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Development of 3-D Optimal Surface for Operation Policies of a Multireservoir in Fuzzy Environment Using Genetic Algorithm for River Basin Development and Management

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Abstract A Multi objective, Multireservoir operation model for maximization of irrigation releases and maximization of hydropower production is proposed using Genetic Algorithm. These objectives are fuzzified and are simultaneously maximized by defining and then maximizing level of satisfaction (λ). In the present study a multireservoir system in Godavari River sub basin in Maharashtra State, India is considered. Problem is formulated with four reservoirs and a barrage. A monthly Multi Objective Genetic Algorithm Fuzzy Optimization (MOGAFUOPT) model for the present study is developed in 'C' Language. The optimal operation policy for maximization of irrigation releases, maximization of hydropower production and maximization of level of satisfaction is presented for existing demand in command area. The entire range of optimal operation policies, for different levels of satisfaction i.e. λ (ranging from 0 to 1), are determined. From the relationships developed amongst irrigation releases, hydropower production and level of satisfaction, a three dimensional (3-D) surface covering the whole range of policies has been developed. This solution surface can be the basis for decision makers for implementing the policies. Considering the future requirements in the command area, both the irrigation and hydropower demands are increased by 10 and 20%. The optimal operation policy for maximization of irrigation releases, maximization of hydropower production and maximization of level of satisfaction is also presented for these cases. The 3-D solution surface is also developed in these cases.

Keywords Optimization · Multi objective analysis · Genetic algorithms · Fuzzy logic · Reservoir operation

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1 Introduction

Scarcity of water for various purposes such as irrigation, hydropower generation, Industrial requirement, and domestic purpose is being faced worldwide. Hence, proper management of available water resources is essential. The Multi Criterion Decision Making (MCDM) methods have been developed for multi objective analysis for use and management of natural resources, like water. Reservoir operation forms an important role in water resources development. Yeh (1985) reviewed reservoir management and operation models. Optimal coordination of the many facets of reservoir systems requires the assistance of computer modeling tools to provide information for rational management and operational decisions. Labadie (2004) has reviewed state-of-the-art in optimization of multi reservoir systems.

The Genetic Algorithm (GA) is a search procedure based on the mechanics of natural selection and natural genetics, which combines an artificial survival of the fittest with genetic operators abstracted from nature (Holland 1975). Searching for an optimal design from a population of possible designs instead of a single design allows GA to maintain a multipoint perspective on many regions of the solution space at the same time and have a high probability of locating a global optimum (Goldberg 1989). Oliveira and Loucks (1997) have presented operating rules for multireservoir systems by using genetic search algorithms. Using simulation they have evaluated each policy to compute performance index for a given flow series. Wardlaw and Sharif (1999) have presented several alternative formulations of a genetic algorithm for reservoir system. Multireservoir systems optimization have been studied by Sharif and Wardlaw (2000). A genetic algorithm approach has been presented by considering the existing development situation in the basin and two future water resource development scenarios. Nagesh Kumar et al. (2000) have presented application of genetic algorithms for optimal reservoir operation for maximization of hydropower production. Chang and Yang (2002) have presented optimizing the rule curves for multi-reservoir operations using a genetic algorithm and HEC-5. A multi-population genetic algorithm has been used to optimize a system of two reservoirs that supplies monthly varying demands and environmental flow requirements (Ndiritu 2003). Srinivasa Raju and Nagesh Kumar (2004) have discussed application of genetic algorithms for irrigation planning. GA was used to determine optimal cropping pattern for maximizing benefits for an irrigation project. Al-Mohseen and Rakesh Khosa (2002a,b) have presented long term operating policy for a single reservoir system by using genetic algorithms. They have applied this technique to Hemavathy reservoir, Cauvery River System, India. A simulation model was designed using Simulink in Matlab environment to test the time reliabilities of derived operating policies.

Anand Raj (1995) has presented multicriteria methods in river basin planning. ELECTRE-I and ELECTRE-II techniques were applied for water resources planning to Krishna river basin, India. Anand Raj and Nagesh Kumar (1996) have presented ranking of river basin alternatives using ELECTRE. Anand Raj and Nagesh Kumar (1997) have presented planning for sustainable development of a river basin using fuzzy logic. Bender and Simonovic (2000) have presented a fuzzy compromise approach to water resource systems planning under uncertainty. Cai et al. (2001) have presented nonlinear water management models using a combined genetic algorithm and linear programming approach. Nagesh Kumar et al. (2001) have presented optimal reservoir operation using fuzzy approach. Comparison of fuzzy and nonfuzzy optimal reservoir operating policies have presented by Tilmant et al. (2002). Simonovic (2000) discussed tools for water management. He discussed the complexity of water resources domain and the complexity of the modeling tools in an environment characterized by continuous rapid technological development. Reis et al. (2005) have presented multi-reservoir operation planning using hybrid genetic algorithm and linear programming which is an alternative stochastic approach.

2 System Description

The Jayakwadi project stage-I (R_1) is built across river Godavari, Maharashtra State, India. The gross storage of reservoir is $2{,}909 \times 10^6$ m^3 and live storage is $2{,}171 \times 10^6$ m^3. Total installed capacity for power generation is 12.0 MW (Pumped storage plant). Irrigable command area is 1,416.40 km^2. The Jayakwadi project stage-II (R_2) is built across river Sindaphana, a tributary of river Godavari, Maharashtra State, India. According to Jayakwadi project proposal, inflows into the Jayakwadi stage-II reservoir (R_2) consists of feeder canal releases from Jayakwadi stage-I reservoir and runoff from the upstream catchment. The gross storage of reservoir is 453.64×10^6 m^3 and live storage is 311.30×10^6 m^3. Total installed capacity for power generation (canal power house) is 2.25 MW. Irrigable command area is 938.85 km^2. The Yeldari dam (R_3) is built across river Purna, Maharashtra State, India. The reservoir R_3 is a hydropower project. The gross storage of reservoir is 934.44×10^6 m^3 and live storage is 809.77×10^6 m^3. Total installed capacity for power generation is 15.0 MW. The Siddheshwar dam (R_4) is built across river Purna, Maharashtra State, India. The gross storage of reservoir is 250.85×10^6 m^3 and live storage is 80.96×10^6 m^3. Irrigable command area is 615.60 km^2. The Vishnupuri project (R_5) is built across river Godavari, Maharashtra State, India. The gross storage of reservoir is 83.85×10^6 m^3. Irrigable command area is 337.24 km^2. The schematic representation of the physical system showing Jayakwadi project stage-I, Jayakwadi project stage-II, Yeldari project, Siddheshwar project and Vishnupuri project is shown in Fig. 1. Monthly historical flow data for 73 years is collected for R_1 and 51 years for R_2 and 75% dependable monthly flows are estimated using the Weibull plotting position formula. For reservoirs R_3, R_4 and R_5 monthly historical flow data for 32 years is collected and 75% dependable monthly flows are estimated with the same procedure. The irrigation demand and inflow is shown in Table 1.

3 Model (MOGAFUOPT) Development

A monthly Multi Objective Genetic Algorithm Fuzzy Optimization (MOGAFUOPT) model is developed to derive an operation plan for the optimal utilization of the water resources available in the basin, as demands are in excess of the availability. The objective of the study is to develop optimal operation policies in a multiple crop, multiple criterion environment, on a number of connected reservoirs (multiple reservoir) in a river sub basin.

3.1 Objective Functions

The two objectives considered in this study are

1. Maximization of irrigation releases (i.e., RI)
2. Maximization of hydro-power production (i.e., P)

$$\text{Maximize Z} = \sum_i \sum_t (RI)_{it} \tag{1}$$

$$\text{Maximize Z} = \sum_i \sum_t (P)_{it} \tag{2}$$

Where i varies from 1 to number of reservoirs (i.e., four reservoirs) and t varies from 1 to number of time steps (i.e., 12 months). P=2,725×RP×H kwh for a 30-day month. In the

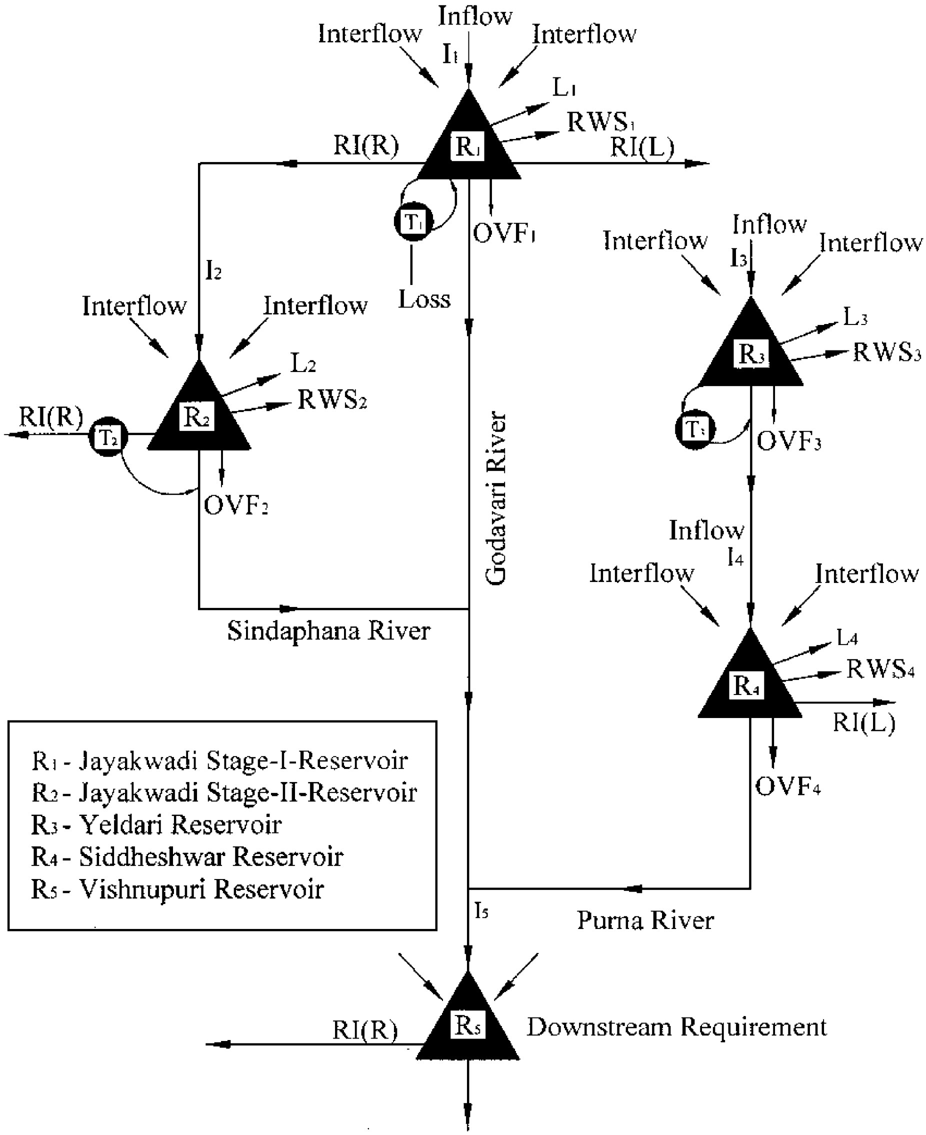

Fig. 1 Schematic representation of the physical system

problem formulation for optimization, four reservoirs are there. The fifth reservoir is considered as downstream control and is incorporated as a constraint in model.

3.2 Constraints

3.2.1 Turbine Release-capacity Constraints

The releases into turbines for power production, should be less than or equal to the flow through turbine capacities (TC) for all the months. Also, power production in each

Table 1 Maximum irrigation demand and inflow in reservoirs in m^3

Month	Jayakwadi Stage-I (R_1)		Jayakwadi Stage-II (R_2)		Yeldari (R_3)	Siddheshwar (R_4)		Vishnupuri (R_5)	
	Irrigation demand $\times 10^6$	Inflow $\times 10^6$	Irrigation demand $\times 10^6$	Inflow $\times 10^6$	Inflow $\times 10^6$	Irrigation demand $\times 10^6$	Inflow $\times 10^6$	Irrigation demand $\times 10^6$	Inflow $\times 10^6$
June	18.55	148.76	7.12	20.98	72.83	33.10	7.71	35.91	16.42
July	26.70	408.25	20.83	43.46	141.09	35.23	2.21	22.97	35.96
August	25.43	610.66	37.64	96.88	200.36	35.23	11.97	31.69	107.32
September	85.79	600.0	46.02	144.17	160.77	93.46	9.18	31.49	246.07
October	267.86	287.75	132.01	75.52	123.10	77.60	1.29	31.95	79.00
November	228.74	196.46	127.05	10.24	49.48	74.68	0.57	22.68	9.91
December	210.88	125.53	89.43	4.27	35.58	65.14	0.89	35.09	7.93
January	230.34	37.65	100.68	0.37	32.18	65.14	1.00	38.46	1.13
February	85.23	21.46	30.02	0.37	24.23	35.50	0.39	23.65	0.00
March	70.06	19.56	28.98	0.16	23.54	37.40	1.00	14.50	0.00
April	85.49	25.50	35.58	0.12	13.15	30.50	0.40	19.06	0.00
May	58.20	46.58	25.88	0.06	13.86	22.30	0.40	28.07	0.00
Total	1,393.2	2,528.17	681.24	396.60	890.17	605.2	37.01	335.5	503.74

month should be greater than or equal to the firm power (FP). These constraints can be written as:

$$\mathrm{RP}(i,j) \le \mathrm{TC}(i)\ \forall i = 1,2,3,4. \tag{3}$$

$$\mathrm{RP}(i,j) \ge \mathrm{FP}(i)\ \forall j = 1,2,3,\ldots\ldots..,12. \tag{4}$$

3.2.2 Irrigation Release-demand Constraints

The releases into canals for irrigation (RI) should be less than or equal to the irrigation demand (ID) on all reservoirs for all the months. Also, the releases into the canals for irrigation should be greater than or equal to the minimum irrigation demand ($\mathrm{ID}_{\min}$). The irrigation release-demand constraint, can, therefore be written as:

$$\mathrm{RI}(i,t) \le \mathrm{ID}(i,t)\ \forall i = 1,2,3,4. \tag{5}$$

$$\mathrm{RI}(i,t) \ge \mathrm{ID}_{\min}(i,t)\ \forall t = 1,2,3,\ldots\ldots\ldots.,12. \tag{6}$$

3.2.3 Reservoir Storage-Capacity Constraints

The storage in the reservoirs (S) should be less than or equal to the maximum storage capacity (SC) and greater than or equal to the minimum storage capacity ($S_{\min}$) for all months. These constraints can be written as:

$$S(i,t) \le \mathrm{SC}(i)\ \forall i = 1,2,3,4. \tag{7}$$

$$S(i,t) \ge S_{\min}(i) \forall t = 1,2,3,\ldots\ldots\ldots\ldots\ldots,12. \tag{8}$$

3.2.4 Hydrologic Continuity Constraints

These constraints relate to the turbine releases (RP), irrigation releases (RI), release for drinking and industrial water supply (RWS) which is taken as a constant, reservoir storage (S), inflows into the reservoirs (IN), Losses from the reservoirs for all months. The losses from the reservoirs are taken as function of storage as given by Loucks et al. (1981). Let A_o is reservoir water surface area corresponding to the dead storage volume and e_t is evaporation rate corresponding to the time period t (in depth units). A_a is the reservoir water spread area per unit volume of active storage. Then the actual evaporation during the time period 't' is given by

$$\text{Evaporation loss} = A_0 e_t + A_a e_t \frac{(S_t + S_{t+1})}{2}$$

$$\text{Put } a_t = \frac{A_a e_t}{2} = 0.5 A_a e_t \text{ then,}$$

$$\text{Evaporation loss} = A_0 e_t + a_t (S_t + S_{t+1})$$

Then the hydrologic continuity constraints for all the reservoirs can be written as:

(a)Reservoir(R_1)

$$\begin{aligned}(1 + \mathrm{a}_t(1,t))\mathrm{S}(1,t+1) = {} & (1 - \mathrm{a}_t(1,t))\mathrm{S}(1,t) + \mathrm{IN}(1,t) - \mathrm{RP}(1,t) - \mathrm{RI}(1,t) \\ & -\mathrm{OVF}(1,t) - \mathrm{RWS}(1,t) - \mathrm{FCR}(1,t) \\ & +\alpha_1 \mathrm{RP}(1,t) - A_0 e_t(1,t) \\ & \forall t = 1,2,3,\ldots\ldots\ldots\ldots,12\end{aligned} \tag{9}$$

(b)Reservoir(R_2)

$$\begin{aligned}(1 + \mathrm{a}_t(2,t))\mathrm{S}(2,t+1) = {} & (1 - a_t(2,t))\mathrm{S}(2,t) + \mathrm{IN}(2,t) + \alpha_2 \mathrm{FCR}(1,t) - \mathrm{RP}(2,t) \\ & -\mathrm{RI}(2,t) - \mathrm{OVF}(2,t) - \mathrm{RWS}(2,t) - \mathrm{A}_0 e_t(2,t) \\ & \forall \mathrm{t} = 1,2,3,\ldots\ldots\ldots\ldots,12\end{aligned} \tag{10}$$

(c)Reservoir(R_3)

$$\begin{aligned}(1 + \mathrm{a}_t(3,t))S(3,t+1) = {} & (1 - a_t(3,t))S(3,t) + \mathrm{IN}(3,t) - \mathrm{RP}(3,t) \\ & -\mathrm{OVF}(3,t) - \mathrm{RWS}(3,t) - A_0 e_t(3,t) \\ & \forall \mathrm{t} = 1,2,3,\ldots\ldots\ldots\ldots\ldots,12\end{aligned} \tag{11}$$

(d)Reservoir(R_4)

$$\begin{aligned}(1 + a_t(4,t))\mathrm{S}(4,t+1) = {} & (1 - a_t(4,t))\mathrm{S}(4,t) + \mathrm{IN}(4,t) + \alpha_3 \mathrm{OVF}(3,t) \\ & +\alpha_4 \mathrm{RP}(3,t) - \mathrm{RI}(4,t) - \mathrm{RWS}(4,t) - \mathrm{OVF}(4,t) - A_0 e_t(4,t) \\ & \forall \mathrm{t} = 1,2,3,\ldots\ldots\ldots\ldots,12\end{aligned} \tag{12}$$

$$\begin{aligned}&(\mathrm{e})\mathrm{Reservoir}(\mathrm{R}_5)\\ &\mathrm{DSREQ(t)} = C_1{*}OVF(1,t) + C_2{*}OVF(2,t) + C_3{*}OVF(4,t)\,,\\ &\qquad +DSIN(t) + \alpha_5 RP(2,t)\\ &\qquad \forall \mathrm{t} = 1,2,3,\ldots\ldots\ldots\ldots,12\end{aligned} \tag{13}$$

$$S(i,1) = S(i,13) \tag{14}$$

Equation (14) is essential to bring the state of the reservoir at the end of the year to the initial storage at the beginning of the next year.

Reservoir R_1 is a pumped storage scheme. The transition loss for pumping turbine releases back into the reservoir is taken as 10% of the turbine releases. Therefore α_1 in the constraint is 0.9 for reservoir R_1. Releases for water supply (RWS) is taken as constant for reservoir R_1 as 31.63×10^6 m^3, 3.55×10^6 m^3 for R_2 and 2.0×10^6 m^3 for R_3 and R_4 for all months. The transition loss for Feeder Canal Release (FCR) from R_1 to R_2 is taken as 10% of FCR. Therefore α_2 in the constraint is 0.9 for reservoir R_2. The transition loss for overflow (OVF) from R_3 to reach to R_4 is taken as 10% of OVF. Therefore α_3 in the constraint is 0.9 for reservoir R_4. The transition loss for turbine releases (RP) from R_3 to reach to R_4 is taken as 10% of RP. Therefore α_4 in the constraint is 0.9 for reservoir R_4. The transition loss for turbine releases (RP) from R_2 to reach to R_5 is taken as 10% of RP. Therefore α_5 in the constraint is 0.9 for reservoir R_5. The transition loss for overflow (OVF) from R_1 to reach to R_5 is taken as 10% of OVF. Therefore C_1 in the constraint is 0.9 for reservoir R_5. The transition loss for overflow (OVF) from R_2 to reach to R_5 is taken as 10% of OVF. Therefore C_2 in the constraint is 0.9 for reservoir R_5. The transition loss for overflow (OVF) from R_4 to reach to R_5 is taken as 10% of OVF. Therefore C_3 in the constraint is 0.9 for reservoir R_5.

4 Results and Discussion

The genetic algorithm operators used are stochastic remainder selection, one point crossover and binary mutation. For fixing GA parameters the MOGAFUOPT model is run for various values of population, generation, crossover and mutation probabilities. The appropriate parameters for population and number of generations are 130 and 500 respectively for present study. For deciding crossover probability and mutation probability, the model is run for different values of crossover and mutation probabilities. The crossover probability is taken as 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, and 1.0 and mutation probabilities are taken as 0.3, 0.2, 0.1, 0.01, 0.009, 0.008, 0.007, 0.006, 0.005, 0.004, 0.003, 0.002 and 0.001. Fitness and number of generations are compared. For maximization of irrigation releases (Z_1), the crossover probability and mutation probability fixed are 0.7 and 0.1 respectively. For maximization of hydropower production (Z_2), the crossover probability and mutation probability fixed are 0.9 and 0.1 respectively. In fuzzy optimization model, for maximization of λ (level of satisfaction), the crossover probability and mutation probability fixed are 1.0 and 0.004 respectively.

The best and worst values for both the objectives i.e. Z_1 for irrigation releases (Z_1^+ and Z_1^-) and Z_2 for hydropower production (Z_2^+ and Z_2^-) are determined by considering one objective at a time, ignoring the other. The maximization for Z_1, Z_2 and λ is achieved by using GA approach. The GA code for maximization is developed in 'C' language using the

Table 2 Best and worst values for objective functions

Objective function (maximization)	Existing demand		Demand=110%		Demand=120%	
	Best value Z^+	Worst value Z^-	Best value Z^+	Worst value Z^-	Best value Z^+	Worst value Z^-
Releases for irrigation (Z_1) $\times 10^6$ m^3	2,218.36	1,807.97	2,420.46	1,951.47	2,622.51	2,095.02
Hydro-power generation (Z_2) $\times 10^4$ kWh	11,739.5	8,559.2	12,736.9	9,166.7	13,722.4	9,766.5

source code provided by the Kanpur Genetic Algorithm Laboratory, Indian Institute of Technology, Kanpur, India. When Z_1 is maximized, the corresponding value of Z_2 is considered to be the worst and vice versa. These values are given in Table 2 for existing demand. Considering the future requirements, the irrigation and hydropower demands are increased by 10 and 20%. The best and worst values for objective functions are also given in Table 2.

In the second step, these objectives are fuzzified by considering linear membership function. In this study, only objectives are taken to be fuzzy and all other parameters of the model are considered crisp in nature. The membership functions for irrigation releases and hydropower production are given by the following Eqs. 15 and 16 and pictorially shown in Figs. 2 and 3 respectively for existing demand.

$$\mu_{Z_1}(x) = \begin{cases} 0 & Z_1 \leq 1807.97 \\ \dfrac{(Z_1 - 1807.97)}{(2218.36 - 1807.97)} & 1807.97 \leq Z_1 \leq 2218.36 \\ 1 & Z_1 \geq 2218.36 \end{cases} \tag{15}$$

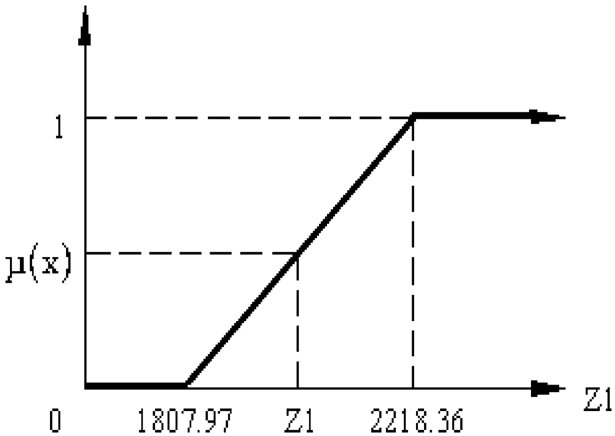

Fig. 2 Membership Function for Z_1 (in $\times 10^6$ m^3) for existing demand

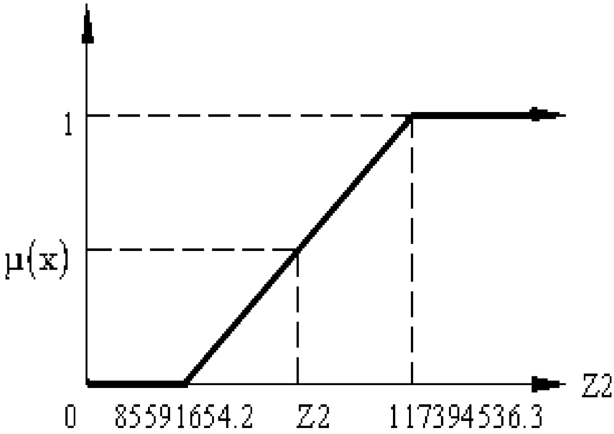

Fig. 3 Membership Function for Z_2 (in kWh) for existing demand

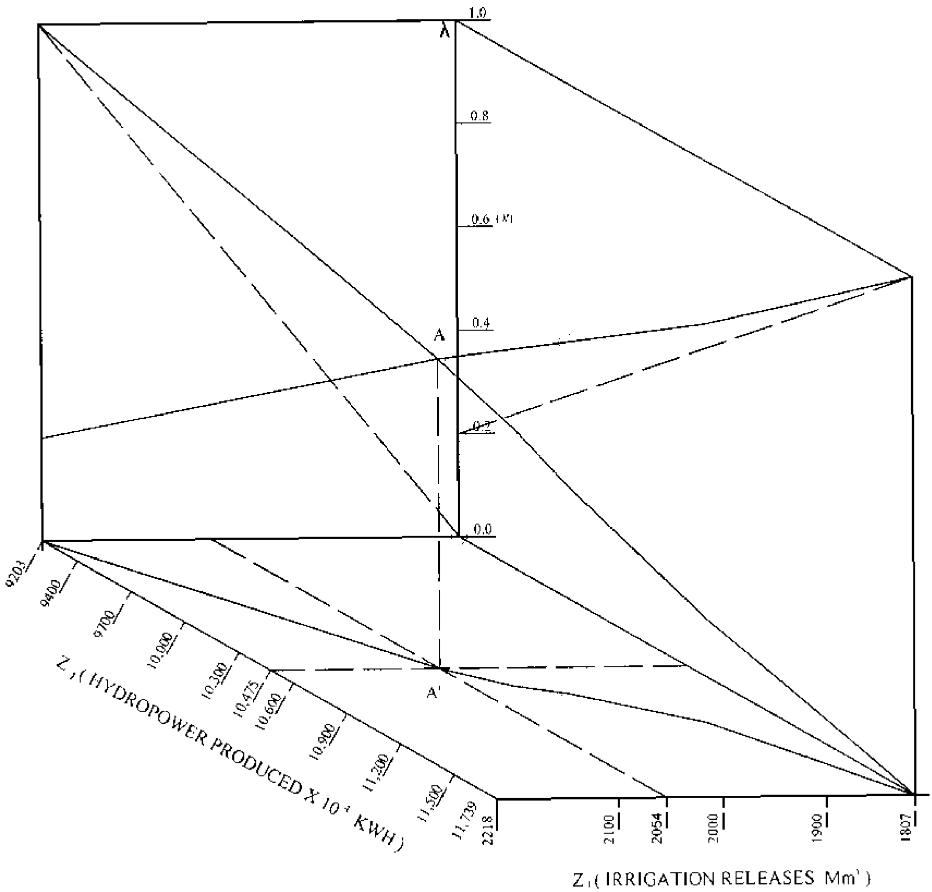

Fig. 4 Summary of relationship between Z_1, Z_2, λ_1, λ_2 for existing demand

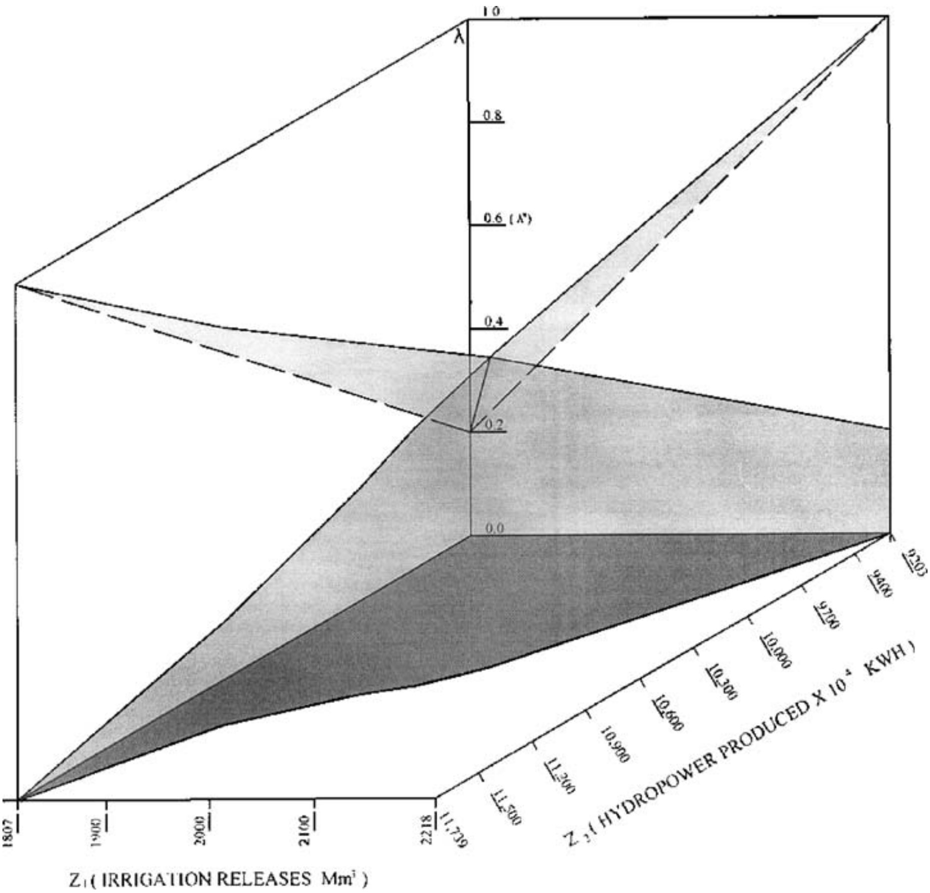

Fig. 5 Optimal surface for existing demand

$$\mu_{Z_2}(x) = \begin{cases} 0 & Z_2 \le 85591654.2 \\ \dfrac{(Z_2 - 85591654.2)}{(117394536.3 - 85591654.2)} & 85591654.2 \le Z_2 \le 117394536.3 \\ 1 & Z_2 \ge 117394536.3 \end{cases} \quad (16)$$

In the third step following modified optimization problem is formulated:

$$\begin{aligned} &\text{Maximize}\lambda \\ &\text{Subjected to,} \\ &410.39\lambda + 1807.97 \le Z_1 \\ &31802882.10\lambda + 85591654.2 \le Z_2 \\ &\text{and all original constraints given in the model and } \lambda \ge 0 \end{aligned}$$

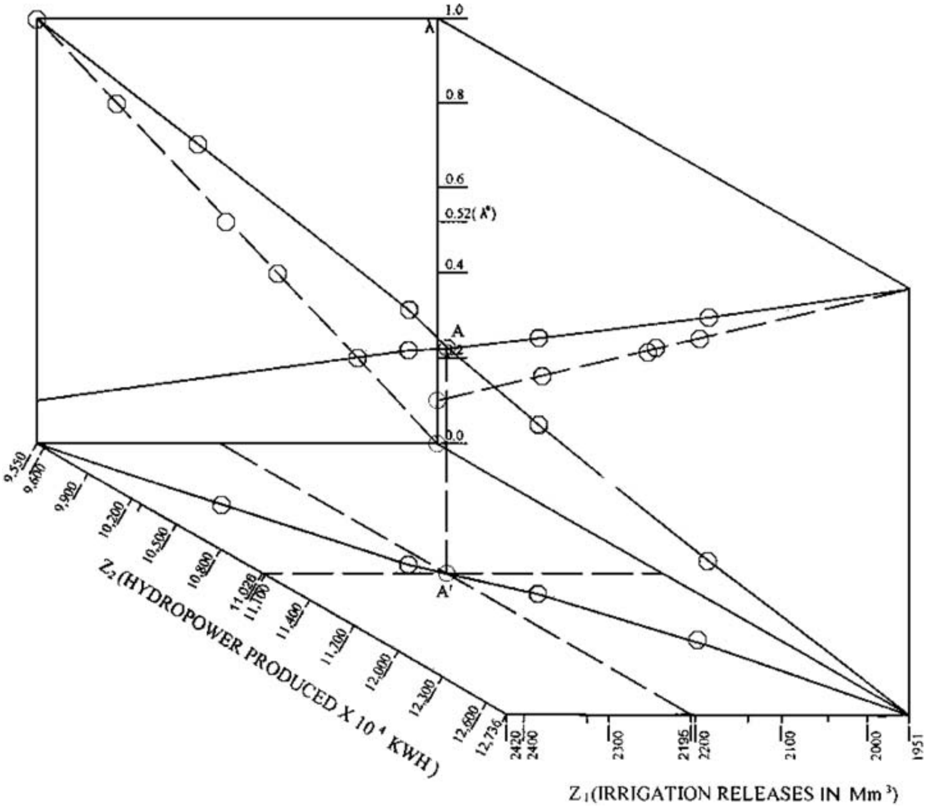

Fig. 6 Summary of relationship between Z_1, Z_2, λ_1, λ_2 for 110% demand

λ is the level of satisfaction derived by simultaneously optimizing the fuzzified objectives Z_1 and Z_2. This model is solved using GA. The λ (Maximum level of satisfaction) was found to be 0.60. The irrigation releases (Z_1^*) and hydropower produced (Z_2^*) corresponding to maximum level of satisfaction are $2{,}054.22\times10^6$ m^3 and $10{,}475\times10^4$ kWh respectively. If the decision maker is satisfied with λ value then the results can be adopted as it is. Otherwise satisfaction levels can be changed for both the objectives and run the model again to get the solution. For this purpose, the whole range of operation policies with satisfaction levels ranging from 0 to 1, for both the objectives, are determined. Then the relationships are established between (1) Z_1 and Z_2, (2) λ_1 and λ_2, (3) λ_1 and Z_1, and (4) λ_2 and Z_2.

The summary of these relationships is shown graphically in Fig. 4. This figure consists of three planes namely Z_1–Z_2 plane, Z_1–λ plane, and Z_2–λ plane. In this figure, the membership function for Z_1 is represented on Z_1–λ plane. The projection of this line in space is shown. Similarly, the membership function for Z_2 is represented on Z_2–λ plane. The projection of this line in space is also shown. These two space curves intersect at a λ value equal to 0.6 as shown by point A. Its projection on Z_1–Z_2 plane is shown by A$^{'}$. The corresponding value of Z_1 and Z_2 are $2{,}054.22\times10^6$ m^3 and $10{,}475\times10^4$ kWh respectively. The trade-off between Z_1 and Z_2 is shown on Z_1–Z_2 plane. The integration of all these curves results into an optimal

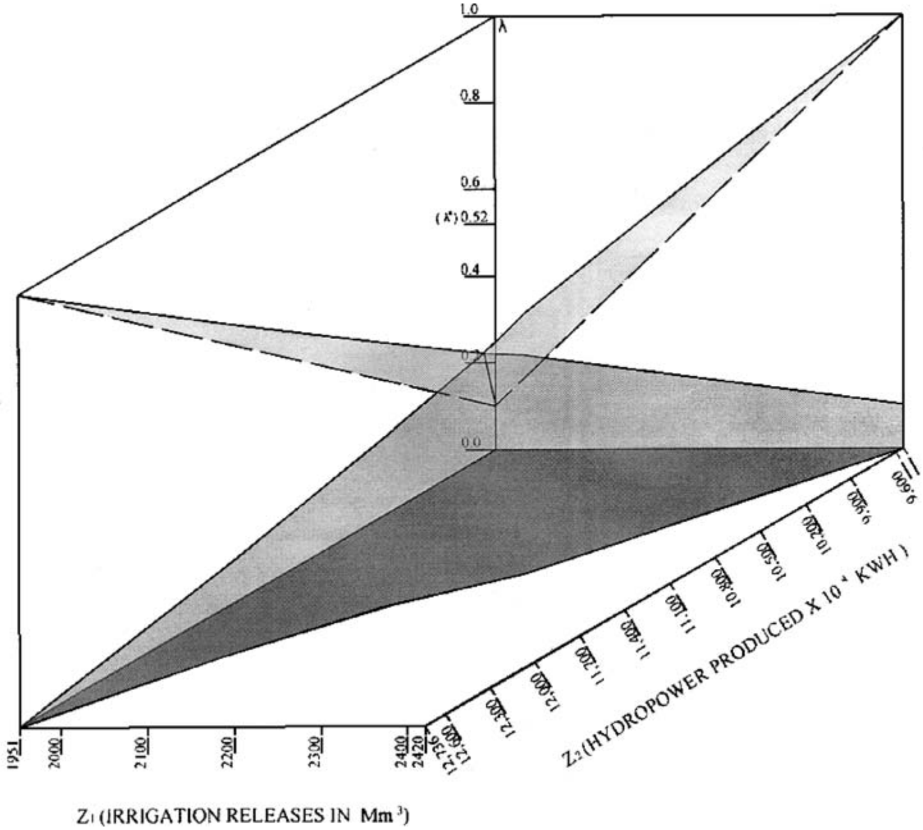

Fig. 7 Optimal surface for 110% demand

feasible 3-D (three dimensional) surface for all combinations of Z_1, Z_2, λ_1 and λ_2 with their possible ranges. This is shown in Fig. 5. The feasible zone for Z_1 and Z_2 is shown on Z_1–Z_2 plane. The optimal solution surface is also shown. This solution surface can be the basis for the decision maker to implement the policies. The results of existing demand without 3-D solution surface have been submitted for publication elsewhere.

The relationships for 10 and 20% increase in irrigation and hydropower demands are established similar to Figs. 4 and 5 and shown in Figs. 6, 7, 8 and 9. For 10% increase in irrigation and hydropower demand, the λ was found to be 0.52 and Z_1^* and Z_2^* are $2{,}195.34 \times 10^6$ m^3 and $11{,}026 \times 10^4$ kWh respectively. Similarly, when both irrigation and hydropower demands are increased to 20%, the λ was found to be 0.47 and the corresponding Z_1^* and Z_2^* are $2{,}342.94 \times 10^6$ m^3 and $11{,}625 \times 10^4$ kWh respectively. Thus as demands increases from the existing level, scarcity of water is very much felt by the system. Thus the implementation of effective operation policies becomes crucial and search for new sources becomes inevitable.

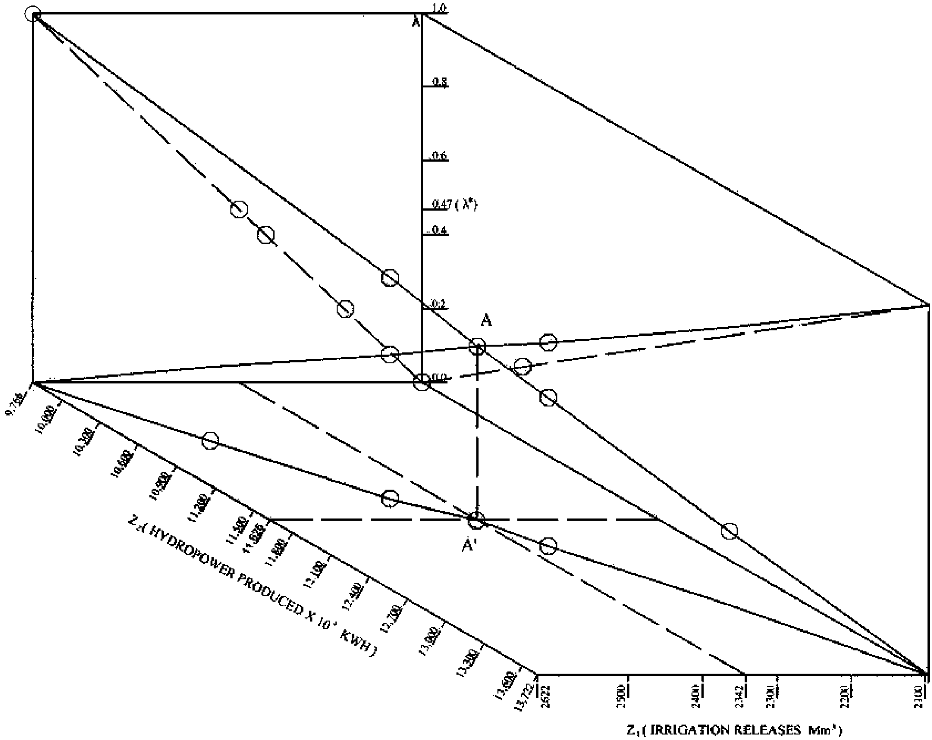

Fig. 8 Summary of relationship between Z_1, Z_2, λ_1, λ_2 for 120% demand

5 Conclusions

In the present study a multireservoir system in Godavari river sub basin in Maharashtra State, India is considered. A Multi objective, Multireservoir operation model for maximization of irrigation releases (Z_1) and maximization of hydropower production (Z_2) is proposed using Genetic Algorithm. These objectives are considered to be fuzzy in this study. These best and worst values of Z_1 and Z_2 are considered for their fuzzification. These fuzzified objectives are simultaneously maximized by defining and then maximizing level of satisfaction (λ). The observations from the study are as given below.

1. Results of the application of MOGAFUOPT indicate that the maximum level of satisfaction (λ*) achieved by maximizing both the objectives simultaneously is 0.60 and the corresponding values of Z_1 and Z_2 are $2{,}054.22\times10^6$ m^3 and $10{,}475\times10^4$ kWh respectively.
2. For an increased demand of 10% in both irrigation and hydropower, the results of the application of MOGAFUOPT indicate that the maximum level of satisfaction (λ*) achieved by both the objectives simultaneously is 0.52 and the corresponding values of Z_1 and Z_2 are $2{,}195.34\times10^6$ m^3 and $11{,}026\times10^4$ kWh respectively.

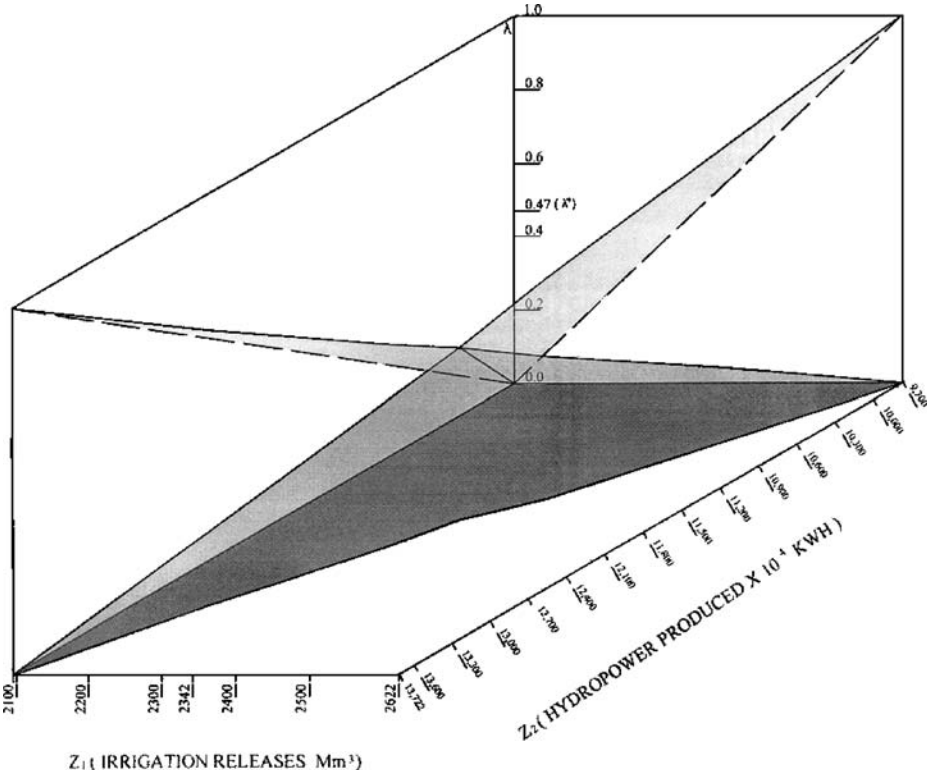

Fig. 9 Optimal surface for 120% demand

3. For an increased demand of 20% in both irrigation and hydropower, the results of the application of MOGAFUOPT indicate that the maximum level of satisfaction (λ*) achieved by both the objectives simultaneously is 0.47 and the corresponding values of Z_1 and Z_2 are $2{,}342.94 \times 10^6$ m^3 and $11{,}625 \times 10^4$ kWh respectively.
4. The entire range of optimal operation policies, for different levels of satisfaction i.e., λ (ranging from 0 to 1), are determined for existing demand, 10% increased demand and 20% increased demand and are presented graphically.
5. From the relationships developed amongst Z_1, Z_2 and λ, a 3-D surface covering the whole range of policies has been developed for existing demand, 10% increased demand and 20% increased demand. This solution surface can be the basis for decision makers for implementing the policies.
6. The 3-D solution surface developed, which covers the whole range of policies for different levels of satisfaction, can effectively be used by the decision makers to make policy decisions and to implement the operation policy more efficiently and judiciously as per their preferences, needs, requirements and demands in the sub basin.
7. The proposed MOGAFUOPT is a general purpose model. Its application can be extended to the entire Godavari river basin and also to the other river basins with little modifications taking physical features and the constraints of the basins into consideration. The 3-D solution surfaces that can be developed for these basins will

become the basis for the decision makers to take policy decisions and for their implementation.

Notation

The following symbols are used in this paper

DSREQ (t)	Downstream requirement during month t;
DSIN (t)	Downstream inflow during month t;
FCR(i,t)	Feeder Canal Releases during month t from reservoirs i;
FP(i,t)	Flow for firm power during month t from reservoirs i;
ID(i,t)	Maximum irrigation demand during month t from reservoirs i;
ID_{min} (i, t)	Minimum irrigation requirement during month t from reservoirs i;
IN(i,t)	Monthly inflow into the reservoir during month t from reservoirs i;
L	Evaporation Loss from reservoir;
OVF(i,t)	Overflow during month t from reservoirs i;
P(i,t)	Hydropower produced during month t from reservoir i;
RI(i,t)	Irrigation releases during month t from reservoirs i;
RP(i,t)	Releases for hydropower production in month t from reservoirs i;
RWS(i,t)	Water supply releases during month t from reservoirs i;
$S(i,t)$	Storage in the reservoir during month t from reservoirs i;
$S_{min}(i)$	Minimum storage capacity for ith reservoir;
SC(i)	Maximum storage capacity for ith reservoir;
T_1, T_2, T_3	Turbines for reservoirs R_1, R_2 and R_3;
TC(i)	Flow for maximum capacity of turbine from reservoirs i;
μ_i(x)	Membership function;
λ	Level of satisfaction;
λ^*	Maximum degree of overall satisfaction;
λ_1	Level of satisfaction for irrigation releases;
λ_2	Level of satisfaction for hydropower produced;
α_1, α_2, α_3, α_4, α_5	Constants; and
C_1, C_2, C_3	Constants.

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