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Deriving Optimal Crop Plan for Dimbhe Reservoir – A Fuzzy Multi-Objective Approach

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Abstract: *A multi-objective fuzzy linear programming model (MOFLP) is formulated to derive an optimal crop plan for a multi-canal irrigation system. In the present study, the vagueness and imprecision in the objectives and inflows are treated as fuzzy variables. These variables are quantified through a membership function in the fuzzy multi-objective framework. The MOFLP model maximizes the degree of satisfaction subject to various physical and economic constraints involving the fuzziness in the input variables. The developed model is used for deriving optimal crop plans for Dimbhe reservoir command area, located in the State of Maharashtra, India. The results of MOFLP model are compared with that of a classical linear programming (LP) model. From the results, it is found that the LP model have resulted in same net benefits (Rs. 1076.24 Million) and crop production (738.41 thousand tonnes) up to 75% dependable inflow levels. The MOFLP model with 0.41 level of satisfaction has resulted in a net benefit of Rs. 962.34 Million and 590.78 thousand tonnes of crop production.*

Keywords: *Optimal Crop Planning, Irrigation, Optimization, Multi-objective Fuzzy Linear Programming, Multi-canal Reservoir system, Dimbhe reservoir*

1. Introduction:

Efficient irrigation water management is a key issue in crop production, since irrigated agriculture is the largest consumer of water, especially in India. However, the uncertainty of rainfall and availability of water over space and time poses a serious challenge to agriculture to cope up the demand for irrigation for different growing seasons as well as for different command area. This necessitates the need to derive a suitable optimal crop plan for efficient operation and management of an irrigation system. Many mathematical models had been developed for deriving optimal crop plan, among which the linear programming (LP) technique was widely used. Moradi-Jalal et al. [1] developed a deterministic LP model for the optimal multi-crop irrigation with the objective of maximizing the annual benefit from the command area. It was reported that the LP technique is an effective tool for determining the optimal multi-cropping patterns and allocating crop areas for a reservoir-irrigation system. Mohan and Jothiprakash [2] derived an optimal crop plan for Sri Ram Sagar Reservoir Project (SRSP), India using a deterministic LP model, with and without conjunctive use. Upon analyzing various policies, it was reported that the conjunctive operation of surface and groundwater is essential in the command area of SRSP. Similarly, Tzimopoulos et al. [3] derived an optimal cropping pattern using a LP model for the irrigation planning of Agios Athanasios Greece with the objective of maximizing the net benefits. It was reported that the LP model provided the best optimal cropping pattern for the region with highest profit both for the cultivator and the water resources. However, a simple LP model does not consider the uncertainty and vagueness in the variables. The uncertainty can be handled either implicit or explicit stochastic approaches.

Chance constraint is one way considering the randomness in the variable. Maji and Heady [4] derived an optimal cropping pattern for Mayurakshi project in India using a chance-constrained LP (CCLP) model and compared the results with deterministic LP model. It was reported that both the deterministic and change-constrained models have resulted a more intensive cropping pattern with more dependence on Rabi than Kharif crops in the region. Raju and Nagesh Kumar [5] developed a CCLP model for the irrigation planning of SRSP, India with the objective of maximization of net benefits. The uncertainty in the inflows was considered as chance constrained for different dependable levels. It was reported that the net benefits obtained for 75% dependable inflow level is 68.8% more than 90% dependable inflow level. Jothiprakash et al. [6] derived an optimal cropping pattern for SRSP, India for various dependable inflows levels using a CCLP model. The cropping pattern was analyzed for different monthly and annual inflow probability levels. Based on this analysis, it was reported for the probability of model time period (monthly) should be considered rather than planning time period (annual). However, these approaches can handle only the statistical uncertainty and not the non-statistical uncertainty namely vagueness or impreciseness present in the data [7]. In such cases, the fuzzy set theory developed by Zadek [8] has been proved as a robust where these kinds of uncertainties can be modelled as fuzzy variables [9].

Mohan and Jothiprakash [7] developed a fuzzy linear programming (FLP) model for the conjunctive operation of SRSP, India. It was reported that the FLP model resulted an optimal crop plan with a degree of satisfaction of 0.78 while considering the fuzziness in different variables. Raju and Nagesh Kumar [10] developed a multi-objective fuzzy linear programming (MOFLP) model for the SRSP, India. It was concluded that the MOFLP is simple and suitable tool for multi-objective problems compared to other methods. Itoh and Ishii [11] proposed a fuzzy crop planning model considering profit co-efficient as fuzzy variables. Raju and Duckstein [12] developed a MOFLP irrigation planning model for the evaluation of management strategy of Jayakwadi irrigation project, Maharashtra, India. While achieving a 0.57 level of satisfaction, it was stated that the net benefits, agricultural production, labour employment were decreased by 4.13, 5.39 and 3.4% compared to the crisp LP model. Regulwar and Gurav [13] achieved a 0.58 level of satisfaction using a MOFLP model for Jayakwadi Project Stage-I in the State of Maharashtra, India. It was reported that the results obtained using MOFLP are promising for sustainable development in irrigation sector and closer to the true picture of the real world problem as it incorporates the fuzziness in both resources and decision variables simultaneously. A two phase MOFLP model was developed by Mirajkar and Patel [14] for the optimal crop planning of Kakrapar Right Bank Main Canal (KRBMC) under Ukai command area in India. It was reported that the developed methodology can be extended further considering other relevant constraints. Even though, some studies have been reported on MOFLP, most of the studies considered the fuzziness only in the technological co-efficient of the objective function and not in the inflow. However, inflow is the main input variable to an optimal crop planning model and has high uncertainty over space and time. Hence in the present study, the vagueness in both the objective function and inflow are considered as fuzzy variables while deriving an optimal crop plan for the multiple canals of Dimbhe reservoir in Maharashtra. The heterogeneity of the crops under various canals is taken into account while deriving the optimal crop plan. The results are compared with the conventional crisp LP model.

2. Study Area:

Dimbhe is a masonry dam across River Ghod in Maharashtra with the global coordinates of 19° 6′ N latitude and 73° 43′ E longitude. The gross storage capacity of Dimbhe is 382.22 x 10^6 m^3 [15]. The schematic sketch of the canals of Dimbhe dam is given in Fig.1. The irrigable command area of Dimbhe reservoir is 36,524 ha through four canals. The Dimbhe Left Bank Canal (DLBC) takes off directly from the dam where as the Dimbhe Right Bank Canal (DRBC) takes off from DLBC at the third kilometre through an aqueduct across Ghod River. Both the canals irrigate the areas in the Ghod and Mina valleys, about a command area of 2,631 ha and 14,549 ha respectively. The Ghod Branch Canal (GBC) takes off from the DLBC and irrigates an area of about 4,330 Ha. The Meena Branch Canal (MBC) also takes off from DLBC and irrigates an area of about 15,014 ha. Kharif and Rabi are the seasons during which crops are cultivated. During Kharif season crops such as Jawar Hybrid, Bajari Hybrid, Paddy drilled, Groundnut, Chillies, and Vegetables are grown and during Rabi, Wheat, Jawar Local Rabi, Jawar Hybrid Rabi, Jawar Rabi (Rattoon), Peas, Vegetables/Onion and Potatoes are cultivated. The irrigation water requirement of different crops is estimated by Modified Penman Method and the monthly demands are estimated incorporating the transmission losses.

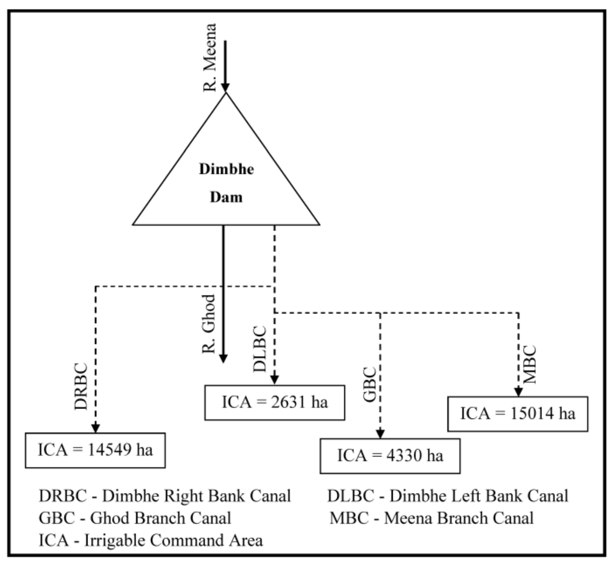

Figure 1. *Schematic sketch of canals of Dimbhe reservoir*

3. Linear Programming (LP) Model:

Initially, a LP model is formulated with the objective of maximizing the net benefits and crop production from the command area of various canals of Dimbhe reservoir.

3.1 Objective Functions:

The first objective to maximize the net benefits from the command area of Dimbhe dam. It is given as

Maximize

$$NB = \sum_{j=1}^{4}\sum_{i=1}^{6} CK_i AK_{i,c} + \sum_{j=1}^{4}\sum_{i=7}^{13} CR_i AR_{i,c} \qquad (1)$$

where i = Crop index [1 = Jawar Hybrid (K), 2 = Bajari Hybrid (K), 3 = Paddy drilled (K), 4 = Groundnut (K), 5 = Chillies (K), 6 = Vegetables (K), 7 = Wheat (R), 8 = Jawar Local Rabi (R), 9 = Jawar Hybrid (R), 10 = Jawar Rabi (Rattoon) (R), 11 = Peas (R), 12 = Vegetables (R) and 13 = Potatoes (R), K = Kharif, R = Rabi]. NB = Net benefits from the whole planning region (Indian Rupees); CK_i = Gross benefits from the Kharif crop 'i' and CR_i = Gross benefits from the Rabi crop 'i' from the command area of Dimbhe dam. The net benefits are calculated after deducting of other input charges from the gross benefits. $AK_{i,c}$ = Area of Kharif crop 'i' grown in the command areas of canal 'c', $AR_{i,c}$ = Area of Rabi crop 'i' grown in the command areas of canal 'c'. c = canal index [1= Dimbhe Right Bank Canal (DRBC), 2 = Dimbhe Left Bank Canal (DLBC), 3 = Ghod Branch Canal (GBC), 4 = Meena Branch Canal (MBC)].

The second objective is to maximize the crop production of various crops from the command area and is given by

$$\text{Maximize } CP = \sum_{c=1}^{4}\sum_{i=1}^{6} Y_i AK_{i,c} + \sum_{c=1}^{4}\sum_{i=7}^{13} Y_i AR_{i,c} \qquad (2)$$

where Y_i = average yield of crop 'i' in tonnes/ha.

3.2 Constraints:

The constraints such as seasonal land availability, spatial land availability, minimum sowing area constraint and canal capacity constraint are considered in model development. In addition to these constraints, the system constraints such, storage, evaporation, releases, overflow and mass balance are also considered in this study. Each constraint is explained in the detail in the following section.

3.2.1 Crop area constraint: The total area for various crops should be less than total area available for cultivation in command area during different crop seasons. Thus the total cropping area constraint for Kharif and Rabi seasons are given by

For Kharif Season

$$\sum_{c=1}^{4}\sum_{i=1}^{6} AK_{i,c} \le CCA_K \qquad (3)$$

For Rabi Season

$$\sum_{c=1}^{4}\sum_{i=7}^{13} AR_{i,c} \le CCA_R \qquad (4)$$

where CCA_K and CCA_R is the maximum area available for cultivation during Kharif and Rabi seasons respectively.

3.2.2 Canal area constraint: The total crop area under each canal should not be more than the maximum area available for irrigation in that canal. It is given as

For Kharif Season

$$\sum_{i=1}^{6} AK_{i,c} \le CCAK_c \qquad c = 1,\ldots,4 \qquad (5)$$

For Rabi Season

$$\sum_{i=7}^{13} AR_{i,c} \le CCAR_c \qquad c = 1,\ldots,4 \qquad (6)$$

3.2.3 Maximum sowing area constraint: The minimum crop area constraint is given to ensure that all the crops in the existing cropping patter mentioned in the project report [15] have entered into cropping area. The minimum sowing area constraint is given by,

For Kharif Crops

$$AK_{i,c} \ge AK_{i,c}^{\min} \qquad i = 1,\ldots,6;\ c = 1,\ldots,4 \qquad (7)$$

For Rabi Crops

$$AR_{i,c} \ge AR_{i,c}^{\min} \qquad i = 7,\ldots,13;\ c = 1,\ldots,4 \qquad (8)$$

3.2.4 Crop water requirement constraint: The water requirement for various crops under each canal is estimated by multiplying the net irrigation requirement for the crop 'i' and area of the crop 'i' during the time period 't'. The net irrigation requirement is using Modified Penman method and accounting water lost during transmission. The crop water requirement in the command area for various seasons is given as

$$R_{t,c} \ge \sum_{i=1}^{6} WR_{i,t} AK_{i,c} + \sum_{i=7}^{13} WR_{i,t} AR_{i,c}$$
$$t = 1,\ldots,12;\ c = 1,\ldots,4 \qquad (9)$$

where $WR_{i,t}$ is the depth of water required for crop 'i' during the time period 't'.

3.2.5 Canal capacity constraint: Irrigation release from the reservoir at any time period 't' should be less than or equal to the carrying capacity of canals:

$$R_{t,c} \le CCC_c \qquad t = 1,\ldots,12 \qquad (10)$$

where CCC_C is the carrying capacity of the canal 'c'.

3.2.6 Mass balance equation: For any given time period 't', the final storage in the reservoir should be equal to the inflow, releases and other losses of the system. Thus the storage at the end of the time period 't' is given as

$$S_{t+1} = S_t + I_t - \sum_{c=1}^{4} R_{t,c} - E_t - O_t$$

$$c = 1,\ldots 4;\ t = 1,\ldots,12 \quad (11)$$

3.2.7 Minimum and maximum storage constraint: Reservoir storage in any month should not be more than the maximum storage capacity of the reservoir, and should not be less than the minimum storage capacity (dead storage) of the reservoir

$$S_{\min} \le S_t \le S_{\max} \qquad t = 1,\ldots,12 \quad (12)$$

where S_{min} and S_{max} are the minimum and maximum storage of reservoir.

3.2.8 Overflow constraint: The overflow from the reservoir during the time period 't' is given as

$$O_t = S_{t+1} - S_{\max} \qquad t = 1,\ldots,12 \quad (13)$$

$$O_t \ge 0 \qquad t = 1,\ldots,12 \quad (14)$$

The model is solved using LP technique and the results are used for formulating the MOFLP model. The formulation of MOFLP is discussed in the following section.

4. Multi-objective Fuzzy Linear Programming (MOFLP) Model:

In the multi-objective fuzzy linear programming (MOFLP) model, the objectives and inflow are considered as imprecise and represented by fuzzy variables by a membership function [9]. The LP model is transferred to MOFLP model by modifying the objectives as maximizing the degree of satisfaction.

$$\text{Maximise} \qquad \lambda \quad (15)$$

Subject to

The first objective maximizing the net benefits is converted in to fuzzy as

$$\frac{NB - NB_L}{NB_U - NB_L} \ge \lambda \quad (16)$$

The second objective maximizing the crop production is converted in to fuzzy as

$$\frac{CP - CP_L}{CP_U - CP_L} \ge \lambda \quad (17)$$

The fuzziness in the inflow is incorporated through the mass balance equation (Eq. 11). In Eq. (11) inflow is represented as

$$I_t = \underline{I}_t + \lambda(\overline{I}_t - \underline{I}_t) \quad (18)$$

where λ is the degree of satisfaction which ranges between 0 and 1. The values of NB_U, NB_L, CP_U and CP_L are obtained from the crisp LP model. $\underline{I}_t$ is the minimum limit of inflow and $\bar{I}_t$ is the normal limit of inflow during the time period 't'. The 80% dependable inflow level is considered as normal limit and 90% dependable inflow level is considered as minimum limit. In addition to the above fuzzy constraints (Eq. 16, 17 and 18), all the constraints considered in LP model is also considered while solving the MOFLP model.

5. Results and Discussion:

In the present study, an optimal cropping pattern for the multiple canals of Dimbhe reservoir is derived using MOFLP technique. The total irrigable area of the Dimbhe dam is around 36,524 ha. The multi-objectives considered are (i) maximization of net benefits from the command area and (ii) maximization of production from various crops. Initially, these two objectives are optimized separately for three inflow scenarios, (i) 50% dependable inflow scenario, (ii) 75% dependable scenario and (iii) 90% dependable inflow scenarios using deterministic LP. The results obtained for these inflow scenarios are given in Table 1. It is found that both 50% and 75% dependable inflow scenarios resulted in same net benefits and crop production. The maximum net benefit obtained for these two inflow scenario is Rs. 1076.24 Million and 738.41 thousand tones crop production. The 90% dependable inflow has resulted in a net benefit of Rs. 787.97 Million and 487.23 thousand tonnes of crop production. On comparing with other two scenarios the net benefit is decreased by 27% and crop production by 34%. This is due to the less inflow observed at 90% dependable inflow level. These results also show that the reservoir is capable of irrigating more area. Only under extreme low inflows, there is a reduction in crop area and net benefits. From the results of the deterministic LP, the upper and lower limits for fuzzy variables are fixed for MOFLP model.

The objective functions and the inflow are considered as fuzzy variables and modelled using MOFLP technique. Since, both the 50% dependable inflow and 75% dependable inflow resulted same, 80% dependable inflow is considered as normal inflow in formulating the fuzzy inflow. The results of MOFLP model is also given in Table 1. The table shows that the MOFLP model has also resulted in a net benefit of Rs. 962.34 Millions and 590.78 thousand tonnes of crop production. It is found that the net benefit decreases by 10.58% and crop production by 20% in MOFLP model compared to 50% and 75% dependable inflows of crisp LP model. This is due to the reduction inflow, since inflow is considered as fuzzy in MOFLP model. However, on comparing with 90% dependable inflow LP model, there is a 21% increases in both net benefit and crop production in MOFLP model. A maximum level of satisfaction of 0.41 is achieved in MOFLP model.

Table 1. *Results of LP and MOFLP models*

Model	Deterministic LP			MOFLP
Inflow	50%	75%	90%	Fuzzy
NB	1076.24	1076.24	789.97	962.34
CP	738.41	738.41	487.23	590.78
λ	-	-	-	0.41

NB = Net Benefits (Million Rupees), CP = Crop Production (‘000 Tonnes), λ = Level of satisfaction

The optimal cropping pattern resulted from LP and MOFLP model is given in Fig. 2. The crop index 1-6 shows the Kharif crops and 7-13 are Rabi crops. From the figure, it is found that the crop area varies only for vegetables during Kharif and wheat during Rabi among the LP and MOFLP models. There is a huge reduction in crop area of vegetables during Kharif and potatoes during Rabi in DLBC for MOFLP model. It is observed that both the 50% and 75% dependable inflow scenarios have resulted same cropping pattern. Both the inflows have resulted a total crop area of 35,931 ha during Kharif and 25,492 ha during Rabi season. It is found that the crop area during Kharif is higher than Rabi under all canals due to less water requirement during Kharif season. However, the crop area under DLBC is same for 50% and 75% dependable inflow during Kharif and Rabi season. All the crops proposed in the project report [15] have entered the crop area because of minimum sowing area constraint. However, only vegetable crops in both Kharif and Rabi have resulted in higher cropping area. All other crops have resulted only the minimum crop area given in constraint Eq. 6 and Eq. 7. This may be is due to that the vegetable crops have high monetary value and also requires comparatively less water than other crops. It also observed that the crops like Paddy which required intensive irrigation have resulted in very less crop area compared to other crops.

The resulted final storage levels for Dimbhe dam from the LP and MOFLP model is given in Fig. 3. From the figure, it can be observed that the 50% dependable inflow has resulted in higher storage levels due to high inflow than inflow scenarios and MOFLP model. Also, the high storage in scenario 1 has resulted in more evaporation than scenario 1. Since, the inflow is considered as fuzzy in MOFLP model, the storage levels are slightly lower than 90% dependable level. However, both the 90% dependable inflow and MOFLP models have resulted in similar pattern.

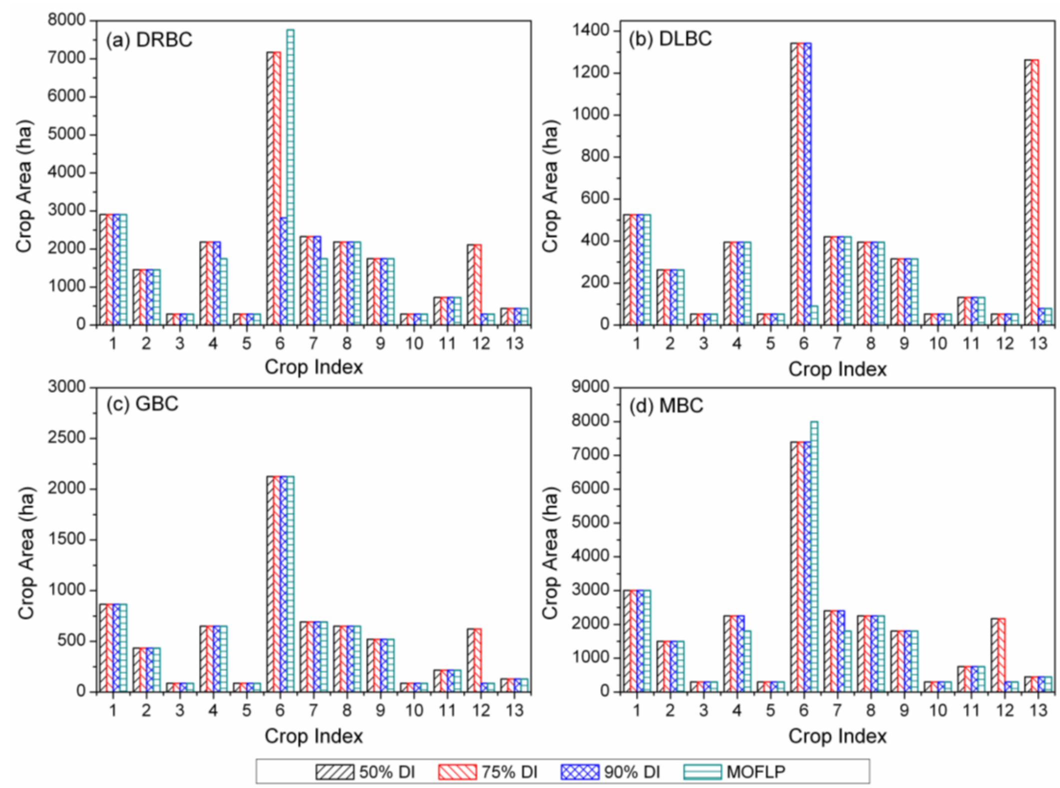

Figure 2. *Resulted Optimal Crop Area for various canals from LP and MOFLP model*

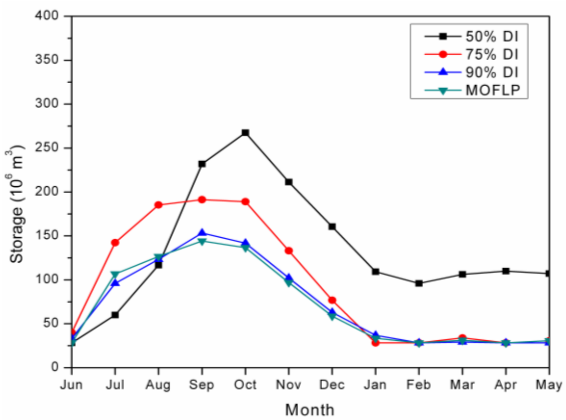

Figure 3. *Final storage levels resulted from LP and MOFLP model*

6. Conclusions:

A multi-objective fuzzy linear programming (MOFLP) model has been developed to derive the optimal crop plans for the command area of multiple canals of Dimbhe reservoir. Initially two separate LP models are formulated with the objective of maximizing the total net benefits and maximizing the crop production from the command of each canal. From the results of the crisp LP models, the MOFLP is formulated and solved for the fuzzified inflow. The MOFLP model resulted a total net benefit of 962.34 Million Rupees and 590.78 thousand tonnes of crop production. It may be concluded that MOFLP is a suitable technique for deriving optimal crop plans for a multi-canal irrigation system having multiple objectives.

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