Optimal reservoir operating policies with conflicting objectives in fuzzy environment by GA-NLP hybrid approach – A case study

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Abstract

The reservoir operator is in a critical position when the objectives are conflicting in nature, like releases to irrigation canals which reduces the reservoir storage while for getting more hydro power generation the storage should be high. This necessitates the study of trade-off analysis between the conflicting objectives and determination of compromised solution to get maximum benefits from the conflicting objectives. Therefore, when goals are uncertain & conflicting, fuzzy optimization is necessary to find the best compromised solution. In the present study, best compromised reservoir operating policies are developed using Multi Objective Fuzzy Genetic Algorithm - Non Linear Programming (MOFGA-NLP) hybrid model. This can be done in three steps. In the first step, models is solved by GA-NLP hybrid approach considering one objective at a time and determined the best and worst values of each objective function. Objectives are fuzzified by considering suitable membership function and the model is reformulated to maximize the level of satisfaction (λ) in step 2. In the last step, the reformulated model is solved and determined best compromised policy. The above model is applied to Nagarjuna Sagar reservoir located on river Krishna, India. Objectives considered in the present study are, maximizing the net benefits from irrigation & hydro power generation. The compromised reservoir operating policies are found for various reliable inflows (75%, 80%, 85% and 90%) entering into the reservoir by considering objective functions as fuzzy. The level of satisfaction is more for hyperbolic membership function compared to linear membership function.

Keywords: Reservoir operation**,** Relative yield, Hydro power, Genetic Algorithm, Non-Linear programming, Fuzzy logic.

Introduction

The rainfall is spatially and temporally varying across the country. This necessitates the construction of large reservoirs to store the water in monsoon season and the reservoir is to be operated optimally serving various intended objectives especially in drought periods. The reservoir operation is a high dimensional, dynamic, non-linear and non-convex optimization problem subject to many constraints. The challenges faced by decision maker to operate the reservoir are, determination of optimal allocation of water under multi-crop environment in different intra seasonal time periods during deficit conditions, releases to be made from the reservoir which serves for conflicting objectives and determination of a compromised operating policy of the reservoir.

Number of simulation and optimization models has been developed in the past decades to obtain optimal reservoir operating policies to allocate water optimally among multiple crops and to determine compromised reservoir policies when the objectives, inflows & demands are uncertain. Optimal reservoir operation and cropping pattern is determined by Linear Programming (LP) considering objectives and constraints are linear. But, most of the problems in water Resources, objective function and constraints are non-linear in nature. So, non-linear optimization techniques like Non-Linear Programming (NLP) and Dynamic programming (DP) are adopted. The NLP requires initial feasible solution and may trap in local optima and DP has curse of dimensionality in case of large complex problems. Stochastic dynamic programming (SDP) and fuzzy logic are to be used when inflows into the reservoir are uncertain. Detailed review of application of these methods in reservoir operation is presented by Yeh (1985). Jothiprakash and Arunkumar (2014) developed NLP model for optimizing hydro-power generation through various hydro-power plants and satisfying irrigation demands for Koyna Hydro Electric Project, India. Shima Soleimani et al. (2016) proposed SDP method which extends the classic SDP method considering uncertainties in stream flow and agricultural demand.

In order to overcome the limitations of the conventional techniques and for faster convergence to global optima, the biologically inspired adaptive systems have been used extensively for solving water resources problems. In these population based methods, the global optimal solution is obtained (Labadie, 2004) at a faster rate after thorough sensitivity analysis of model parameters like population size, number of generations, crossover and mutation.

Genetic Algorithm (GA), Ant colony optimization (ACO), Particle Swarm Optimization (PSO), Simulated Annealing (SA), Differential Evolution (DE), Bat algorithm (BA) and Firefly algorithm (FA) etc. are the different EA’s which are applied for finding the best management practices in water resources problems. Out of all EA’s Genetic Algorithm (GA) is more popularly used method especially in reservoir operation. Genetic Algorithm (GA) is adaptive heuristic search algorithm based on the evolutionary ideas of natural selection and genetics. GA represents an intelligent exploitation of a random search used to solve optimization problems. GA, although randomized, exploit historical information to direct the search into the region of better solution within the search space. It was first developed by Holland (1975). Many works have been carried out by using GA for solving various complex problems. Goldberg (1989) identifies the fundamental differences between the GA and conventional optimization techniques.

There are various applications of GA in water management problems, viz., optimal reservoir operating policies (e.g., East and Hall, 1994; Fahmy et al., 1994; Hashemi et al. 2008; Janga Reddy and Nagesh Kumar, 2007; Jothiprakash et al., 2006; Oliveira and Loucks, 1997; Wardlaw and Sharif, 1999), irrigation scheduling (Haq and Anwar, 2010; Nagesh Kumar et al., 2006;), water distribution systems design (e.g., Babayan et al., 2005; Savic and Walters, 1997; Simpson et al., 1994; Srinivasa Prasad & Leela Krishna, 2019), .

Multi-objective GA is applied to determine optimal trade-off between the conflicting objective (e.g., Adeyemo, 2011; Janga Reddy et al., 2006; Kim and Heo, 2006; Labadie, 2004; Samer and Hamdy, 2014). Multi-reservoir problem is solved by GA maximizing the benefits from power generation and irrigation (East and Hall, 1994; Fanuel et al., 2018; Hincal et al., 2011; Li and Wei, 2008). Hybrid models are used to optimize monthly operating rules of a reservoir and other applications to determine global optimal solution at a faster rate (Adeyemo, 2018; Mahyar et al., 2015; Yengui et al., 2012).

Most of the dams constructed are acting as a multi-purpose in nature like irrigation, hydro power generation, municipal & industrial water supply, flood control and navigation etc. The reservoir operator is in a critical position when the objectives are conflicting in nature, like releases to irrigation canals which reduces the storage while for getting more hydro power the storage should be high. Therefore, when goals are uncertain & conflicting, fuzzy optimization is necessary to find the best compromised solution.

Bellman and Zadeh (1970) proposed the concept of fuzzy decision-making. Zimmermann (1978) introduced Fuzzy Linear Programming (FLP). Rommelfanger (1996) has outlined fuzzy linear programming and its applications considering both objectives and constraints in fuzzy. Srinivasa Raju and Nagesh Kumar (2000) demonstrated the uncertainty in objective function values by a membership function in multi-objective domain. Nagesh Kumar et al. (2001) has developed a best compromised reservoir operating policy using Multi Objective Fuzzy Linear Programming (MOFLP) by considering only objectives are in fuzzy and all other parameters to be crisp.

FLP problems with linear membership functions has solved by Gasimov and Yenilmez (2002). Labadie (2004) has given a detailed state-of–the-art review on optimal multi-reservoir systems operation. A methodology is developed for determining efficient solutions to fuzzy multi-objective linear programming by Li et al. (2006). Linear membership functions were considered for multi-objective reservoir modelling (Regulwar and Anand Raj, 2009), non-linear membership functions were considered in irrigation planning and management (Morankar et al., 2013). The different optimization methods adopted in fuzzy multi-objective reservoir operation are, fuzzy linear programming (Regulwar and Gurav, 2014), GA in fuzzy environment (Regulwar and Anand Raj, 2008).

From the literature, it is observed that many of the researchers applied different optimization techniques in determining operating policies of the reservoir by taking objectives as maximization of sum of the irrigation releases, energy production, yield from the crops independently or in combination. Limited research work on fuzzy multi-objective reservoir operation is carried out finding optimal reservoir releases for power and irrigation integrating irrigation scheduling considering yield response to water deficit in multi-crop environment. Hence the present study aims to develop steady state multi-objective reservoir operating policies maximizing the benefits from irrigation and power by GA-NLP hybrid approach and determination of best compromised operating policies of the reservoir by MOFGA-NLP by fuzzifying the objectives considering linear and hyperbolic membership functions.

Case study

The study area considered is Nagarjuna Sagar reservoir, serving multiple purposes, created by building a dam across river Krishna at Nagarjuna Sagar in between the borders of Nalgonda district, Telangana state and Palnadu district, Andhra Pradesh state, India as shown in Fig. 1.The coordinates of the reservoir is at latitude $16^{\circ}34'32''$ N and longitude $79^{\circ}18'42''$ E. The reservoir has a catchment area of 215000 km^2 and reservoir water surface area at full reservoir level is 285 km^2. The gross storage of the reservoir is 11560 Mm^3(MCM) having an active storage of 5730 Mm^3. The dam is 180 m height from the deepest bed level and 1.6 km long consists of 26 spillway crest gates which are 13 m wide and 14 m tall. The dam provides water for irrigation to Nalgonda, Suryapet, Khammam districts through NSLC (Nagarjuna Sagar Left main Canal) and Palnadu, Guntur, Bapatla, Prakasam, Krishna, NTR, Eluru and West Godavari districts through NSRC (Nagarjuna Sagar Right main Canal). The both canals having equal carrying capacity of 311.5 m^3/s. The length and command areas of left canal are 179 km & 0.3869 million hectares (M Ha) while they are 203 km & 0.4505 M Ha for right canal. A main power house of 810 MW is located on the d/s (downstream) river bed. In addition to it, a minor power house on each of right & left canal with capacity of 90 MW & 60 MW respectively and runs when flow is available for irrigation. The releases from the main power house are allowed to stabilize the irrigation requirements under Krishna delta system command area. Computation of irrigation demands under each canal is carried out by using the meteorological data obtained from Rentachintala and Khammam IMD stations as shown in Table 1. Agro economic parameters of various crops are listed in Table 2. Crops are grown under two different seasons: Kharif (monsoon) and Rabi (winter) in the study area. The Kharif season starts from July to October and Rabi season starts from November to February. The major crops grown under canal command area are rice, groundnut, sorghum, grams, cotton and chilli. General cropping pattern and canal efficiency (η=0.6) are taken from department of Irrigation & Command Area Development (I&CAD), Andhra Pradesh under NSLC & NSRC command areas and is shown in Table 3. Fortnight reservoir inflows, irrigation demands and minimum d/s requirements are listed in Table 4.

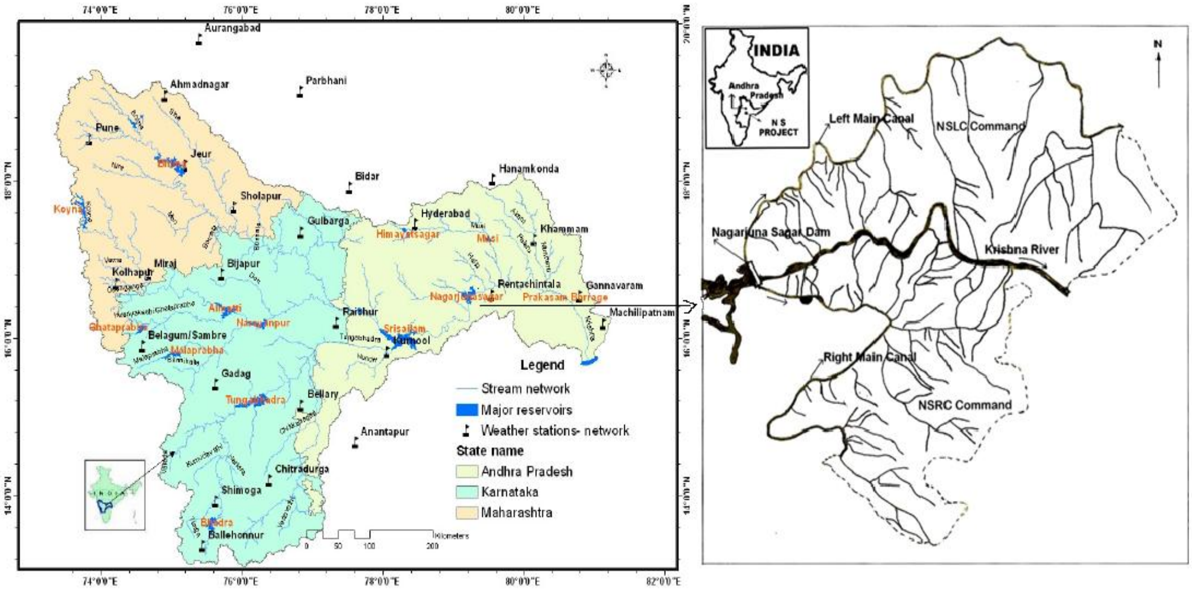


Fig. 1. Nagarjuna Sagar reservoir

Table 1. Meteorological data of two IMD stations (**Source**: IMD, Pune)

(in mm)

Month	Rentachintala		Khammam		Reservoir evaporation
	ET_o	Rainfall	ET_o	Rainfall	
Jan	120	0.4	116.7	1.6	90
Feb	141.6	9.3	154.2	7.3	90
Mar	168.6	6.1	195.3	10.5	174
Apr	184.8	9.6	208.0	25.5	228
May	193.2	40.8	224.1	27.1	240
Jun	170.1	86.2	180.9	126.5	180
Jul	147.6	115.3	120.4	260.1	144
Aug	139.2	114.6	116.4	185.5	144
Sep	130.2	146.1	115.8	164.5	144
Oct	123.3	123.8	110.9	107.1	126
Nov	114.3	41.1	106.4	33.8	99
Dec	111	13.3	115.3	3.9	99

Table 2. Agro economic parameters

(**Source**: Acharya N. G. Ranga Agricultural University, Guntur, Andhra Pradesh)

crop (season)	Maximum yield (kg/Ha)	Net benefit (Rs./Ha)
Rice (Kharif)	5,400	18,045
Groundnut (Kharif)	2,500	13,227
Sorghum (Kharif)	3,000	9,600
Grams (Kharif)	1,300	12,740
cotton	3,000	24,523
chillies	3,200	27,389
Groundnut (Rabi)	2,500	26,743
Sorghum (Rabi)	3,000	9,200
Grams (Rabi)	1,300	12,187

Table 3. Details of crop grown under Nagarjuna Sagar Project

Crop (Season)	Sowing Date	Area (ha)
NSRC		
Rice1 (Kharif)	16th July	50000
Rice2 (Kharif)	1st August	50000
Groundnut (Kharif)	1st July	40000
Sorghum (Kharif)	16th July	70000
Grams (Kharif)	16th July	100000
Cotton	16th July	100000
Chilli	16th August	40000
Groundnut (Rabi)	1st November	40000
Sorghum (Rabi)	1st November	30000
Grams (Rabi)	1st November	80000
NSLC		
Rice1 (Kharif)	16th July	100000
Rice2 (Kharif)	1stAug	100000
Cotton	16th July	10000
Chilli	16th August	10000
Groundnut (Rabi)	16th October	40000
Sorghum (Rabi)	16th October	80000
Grams (Rabi)	16th October	80000

Table 4. Inflows, NSLC & NSRC irrigation demands and minimum d/s flow Requirements (in MCM)

*Fortnight	Various Probable Inflows				NSLC irrigation demand	NSRC irrigation demand	D/S minimum flow requirement
	75 % PE	80% PE	85% PE	90% PE			
1	587.500	326.075	250.125	25.845	0.0	19.988	302.357
2	587.500	326.075	250.125	25.845	186.187	305.761	302.357
3	1600.760	1430.350	1250.075	967.180	385.512	408.094	320.508
4	1600.760	1430.350	1250.075	967.180	310.233	413.261	320.508
5	1229.300	1182.250	860.075	718.445	347.486	311.567	341.916
6	1229.300	1182.250	860.075	718.445	351.742	322.496	341.916
7	1127.520	1054.930	875.270	765.640	425.130	358.090	227.413
8	1127.520	1054.930	875.270	765.640	469.078	302.208	227.413
9	444.180	379.400	366.060	294.880	389.382	364.584	89.372
10	444.180	379.400	366.060	294.880	178.030	230.465	89.372
11	307.500	226.350	182.075	158.550	218.934	277.528	89.372
12	307.500	226.350	182.075	158.550	218.299	280.913	89.372
13	197.300	174.335	152.775	130.570	218.258	285.510	108.684
14	197.300	174.335	152.775	130.570	170.022	238.110	108.684
15	146.080	133.720	127.075	109.025	38.256	155.798	223.311
16	146.080	133.720	127.075	109.025	0.0	35.770	223.311
17	108.500	100.900	91.280	82.620	0.0	0.0	304.046
18	108.500	100.900	91.280	82.620	0.0	0.0	304.046
19	87.050	79.200	76.075	60.125	0.0	0.0	89.372
20	87.050	79.200	76.075	60.125	0.0	0.0	89.372
21	44.050	37.685	22.630	12.210	0.0	0.0	89.372
22	44.050	37.685	22.630	12.210	0.0	0.0	89.372
23	78.420	75.435	60.075	45.950	0.0	0.0	90.430
24	78.420	75.435	60.075	45.950	0.0	0.0	90.430
Total	11916.320	10401.260	8627.180	6742.08	3906.5	4310.1	4552.3

(*Fortnights starting from 1st fortnight of July up to 2nd fortnight of June are numbered sequentially from 1 to 24).

MOFGA-NLP Model Formulation

Steady-state fortnightly reservoir planning model is formulated for a period of year. The formulated model is to find optimal fortnight reservoir releases to each crop grown under left & right main canals and all power houses maximizing the total annual benefits from yield of various crops and hydro power of all the power houses. In the present work, objectives only are considered as fuzzy.

Objective functions

Objective function-1 (F_1): maximization of total annual net benefits from irrigation considering yield response factors.

Reduction of crop yield is proportional to the deficit of water in any growth stage of the crop (Doorenbos & Kassam, 1979) and its relation is,

$$\left(1-\frac{Y_a}{Y_m}\right)= K_y\left(1-\frac{AET}{PET}\right) \tag{1}$$

$$\text{Relative yield } (Ry) = \frac{Y_a}{Y_m} = 1- K_y\left(1-\frac{AET}{PET}\right) \tag{2}$$

Where, Y_m is maximum yield without any deficit in irrigation, Y_a is the actual yield, K_y is the yield response factor, *AET & PET* are the actual evapotranspiration and the maximum evapotranspiration requirement of the crop (Doorenbos & Pruitt, 1977).

The equation considered in the present research work is,

$$R_y = 1-K_y\left(1-\frac{R+R_e}{PET}\right) \tag{3}$$

$$\text{Seasonal crop production measure } (Ry_c) = \prod_{t=1}^{nt} Ry_t \tag{4}$$

where, R is the depth of irrigation water applied and R_e is the depth of effective rainfall.

The objective function-1 is written as,

$$F_1 = \sum_{i=1}^{2}\sum_{c=1}^{NC_i}\left(Ry_c * Ym_{i,c} * A_{i,c} * B_{i,c}\right) \tag{5}$$

where, i,c are canal and crop indexes respectively. Ym_c, A_c and B_c are maximum yield without any deficit, area and coefficient of benefit for each crop.

Objective function -2 (F_2): maximization of total annual benefits from energy production from all power houses.

$$F_2= \sum_{t=1}^{24} \alpha(Rd_tHd_t + PR1_tH1_t + PR2_tH2_t) \tag{6}$$

where, α is a constant and its value is $17.394\text{x}10^{-3}$, t is time period index, $Rd_t, PR1_t, PR2_t$ are the releases in Mm^3 and Hd_t, $H1_{t,}$, $H2_t$ are the effective head available corresponding to main, left and right canal power houses respectively in time period t.

The list of constraints to be satisfied is as following,

Lower and upper bounds on release to crop

$$0.5D_{i,c,t} \leq R_{i,c,t} \leq D_{i,c,t} \qquad \forall t \tag{7}$$

where $R_{i,c,t}$ is the release to a particular crop ‘c’ in a particular time period ‘t’ under any canal.

Reservoir releases for irrigation

Gross irrigation releases considering canal efficiency are,

$$R1_t = \frac{\sum_{c=1}^{Nc}\sum_{t=1}^{Nt} R_{1,c,t}}{\eta} \qquad \forall t \tag{8}$$

$$R2_t = \frac{\sum_{c=1}^{Nc}\sum_{t=1}^{Nt} R_{2,c,t}}{\eta} \qquad \forall t \tag{9}$$

Where $R1_t$ and $R2_t$ are the gross irrigation releases & $R_{1,c,t}$ and $R_{2,c,t}$ are the water allocated to each crop in a particular time period under left and right main canals respectively.

Maximum canal releases

$$R1_t \leq C_{max} \qquad \forall t \tag{10}$$

$$R2_t \leq C_{max} \qquad \forall t \tag{11}$$

where C_{max} is canal carrying capacity.

Maximum releases into left & right canal power houses

$$PR1_t \leq PR1_{max} \qquad \forall t \tag{12}$$

$$PR2_t \leq PR2_{max} \qquad \forall t \tag{13}$$

where $PR1_{max}$ and$PR2_{max}$ are maximum releases into left & right main canal power houses.

Relation between canal and power house releases

$$R1_t = CR1_t + PR1_t \qquad \forall t \tag{14}$$

$$R2_t = CR2_t + PR2_t \qquad \forall t \tag{15}$$

where $CR1_t$ & $CR2_t$ are the releases into left & right main canals in excess of maximum releases through left & right canal power houses.

Lower and Upper bounds on d/s releases

$$Rd_{min,t} \leq Rd_t \leq Rd_{max} \qquad \forall t \tag{16}$$

where Rd_t is the d/s releases in period t, $Rd_{min,t}$ and Rd_{max} are the minimum and maximum d/s releases.

Active storage bounds

$$0 \leq S_t \leq S_{max} \qquad \forall t \tag{17}$$

where S_t is the storage in time period t and S_{max} is active storage capacity of the reservoir.

Relation between reservoir water surface elevation and active storage

$$H_t = 0.004\, S_t + 156.3 \qquad \forall t \tag{18}$$

where H_t is the reservoir water elevation in time period t.

Limiationt on Energy production

$$\alpha Rd_t Hd_t \leq DP_{max} \qquad \forall t \tag{19}$$

$$\alpha PR1_t H1_t \leq LP_{max} \qquad \forall t \tag{20}$$

$$\alpha PR2_t H2_t \leq RP_{max} \qquad \forall t \tag{21}$$

where DP_{max}, LP_{max}, RP_{max} are the maximum energy production from the main, left & right main canal power houses respectively.

Continuity equation

$$S_{t+1} = S_t + I_t - (R_{1,t} + R_{2,t} + Rd_t) - SP_t - E_t \qquad \forall t \tag{22}$$

where I_t and E_t are the reservoir inflow and evaporation in time period t.

Steady state policy

The initial storage of the reservoir should be the same for next years to get steady state operating policy.

$$S_{25} = S_1 \tag{23}$$

Deficit irrigation is to be done for reservoir inflows higher than 70% reliability to meet the demands. So, in the present study various levels of dependable inflows higher than 70% reliability (75%, 80%, 85% & 90%) are considered to distribute deficits optimally obtaining maximum benefit.

GA-NLP Hybrid Approach

Genetic Algorithm (GA) is adaptive heuristic search algorithm based on the evolutionary ideas of natural selection and genetics. GA is a part of Evolutionary computing, a rapidly emerging area of artificial intelligence. It was first developed by Holland (1975). Many works have been carried out by using GA for solving various complex problems. Goldberg (1989) identifies the fundamental differences between the GA and conventional optimization techniques.

A thorough tuning is required for choosing the GA parameters for determining the global optimal solution and a feasible solution is required for NLP for getting global optima at a faster rate. GA-NLP hybrid approach is considered in the present study to overcome the above limitations and to obtain global optima at a faster rate by using MATLAB software. Flow chart of GA-NLP is shown in Figure 2.

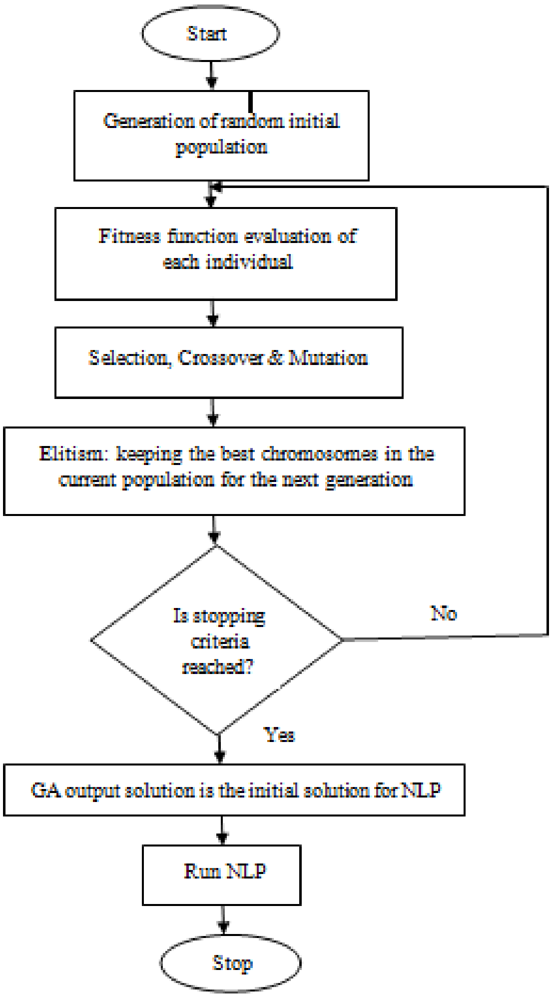


Figure 2: Flow chart of GA-NLP hybrid approach

Fuzzy set theory

In traditional designs, the optimization problem is represented in precise mathematical terms. However, in many real life problems, design variables, objectives and constraints are stated in imprecise or vague and linguistic terms. Fuzzy set theory is useful when the design system involves imprecise and uncertain.

Linear membership function

Linear membership function for any objective F can be represented as Figure 3 (a)

$$\mu_F\,(X) = \begin{cases} 0 & for\ F \le F^- \\ \left(\frac{F-F^-}{F^+-F^-}\right) & for\ F^- < F < F^+ \\ 1 & for\ F \ge F^+ \end{cases} \tag{24}$$

Where F^+ and F^- are maximum and minimum acceptable values of the each objective.

The problem can be reorganized as,

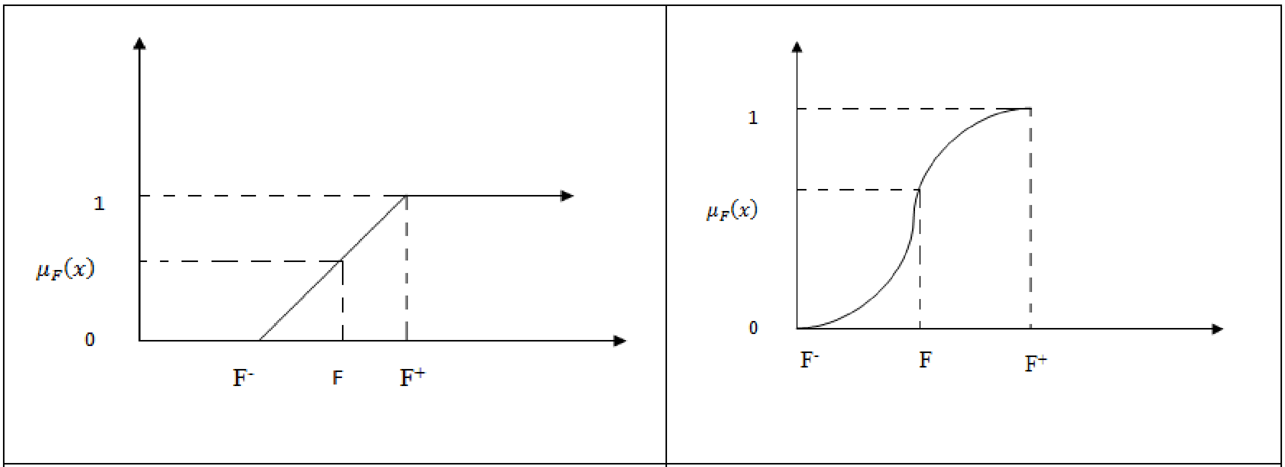
Maximize λ

Subject to

$$\left(\frac{F-F^-}{F^+-F^-}\right) \ge \lambda \quad \text{for each objective function F,} \tag{25}$$

$$0 \le \lambda \le 1 \tag{26}$$

And all the other actual constraints.



(a) Linear membership function

(b) Hyperbolic membership function

Figure 3. Representation of Linear and Hyperbolic membership function

Hyperbolic membership function

Hyperbolic membership function for maximization problem can be represented Figure 3(b) (Morankar et al. 2013).

$$\mu_F\,(X) = \begin{cases} 0 & for\ F \le F^- \\ \frac{1}{2}\tanh\left[\left(F - \frac{F^-+F^+}{2}\right)\propto_p\right] + \frac{1}{2} & for\ F^- < F < F^+ \\ 1 & for\ F \ge F^+ \end{cases} \tag{27}$$

here α_p is a parameter defined as $\frac{6}{F^+-F^-}$

It is further simplified by representing with a new variable,

$$U = \tanh^{-1}(2\lambda - 1) \tag{28}$$

The equivalent crisp model for the fuzzy model can be expressed as,
Maximize U
Subjected to

$$F\alpha_p - \frac{\alpha_p}{2}(F^+ - F^-) \geq \lambda \tag{29}$$

$$0 \leq U \leq 1 \tag{30}$$

in addition to all other existing constraints and bounds.

Step by step procedure of MOFGA-NLP

The step by step procedure of MOFGA is explained below.

Step 1: Solve the model by GA-NLP hybrid approach considering one objective at a time and find the best and worst values of each objective function corresponding to the optimal solution set (x^*).

Step 2: Define linear and hyperbolic membership function for each objective as represented in equations 26 & 29.

Step 3: Reformulate an equivalent model to maximize the level of satisfaction (λ) subjected to equations (27), (28), (31) & (32) and all other original constraints for *x*.

Step 4: Solve the formulated problem in step 3 for maximum level of satisfaction (λ) and best compromised solution.

Results and discussions

The above Multi Objective Fuzzy Genetic Algorithm - Non Linear Programming (MOFGA-NLP) model formulated is demonstrated through a case study of Nagarjuna Sagar reservoir project using GA–NLP hybrid approach by MATLAB software and best compromised reservoir operating policies are obtained for different dependable inflows.

By following step 1 of MOFGA-NLP algorithm, the model is solved by GA as well as with GA-NLP hybrid approach considering each objective at a time and the corresponding best and worst values of objectives is obtained. The GA parameters values considered are population size=100, crossover probability=0.8 and number of generations=500. Objective function values with GA model and GA-NLP hybrid approach are 4824.91 and 12446.23 respectively for maximizing irrigation benefits only with 75% dependable inflows. Similar results are found for maximizing benefits from hydro power and the other inflow patterns also. This shows that GA-NLP hybrid approach performs well compared to GA for getting global optima, minimizing the number iterations by varying the GA parameters values. The same procedure is repeated for all cases of dependable inflows and results are obtained are shown in Table 5.

Table 5. Best and worst values of objective functions for different dependable inflows

Dependable Inflow	Objective function values			
	Annual net benefits from irrigation (F_1)		Annual net benefits from Energy production (F_2)	
	Best value (F_1^+)	Worst value (F_1^-)	Best value (F_2^+)	Worst value (F_2^-)
75%	12446.23	3895.46	14099.13	8586.65
80%	8416.50	3895.46	11067.40	8249.45
85%	5942.33	2649.73	10401.60	7379.52
90% (**No Kharif**)	5731.16	2328.01	9865.58	7240.10

On obtaining upper and lower boundaries of objective functions F_1 & F_2, objective functions are fuzzified in second step considering linear and hyperbolic membership functions.

In the third step, the GA model is reformulated to find the maximum level of satisfaction (λ) by using the linear and hyperbolic membership function equations as represented in equations 24 & 27.

In the last step, reformulated GA model is solved for best compromised solution for 75% dependable inflows and the maximum level of satisfaction is obtained as 0.445 & 0.876 for linear and hyperbolic membership functions respectively. Values of objectives F_1& F_2 are found to be 7447.18 & 10785.4 and 10003.97 & 8780.28 by linear & hyperbolic membership functions respectively. The compromised optimal reservoir operating policies corresponding to two membership functions thus obtained are shown in Tables 6 & 7.

For 75% dependable inflows, optimal % irrigation demand met by each objective independently as well as fuzzy compromised approach are shown in Figure 4. In the case of irrigation priority, full irrigation is given in JUL I, DEC, JAN & FEB months and deficit irrigation in the remaining fortnights, while 50% demand (i.e. minimum irrigation requirement) is met in the case of power priority for all time periods. In case of fuzzy compromised approach considering linear membership function, the total irrigation releases are 16.7 % higher than that of power priority and 25% less with irrigation priority cases. While in case of hyperbolic membership function, the total irrigation releases are 33.6% higher than that of power priority and 14.1% less with irrigation priority cases. The % optimal allocation of water to various crops grown under both canal command area by linear and hyperbolic membership functions are given in Tables 8 & 9 respectively.

Energy production in terms of % installed capacity for different cases are presented in Figure 5. The annual energy production by linear membership function is 28.5% higher when compared to irrigation priority case and it is 21.7% lesser with power priority case. While, the annual energy production by hyperbolic membership function is 2.3% higher when compared to irrigation priority case and it is 37.7% lesser with power priority case.

Variations of fortnight reservoir active storages for all the cases (irrigation priority, power priority & fuzzy compromised policies) are shown in Figure 6. It shows that the storage is increasing from AUG to NOV because of the monsoon inflows into the reservoir and there after it is decreasing in all the cases. The initial storages to be maintained in the reservoir are 451.21 MCM, 4300.464 MCM, 921.32 MCM and 339.5 MCM for irrigation priority, power priority & best compromised policy by linear & hyperbolic membership functions respectively. It is observed that the storages in all fortnights for best compromised policy by linear membership function are above the irrigation priority case and below the power priority case, while they are below the irrigation priority case for hyperbolic membership function.

Simulation studies are also done to evaluate the performance of the GA-NLP policy with Standard Operating Policy (SOP). Reliability of meeting flow requirements with SOP is 56% while with the proposed GA-NLP model is 68% for 75% dependable inflows. Reliability with proposed GA-NLP outperforms with SOP for all other inflows. This reveals that the developed policy is more effective in drought periods.

Optimal solution is found with 75% & 80% reliable fortnight flows of the reservoir. No feasible solution is found for higher reliable inflows with the existing cropping pattern and constraints. By relaxing the minimum irrigation requirement from 50% to 30%, optimal solution is found for 85% reliable inflows. For very low flows of 90% reliability, optimal solution is obtained with three proposed alternative cropping patterns (eliminating Kharif season, cultivating only dry crops, reducing the area of cultivation).The elimination of cultivating crops in Kharif season is best when compared to elimination of wet crops and reduction of the cropping area for the flows of 90% reliability.

The above procedure is repeated for different dependable inflows (80%, 85% & 90% PE) and corresponding best compromised operating policies of the reservoir are determined. The objective function values and level of satisfaction by different dependable inflows by fuzzy compromised approach are presented in Tables 10 & 11. The observations from the tables are, the overall benefits are more for hyperbolic membership function when compare to linear membership function.

The storage policies for various dependable inflows for best compromised policy by the two membership functions are presented in Figures 7 & 8. The reservoir storages at the beginning of the operational year i.e. JUL for 75%, 80%, 85% & 90% dependable flows are found to be 921.322, 859.324, 784.433 and 1255 MCM respectively in case of linear membership function, while for hyperbolic membership function they are 339.5, 840.05, 837.72 and 628.2 MCM respectively. The observations are, storage is increasing during the surplus period from AUG I to NOV I in all the cases and the storages are higher for 75% dependable inflows when compared to other inflow patterns by linear membership function giving more effective heads thereby increasing more hydro power generation, while in case of hyperbolic membership function the storages are lesser giving more irrigation releases thereby increasing the more crop yield.

Table 6. Best Compromised reservoir operating policy by MOFGANLP-LM for 75% dependable inflows

(MCM)

Time period	Initial active storage	Irrigation release to left canal	Irrigation release to right canal	Release to river bed turbines
1	921.322	0.405	10.279	344.744
2	838.784	93.230	153.931	302.475
3	562.291	193.082	205.378	645.953
4	1104.093	155.692	231.456	320.851
5	1981.317	174.725	175.766	342.502
6	2501.110	177.076	182.372	343.079
7	3010.646	217.132	198.992	260.862
8	3445.600	245.772	160.444	265.148
9	3885.652	218.587	234.339	116.177
10	3747.715	115.618	184.389	113.567
11	3765.367	144.743	212.858	206.263
12	3496.176	141.987	189.871	241.959
13	3217.305	138.330	184.421	307.543
14	2773.277	107.425	161.633	279.385
15	2411.457	37.803	101.685	355.700
16	2051.998	0.767	35.059	300.970
17	1851.174	0.689	0.775	421.209
18	1517.804	0.970	0.719	304.841
19	1301.072	0.615	0.785	158.569
20	1204.216	0.589	0.647	104.861
21	1161.386	0.554	0.600	105.604
22	1073.700	0.609	0.661	103.855
23	987.855	0.607	0.525	93.157
24	953.517	0.462	0.475	91.268

Table 7. Best Compromised reservoir operating policy by MOFGANLP-HM for 75% dependable inflows

Time period	Initial active storage	Irrigation release to left canal	Irrigation release to right canal	Release to river bed turbines
1	339.489	0.002	9.996	302.358
2	300.808	93.094	179.265	302.358
3	0.003	286.148	277.330	846.086
4	177.697	155.119	260.653	710.900
5	637.837	174.724	205.395	341.916
6	1130.487	176.957	202.792	341.917
7	1622.816	217.034	233.592	227.413
8	2058.383	245.906	184.444	227.413
9	2513.690	234.811	287.853	89.373
10	2334.212	127.140	192.259	89.373
11	2358.078	147.748	227.645	89.373
12	2189.341	170.709	251.082	89.373
13	1974.399	175.484	246.763	108.685
14	1630.801	133.062	213.650	108.685
15	1363.009	38.250	104.037	223.312
16	1134.017	0.005	35.766	223.313
17	1011.692	0.111	0.006	304.046
18	798.235	0.007	0.008	304.048
19	585.262	0.004	0.003	89.373
20	560.491	0.003	0.002	89.373
21	535.775	0.002	0.002	89.373
22	466.950	0.001	0.002	89.373
23	398.290	0.002	0.002	90.431
24	368.863	0.002	0.001	90.431

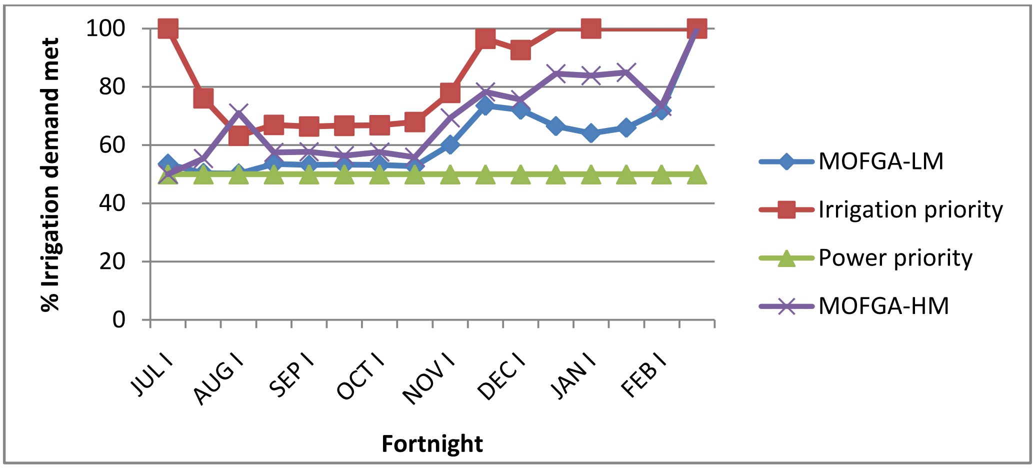


Figure 4. % Irrigation demand met by MOFGA-NLP for 75% dependable inflows

Table 8. Typical optimal % allocation of water to each crop by MOFGANLP-LM with 75% inflows

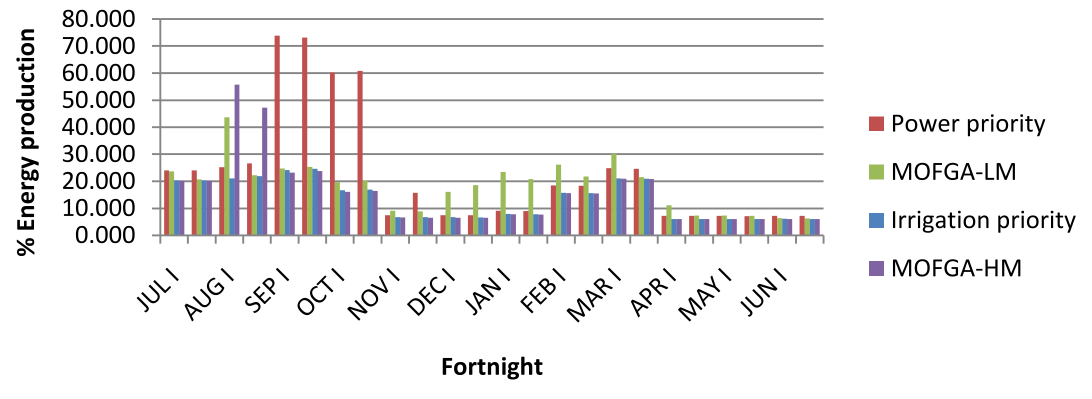
Fortnight	NSLC crops						
	Rice1(K)	Rice2(K)	Cotton	Chilli	Groundnut (R)	Sorghum (R)	Grams (R)
1							
2	50						
3	50	50					
4	50	50					
5	50	50	74	84			
6	50	50	91	83			
7	50	50	97	97			
8	50	50	97	96	95	51	51
9		50	98	99	98	50	50
10			99	99	99	51	51
11			99	99	100	52	53
12			96	99	100	51	51
13			82	98	100	50	50
14			96		97	50	51
15					99		
16							

Fortnight	NSRC crops									
	Rice1 (K)	Rice2 (K)	Groundnut(K)	Sorghum(K)	Grams (K)	Cotton	Chilli	Groundnut (R)	Sorghum (R)	Grams (R)
1			51							
2	50		51	51	50	51				
3	50	50	51	51	50	51				
4	50	50	98	51	50	51	99			
5	50	50	96	60	66	51	98			
6	50	50	94	53	53	67	98			
7	50	50	52	53	52	72	99			
8	50	50	58	51	52	52	99			
9		50		51		75	100	98	51	50
10						92	100	98	51	50
11						88	100	94	51	50
12						54	100	100	54	56
13						51	100	100	51	51
14						73		100	52	51
15								98	51	51
16								98		

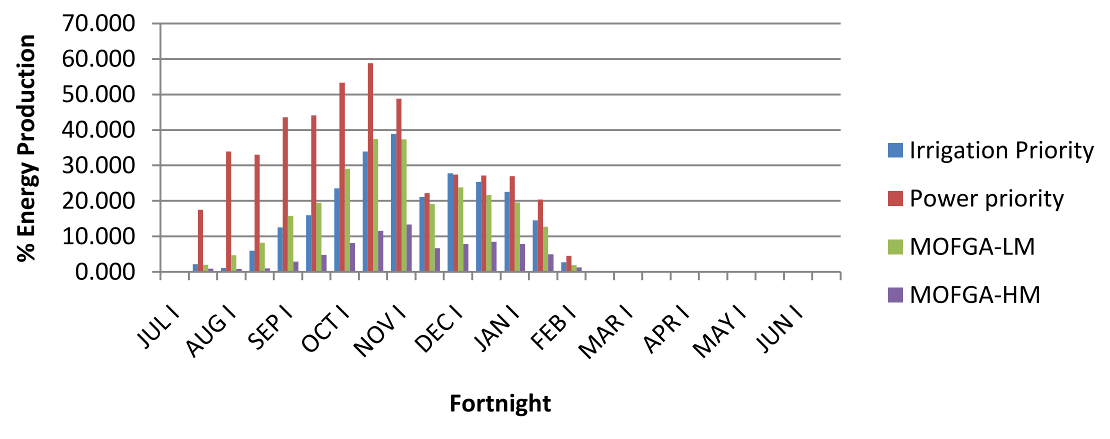
Table 9. Typical optimal % allocation of water to each crop by MOFGANLP-HM with 75% inflows

Fortnight	NSLC crops						
	Rice1(K)	Rice2(K)	Cotton	Chilli	Groundnut (R)	Sorghum (R)	Grams (R)
1							
2	50						
3	64	81					
4	50	50					
5	50	50	100	100			
6	50	50	100	100			
7	50	50	100	100			
8	50	50	100	100	100	50	50
9		50	100	100	100	77	50
10			100	100	100	70	50
11			100	100	100	50	58
12			100	100	100	50	88
13			100	100	100	50	94
14			100		100	50	89
15					100		
16							

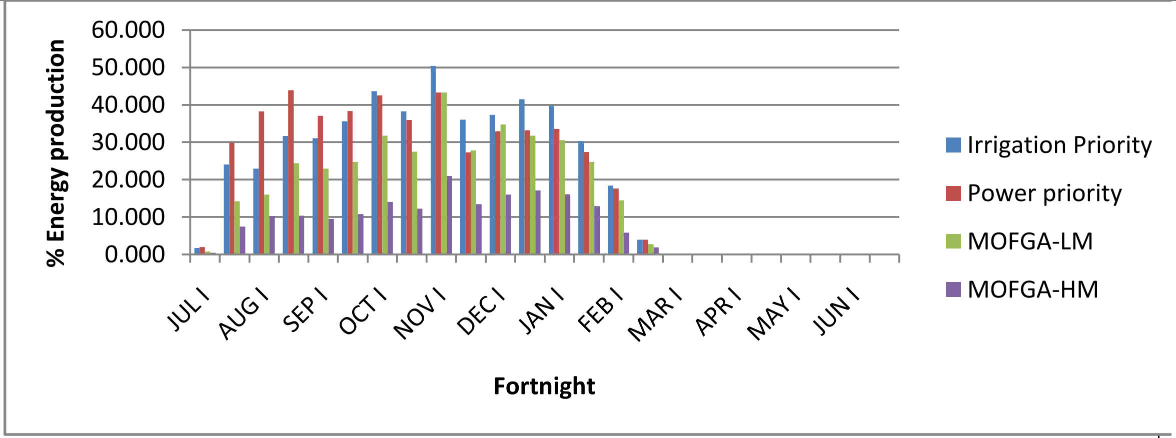
Fortnight	NSRC crops									
	Rice1 (K)	Rice2 (K)	Groundnut(K)	Sorghum(K)	Grams (K)	Cotton	Chilli	Groundnut (R)	Sorghum (R)	Grams (R)
1			50							
2	50		68	50	50	100				
3	79	50	100	74	50	100				
4	50	50	100	67	50	100	100			
5	50	50	100	100	79	100	100			
6	50	50	100	72	58	100	100			
7	50	50	50	97	73	100	100			
8	50	50	50	50	50	100	100			
9		50		100		100	100	100	100	59
10						100	100	100	50	50
11						100	100	100	50	50
12						100	100	100	50	80
13						100	100	100	50	72
14						100		100	50	89
15								100	50	53
16								100		



(a) % Energy production with main power house



(c) % Energy production with left power house



(e) % Energy production with right power house

Figure 5. Fortnight wise % energy production through main, left & right power houses

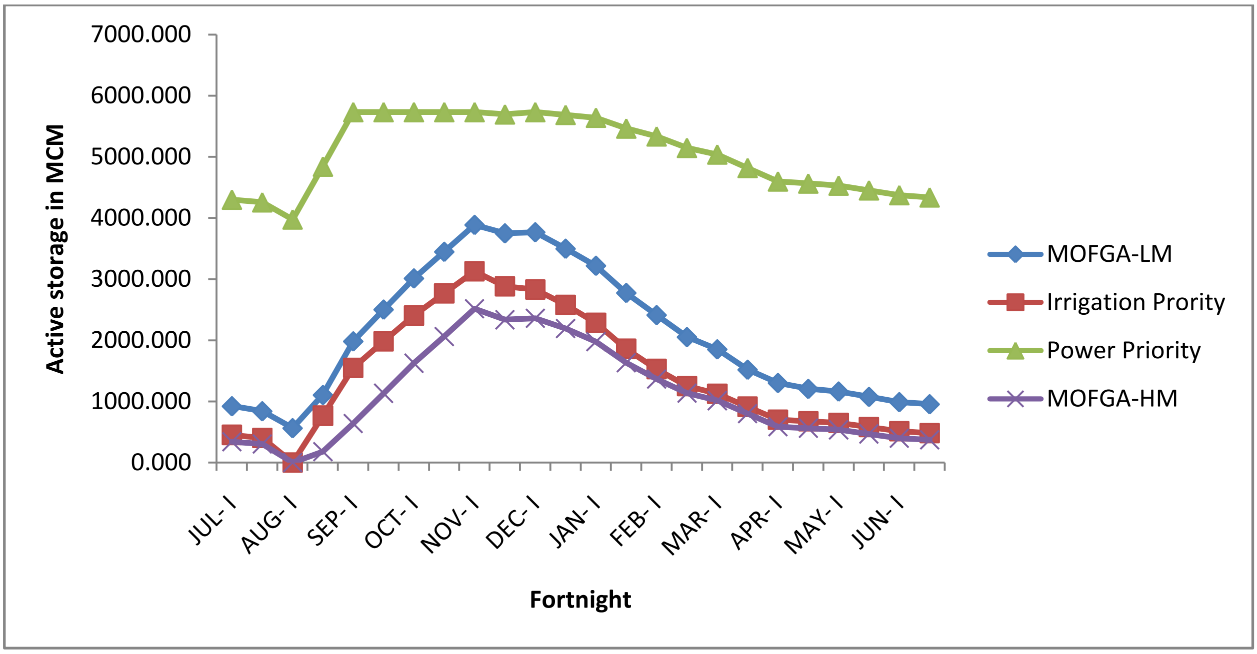


Figure 6. Storage policy for 75% dependable inflows

Table 10. Maximum level of satisfaction and corresponding objective function values for various dependable inflows for linear membership function

Dependable Inflow	Maximum Level of satisfaction (λ)	F_1	F_2
75% PE	0.44	7447.18	10785.4
80% PE	0.20	4461.39	8466.48
85% PE	0.19	3308.23	6825.16
90% PE	0.46	3862.57	8418.26

Table 11. Maximum level of satisfaction and corresponding objective function values for various dependable inflows for hyperbolic membership function

Dependable Inflow	Maximum Level of satisfaction (λ)	F_1	F_2
75% PE	0.876	10003.97	8780.28
80% PE	0.876	6581.55	7961.18
85% PE	0.876	5631.90	7419.47
90% PE	0.876	4461.56	7302.74

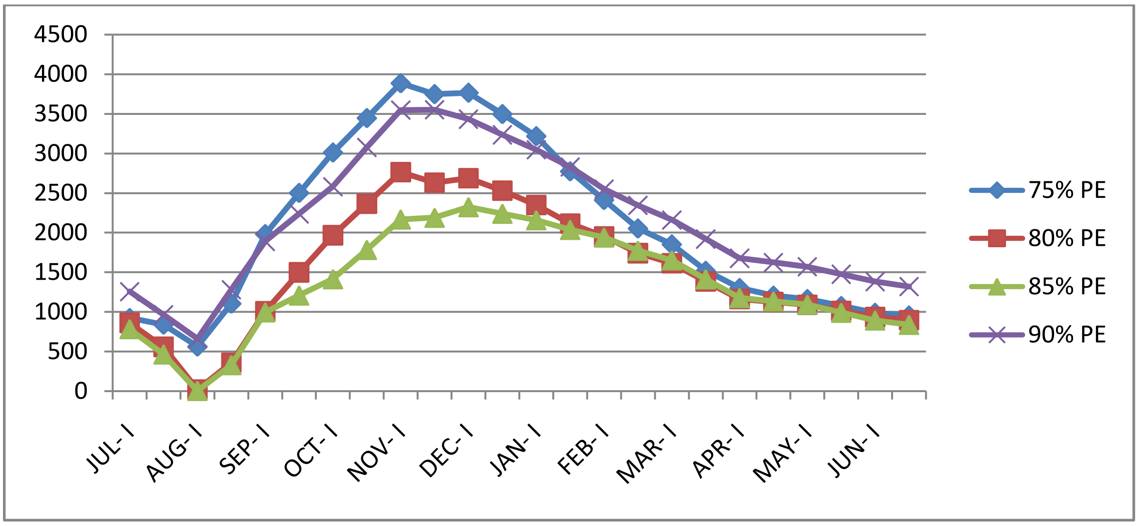


Figure 7. Storage policy by MOFGANLP-LM for various inflows

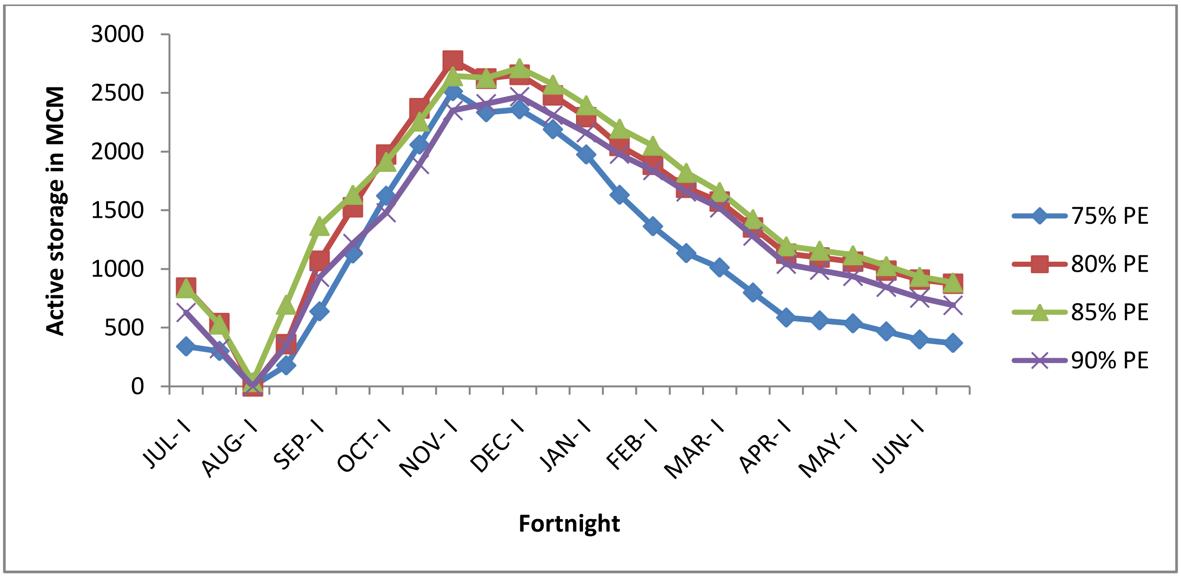


Figure 8. Storage policy by MOFGANLP-HM for various inflows

Summary and conclusions

Multi Objective Fuzzy Genetic Algorithm- Non Linear Programming (MOFGA-NLP) model is formulated to find best compromised operating policies and applied to the case study, Nagarjuna Sagar reservoir on river Krishna in India. The two objective functions considered are maximization of Net benefits from irrigation considering sensitivity of yield with water deficit and energy production from all the power houses installed. GA-NLP hybrid model is more effective compared to GA for obtaining global optima, minimizing the number iterations by changing GA parameters values. Best compromised operating policies of the reservoir are obtained by MOFGA-NLP by linear and hyperbolic membership functions considering the objectives are in fuzzy. The maximum level of satisfaction and overall benefits obtained by hyperbolic membership function is more compared to linear membership function. The optimum fortnight crop water allocations, reservoir releases into both left & right main canals, releases into all the power houses and active storages (rule curves) to be maintained in the reservoir are also found for different dependable inflows. These rule curves will be useful to guide the decision maker.

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