoir during time period t, $R_{d1,t}$ is the irrigation and M&I release during time t. $R_{ds1,t}$ is downstream irrigation release during time t, $O_{1,t}$ is the overflow from Ravishankar during time t, $R_{2,t}$ and $R_{3,t}$ are the releases from Murumsilli and Dudhawa reservoir respectively, $O_{2,t}$ and $O_{3,t}$ are the spill from Murumsilli and Dudhawa reservoir respectively, $A_{1,o}$ reservoir water surface area corresponding to the dead storage volume, $e_{1,t}$ is the evaporation rate for period t in depth units, $a_{1,t} = 0.5 A_{1,a} e_{1,t}$ (as defined in equation 10) and $A_{1,a}$ is the reservoir water spread area per unit volume of active storage above $A_{1,o}$ for Ravishankar.

Similarly, continuity constraints for Murumsilli reservoir

$$(1 + a_{2,t}) S_{2,t+1} = (1 - a_{2,t}) S_{2,t} + I_{2,t} - R_{2,t} - O_{2,t} - A_{2,o} e_{2,t} \tag{13}$$

where $S_{2,t+1}$ is the storage in the Murumsilli at the end of the period t , $S_{2,t}$ is the storage at the beginning of period t, $I_{2,t}$ is the inflow into Murumsilli reservoir during time period t, $R_{2,t}$ is release during time t from Murumsilli, $O_{2,t}$ is the overflow from Murumsilli during time t, $A_{2,o}$ reservoir water surface area corresponding to the dead storage volume, $e_{2,t}$ is the evaporation rate for period t in depth units, $a_{2,t} = 0.5 A_{2,a} e_{2,t}$ (as defined in equation 10) and $A_{2,a}$ is the reservoir water spread area per unit volume of active storage above $A_{2,o}$ for Murumsilli.

Continuity constraints for Dudhawa reservoir

$$(1 + a_{3,t}) S_{3,t+1} = (1 - a_{3,t}) S_{3,t} + I_{3,t} - R_{3,t} - O_{3,t} - A_{3,o} e_{3,t} \tag{14}$$

In the above equation t represents time period in month of the year, $S_{3,\,t+1}$ is the storage in the Dudhawa at the end of the period t, $S_{3,t}$ is the storage at the beginning of period t, $I_{3,t}$ is the inflow into Dudhawa reservoir during time period t, $R_{3,t}$ is release during time t from Dudhawa, $O_{3,t}$ is the overflow from Dudhawa during time t, $A_{3,o}$ reservoir water surface area corresponding to the dead storage volume, $e_{t,3}$ is the evaporation rate for period t in depth units, $a_{3,t} = 0.5A_{3,a}e_{3,t}$ (as defined in equation 10) and $A_{3,a}$ is the reservoir water spread area per unit volume of active storage above $A_{3,o}$ for Dudhawa.

4. Overflow constraints

This constraint takes care of the situation when the final storage exceeds the capacity of the reservoir. Mathematically this constraint is given by:

$$O_{n,t} = S_{n,t+1} - S_{n,\max} \quad n = 1, 2, 3 \text{ and } \quad t = 1, 2, \dots, 12 \quad \text{and} \qquad (15)$$

$$O_{n,t} \geq 0 \quad n = 1,2,3 \text{ and } t = 1, 2, \dots, 12 \qquad (16)$$

The various steps involved in genetic algorithms are well presented in Goldberg (1989). The first step to solve a problem using a GAs is to construct a string that can represent the decision variables that need to be determined. In reservoir optimization releases are the decision variables. For Ravishankar reservoir, there are 12 monthly diversion and downstream releases each in the optimization horizon, the chromosome representing a solution to such a problem consists of 24 genes (sub-string) representing the decision variables (releases) of the problem. 12 monthly decision releases were taken as 12 genes each for Murumsilli and Dudhawa. Upper and lower boundaries for each decision release were determined based on the release constraints as described in the previous section. Real coding was used to represent decision variables. In addition, constraints on storage were handled by using a penalty function. A constrained problem was converted into unconstrained problem in GAs by introducing a penalty function.

After the fitness function evaluation, the crucial mechanism of the “Survival of the fittest” is applied to the strings based on stochastic remainder roulette-wheel selection method to form the next generation. In reproduction, good strings in a population are probabilistically assigned a larger number of copies and a mating pool is formed. Next to this, new population of reproduced solutions is paired; assuring that each solution of a pair is not identical to the other solution in that same pair. These pairs of solutions are called parents. These parents will produce children; other solutions having many but not all of the characteristics of their parents. Children solutions are produced from parent pairs of solutions using crossover.

In this study single point cross over was used throughout. It is a recombination operator, which produces in three steps. First, the reproduction operator selects at random a pair of two individual strings (parent strings) for mating, then a cross-site is selected at random along the string length and the position values are swapped between two strings following the cross-site. Finally, each generated child solution resulting from these reproductions, pairing, and crossover operation is mutated with selected mutation probability. The need for the mutation is to create a point in the neighborhood of the current point, thereby achieving a local search around the current population.

Sensitivity to crossover and mutation probabilities

Sensitivity analysis was carried out to fix the best parameter setting viz. crossover probability and mutation probability for different GAs models. Three GAs models were considered in this study for deriving optimal operating policy. Crossover probability in range 0.7-0.9 and mutation probability in range 0.01-0.2 was tested to find the best values of crossover and mutation probabilities with respect to fitness function values for a population of 160 for Ravishankar reservoir and 100 each for Murumsilli and Dudhawa reservoir. Consideration was given to the influence of population size on the performance of GAs. With the best values of crossover and mutation probabilities, populations vary from 80 to 160, 40 to 120 and 40 to 120 were tried for Ravishankar, Murumsilli and Dudhawa reservoir respectively. For sensitivity to population, a crossover probability of 0.85 and mutation probability of 0.05 was used. Termination criterion was set to perform 800 generations of GAs simulation i.e. program will terminate with 800th generation.

RESULTS

The results were obtained sequentially using historic inflow data and irrigation demands of 20 years for the period from 1996 to 2015 by following the heuristic approach as described previously. The carryover storage of a year is taken care of by giving the final storage of the last month of previous year as the initial storage to the first month of the year.

Efforts were made to compare the solution of GAs with historical and revised inflow into Ravishankar in terms of diversion releases, downstream releases, spill from Ravishankar and demand deficit for the operation period. These comparisons for the operation period were as follows: -

1. Total diversion release with revised inflow was 2.4% higher than that with the historical inflow (Fig. 2).
2. Total downstream release was 7.1% higher with revised inflow than the historical inflow (Fig. 3)
3. Total spill of 15551 Mm^3 was observed with the historical inflow whereas it was 13940 Mm^3 with the revised inflow (Fig. 4).
4. With revised inflows 60% times no deficit in the total demand was observed whereas it was 30% times with historical inflows. Total deficit in demand was 5332 Mm^3 with historical inflow and 4566 Mm^3 with revised inflow (Fig. 5).
5. Average optimal storage trajectories with historical and revised inflow are shown in Fig. 6. More storages were observed from June to November with historical

inflow whereas from December to May with revised inflow.

6. Average monthly sum of square of demand deficit for historical and revised inflow is shown in Fig. 7. Except in month of December the sum of square of demand deficit was less with revised inflow.

20 years of data were used to evaluate the performance of model in terms of objective function value, releases to MMC and MFC, spills and number of failure years with historical and revised inflows. Table 4 presents the overall comparisons.

The above results reveal that the GAs model with revised inflow performed better in all.

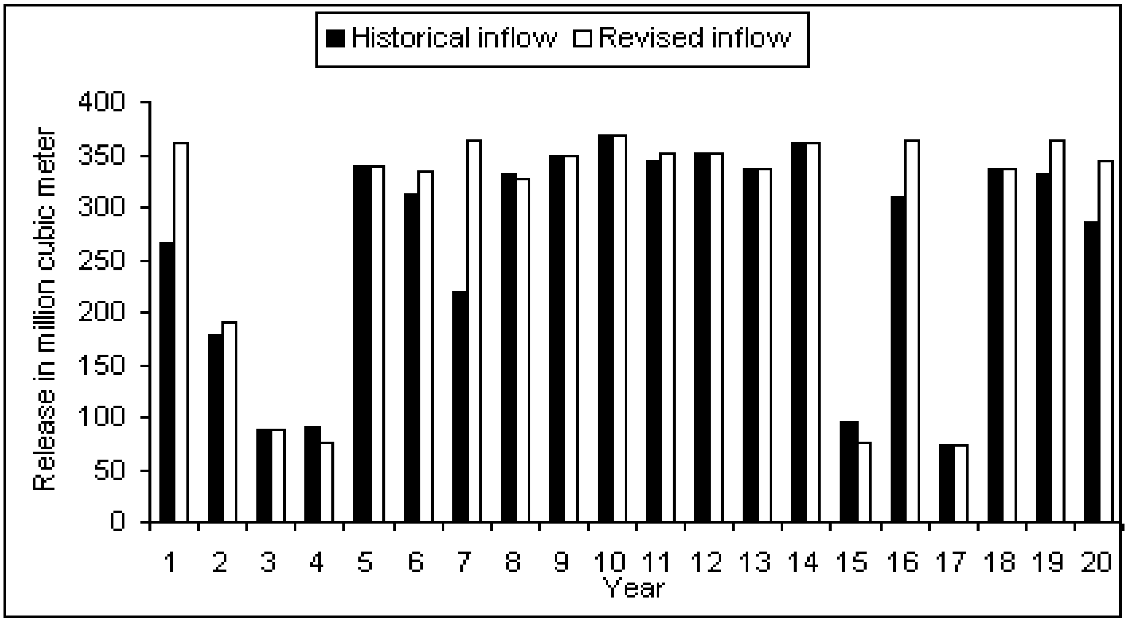

Fig. 2. Comparison of diversion releases during operation period.

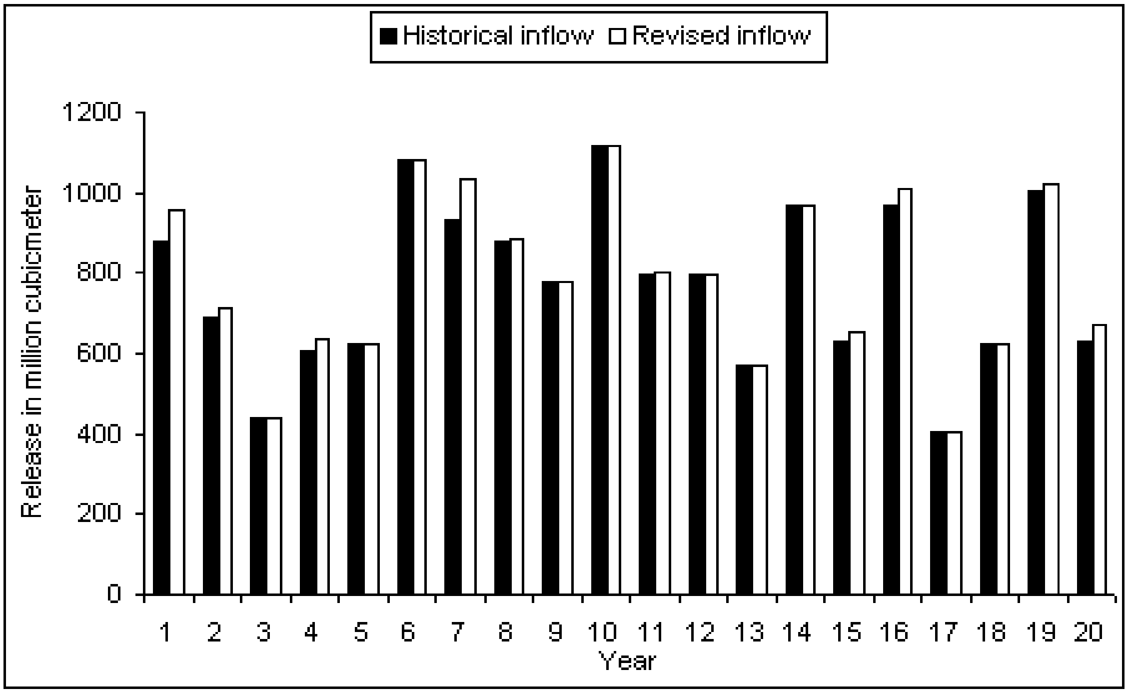

Fig. 3. Comparison of downstream releases during operation period.

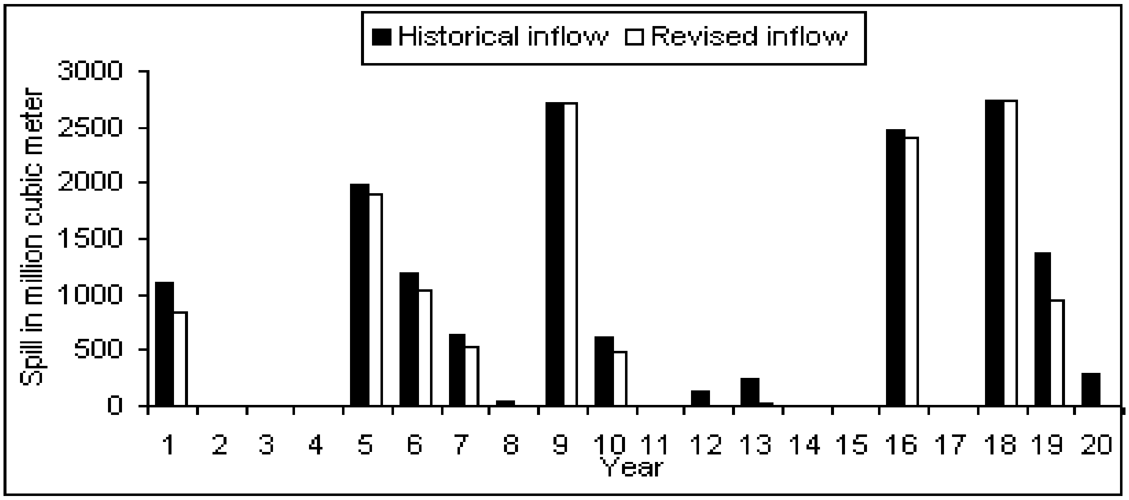

Fig. 4. Spills from Ravishankar reservoir

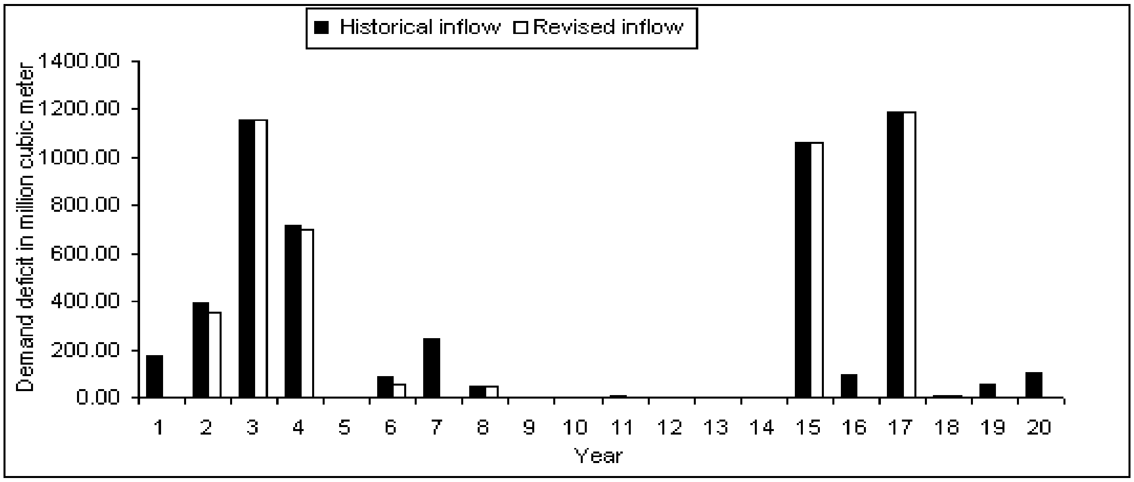

Fig. 5. Total demand deficits during operation period.

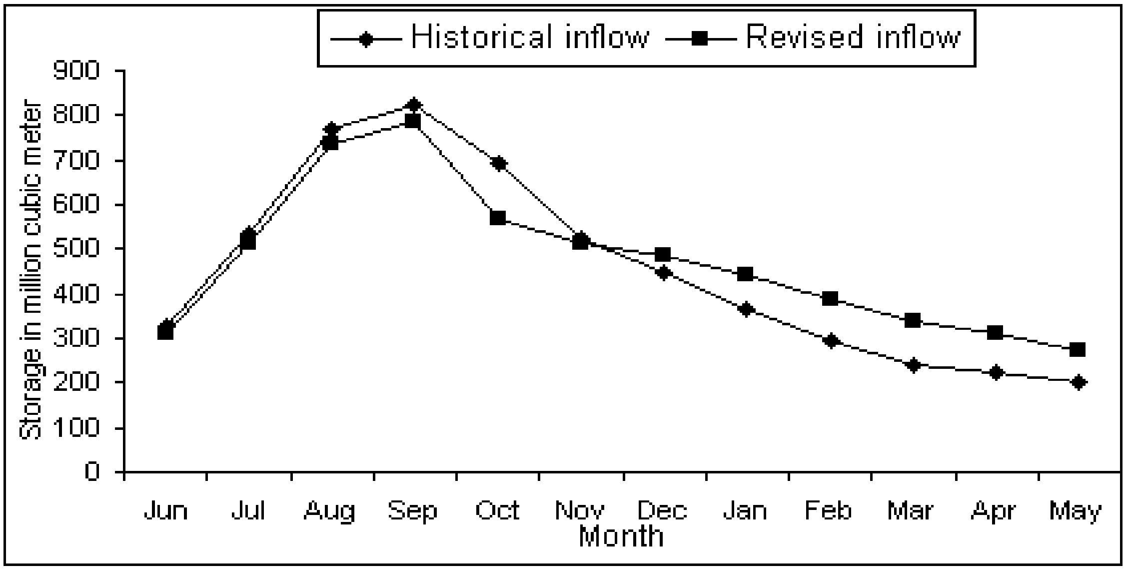

Fig 6. Average optimal storage trajectories.

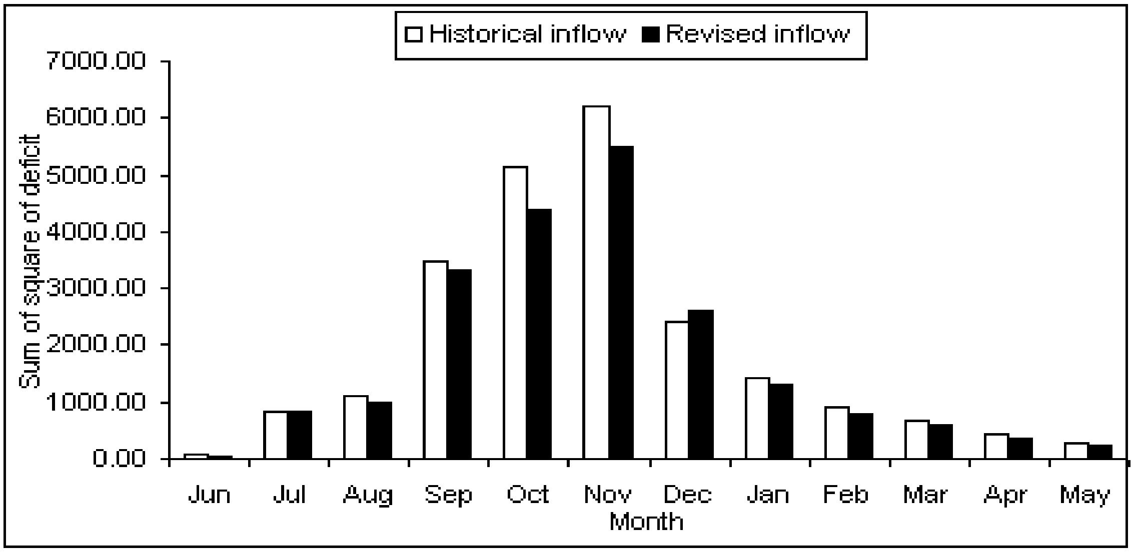

Fig. 7. Average monthly sum of squared deficit of demand in Mm^3 for Ravishankar reservoir.

Table 4: Comparison of Model Results for 20 Years of Operation Period for Ravishankar Reservoir with Historical and Revised Inflows

S. No.	Particulars	Historical inflow	Revised inflow
1	Total release to MMC in Mm^3	15403	15799
2	Total release to MFC in Mm^3	5333	5752
3	Spills in Mm^3	14520	13940
4	Number of failure years	14	8

CONCLUSIONS

A heuristic approach was applied for the optimal operation of three-reservoir in Mahanadi basin in Raipur Chhattisgarh. The approach utilized genetic algorithms technique for optimal operation of three-reservoir system. The linkage between the reservoirs within the system was provided by means of a 'desired target' approach. The optimal operating policy at the downstream reservoir was used to develop targets for the optimal operation of the upstream reservoirs. The objective for Ravishankar reservoir was minimizing the sum of squared deficit of monthly diversion irrigation demand and monthly downstream irrigation and M&I demand and for both Murumsilli and Dudhawa, it was to maximize the total releases. The overall performance of GAs model with revised inflow performed well. Results are proving that by using this heuristic approach overall performance of the reservoir system is improved. GAs can be used as an optimization technique in reservoir operation and it can be extended for more complex system involving non-linear objective function

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