Multiobjective Intuitionistic Fuzzy Optimization Approach in optimal Irrigation Planning and Operation of Reservoir

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Multiobjective Intuitionistic Fuzzy Optimization Approach in optimal Irrigation Planning and Operation of Reservoir

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Abstract

The present study includes the formulation of a Multiobjective Intuitionistic Fuzzy Linear Programming model for optimal scheduling of crops in the command area of the Ukai-Kakrapar Irrigation project, Gujarat, India. The crisp linear programming approach has been used to obtain the optimal solutions of four conflicting objectives, viz., maximization of net irrigation benefits, employment generation, minimization of cost of cultivation, and maximization of revenue generation from industrial and municipal supplies. The crisp solutions were, in turn, used to develop Intuitionistic Fuzzy Optimization Multiobjective fuzzy linear programming (IFO MOFLP), IFO MOFLP with hesitation index, and two-phase IFO MOFLP (TPIFO MOFLP) models. The performance of IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP models are compared in terms of the degree of acceptance, degree of rejection, and hesitation index for inflows at 75% probability of exceedance. The results obtained from IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP are also compared with the Compromised MOFLP (Average Operator Case-I) solutions given by Mirajkar and Patel (2016) for the same command area. The irrigation intensity for the entire command area from the proposed TPIFO MOFLP model (112.19%) is considerably higher than those obtained from the Average Operator Case-I (104.60%) model proposed by Mirajkar and Patel (2016). The net irrigation benefits, employment generation, cost of cultivation, and revenue generation from municipal and industrial supplies, resulting from the proposed TPIFO MOFLP model are Rs 10,836.19 million, 34,980.4 thousand workdays, Rs 5,672.23 million, and Rs 2,314.03 million, respectively along with the degree of acceptance, α=0.68, degree of rejection, β =0.19 and degree of hesitation, π =0.13. The corresponding values reported from the Compromised MOFLP model (Average Operator Case-I) (Mirajkar and Patel,2016) were Rs 11,058.27 million, 33,414.62 thousand workdays, Rs 5,622.20 million, and Rs

2,686.25 million, respectively. The releases from the reservoir corresponding to the proposed TPIFO MOFLP model are comparatively lesser than the Compromised MOFLP (Average Operator Case-I) model, indicating the optimal allocation of available water in the command area. Apart from giving better values of selected objective functions, the proposed model also gives additional uncertainty measures like degree of acceptance, degree of rejection, and degree of hesitation which would help the planner to make better decisions for a real-world problem.

Keywords: Intuitionistic fuzzy optimization, degree of acceptance, degree of rejection, hesitation index, optimal irrigation planning, Ukai-Kakrapar Irrigation project, Reservoir operation

1. Introduction

Water is increasingly becoming a precious resource due to climatic and anthropogenic changes across the globe. The water demands have increased manifolds due to the accelerated growth of population and industries in recent years. The planning and management of water resources are becoming a complex issue due to inconsistent and conflicting demands of different stakeholders which are to be met simultaneously. Under the above situation, it is important to implement scientific and well-organized water management approaches to preserve and optimize the existing water resources. The scheduling and prioritization of water resources schemes under multi-sectoral demands, is a complex task as it involves uncertainty and vagueness in irrigation demand, accessibility of labor in the command area for farming, benefits from crops, and inflows into the reservoir, etc. Fuzzy set theory has been identified as an alternative approach to handle such uncertainty and vagueness in planning the water resources schemes with multiple objectives. The following paragraphs include the applications of multi-objective fuzzy optimization approach in integrated management of water resources.

Morankar *et al*. (2016) applied the particle swarm optimization (PSO) technique in multiobjective irrigation planning of the Khdakwasala water resources project in India while considering three objectives, namely, i.e., maximization of net irrigation benefits, crop production, and labor employment in the command area. Uncertainty in the objective functions were tackled by applying fuzzy approach with hyperbolic and exponential membership functions, and concluded that PSO using hyperbolic membership function is superior to the exponential membership function for their case study. Regulwar and Gurav (2010) developed an irrigation planning model using multi-objective fuzzy linear programming (MOFLP) approach for optimal crop planning in the command area of Jayakwadi project stage I, Maharashtra state, India. The MOFLP model in the study was formulated using four objective functions, namely, net irrigation benefits (NB), crop /yield production (YP), Employment generation (EG), and Manure Utilization (MU), in which the objective functions and constraints were crisp in nature. The results of the MOFLP and LP were compared, and concluded that the proposed methodology was efficient with an overall degree of satisfaction of 0.58. Mirajkar and Patel (2011) demonstrated the application of fuzzy-based optimal irrigation planning for the Kakarapar right bank canal command area in India using a multiobjective linear programming model with a fuzzy decision set while considering three objectives, and arrived at a compromised solution with the level of satisfaction (λ) as 0.501. Regulwar and Gurav (2012) highlighted fuzzy logic for modeling uncertainty in water resources systems. In this study, objectives and constraints were treated as fuzzy in nature for the programming of reservoir operation models. These models were applied to a case study of Jayakwadi reservoir stage-II, Maharashtra State in India with the objective of maximization of releases for irrigation and hydropower. The study concluded that the MOFLP model, having the fuzziness in all the parameters, provides the best adaption to deal with real-world situations of sustainable irrigation planning. Raju and Kumar (2000) applied the Multi-Objective Fuzzy Linear Programming approach in irrigation planning using three conflicting objectives. The study was implemented for the Sri Ram Irrigation Project in India. The compromised solution for these three objective functions was worked out with the degree of truth (λ) as 0.69. Raju *et al.* (2012) applied multi-objective Differential Evolution (MODE) in irrigation planning and its application is demonstrated through a case study of Mahi Bajaj Sagar Project, Rajasthan, India. Three conflicting objectives, namely, net benefits, agricultural production and labour employment, are considered for analysis using multi-objective differential evolution (MODE); and non-dominated alternative was generated with K means cluster analysis for effective decision in irrigation planning. Mirajkar and Patel (2012) implemented a crisp linear programming methodology to acquire individual solutions for three conflicting objectives, i.e., maximization of net irrigation benefits, employment generation, and minimization of cost of cultivation. The crisp solutions were further used to get the optimal solution using a fuzzy multiobjective approach which is based on maximum-minimum operators. The solution obtained through maximum-minimum operators was extended further using two-phase fuzzy compromised solutions. These algorithms were validated for a case study of the Kakrapar Right bank main canal (KRBMC) under the Ukai command area in India. Mirajkar and Patel (2013) developed a sustainable irrigation planning model using a multi-objective (i.e., Maximization of net benefits, employment generation, and revenue generation, and minimization of cost of cultivation) fuzzy linear programming approach for the Ukai-Kakrapar irrigation project for the most critical, critical, normal and wet years. The study revealed that probable inflow equivalent to 75% dependability is just sufficient to meet the prerequisite of the study area, and there is a shortage of water in the command area for 85% dependable inflow condition. Morankar *et al.* (2013) considered a multiobjective fuzzy methodology for the Khadakwasala irrigation project while considering three objectives, i.e., maximization of net benefits, crop production, and labor employment, for three types of membership functions, namely, nonlinear, hyperbolic, and exponential membership functions. The study revealed that exponential and hyperbolic membership functions provide similar cropping patterns for most of the situations whereas nonlinear membership functions provide different cropping patterns. The irrigation intensity was found to be more than the actual irrigation intensity for all three membership functions. Mirajkar and Patel (2016) determined the optimal operational schemes for whole command areas of the Ukai Reservoir in India. These strategies were derived from four conflicting objective functions i.e., maximization of net benefits, employment generation, minimization of cost of cultivation, and also maximization of revenue generation from municipal and industrial supplies. Maximum minimum operator (max-min), two-phase MOFLP (TPMOFLP), along with fuzzy compromise approach, i.e., average operator, were used as a multi-objective fuzzy linear programming (MOFLP) models to achieve optimized values of the relative objective functions. The obtained results revealed that the average operator gives maximum irrigation intensity as compared to the max-min and TPMOFLP models. Arunkumar and Jothiprakash (2016) applied Multiobjective fuzzy linear programming approach with the objectives of minimization of Net benefits and crop production. This methodology is validated to the case study of Kukadi Irrigation project (KIP) in Maharashtra, India. The MOFLP model resulted in a level of satisfaction of 0.46, with an irrigation intensity of 102.18% along with the total crop area of 1,49232 ha. Also, study reveals that all the canals in the system performed well with a reliability exceeding 0.95. Ren *et al.* (2017) explored the MOFLP model for optimizing usage of water and land resources for irrigation under uncertainty. The MOFLP model considered three objectives namely, administrative objective i.e., minimizing the irrigation water by reducing the irrigation areas on the basis of guarantee food security, economic objective i.e., maximizing crop yield of irrigation areas and ecological objective i.e., minimizing the exploitation of groundwater levels. The methodology was validated for a case study of Wuwel, Gansu Province, China. The study concluded that the proposed method gives the most favorable plans for irrigation water and land use under uncertainty.

Atanassov (1986) introduced the concept of an intuitionistic fuzzy set (IFS). The properties of the intuitionistic fuzzy set were derived and linked with operations and relations over the set. Angelov (1997) considered the extension of fuzzy optimization in addition to the application of Intuitionistic fuzzy sets. The study clarified that the degree of non-membership, i.e., the degree of rejection, is not complimentary to the degree of membership (the degree of acceptance), of objective functions. The study concluded that solutions of Intuitionistic Fuzzy optimization (IFO) satisfy the objective functions with a greater degree of satisfaction than those obtained using simply fuzzy and crisp optimization techniques. Hernandez and Uddameri (2010) applied a multi-criteria decision-making method based on Atanassov's intuitionistic fuzzy sets (A-IFS) theory. This study used the ranking of best management practices in an agricultural field in the South Texas region of the USA. The solution resulted in the ranking of the different alternatives. The 'irrigation scheduling' was found to be the most preferred alternative and 'brush control' was the least preferred alternative. Hashemi et al. (2013), based on Atanassov's intuitionistic fuzzy sets theory, introduced an innovative compromise ratio method for multiple criteria decisions making in water resources management. The concept of hesitation index was introduced by Garai and Roy (2013) for optimization of a hypothetical mathematical problem while considering the maximization of the degree of acceptance, minimization of the degree of rejection, and minimization of degree of hesitation as the objective function. Bharati and Singh (2014) explained multi-objective linear programming using IFO and made a relative study of linear and non-linear membership functions and their influence on optimization using a numerical example. From this study, it was concluded that the IFO algorithm using non-linear membership and non-membership had shown better performance than the IFO algorithm using linear membership and non-membership functions. Li *et al.* (2017) demonstrated the intuitionistic fuzzy multi-objective non-linear programming model for the distribution of irrigation water under dry and wet conditions for reducing the water scarcity, and giving multiple solutions like crop yield, saving in water, and reduction of cost, to get a balanced water allocation scheme for the system. Jafarian *et al.* (2017) proposed intuitionistic fuzzy multiobjective geometric programming method for solving multiobjective non-linear programming problems subjected to the strict or flexible constraints. The proposed methods are illustrated through a numerical example considering the three objective functions and concluded that the proposed method gives the best compromise solution of objective functions for different approaches along with the values of membership function and non-membership function.

Pawar *et al.* (2020) applied the IFO approach as a new optimization method for the planning of optimal cropping pattern in the Kakarapar Right Bank Main Canal command area of the Ukai-Kakrapar water resources project in India. This methodology resulted in optimal irrigation planning along with additional parameters like degree of acceptance, degree of rejection, and degree of hesitation. Pawar *et al.* (2022) applied Intuitionistic Multiobjective fuzzy linear programming (IFO MOFLP) models for optimal allocation of crops in the command area of the Ukai-Kakrapar irrigation project, India. Three IFO MOFLP models i.e., IFO MOFLP, IFO MOFLP with hesitation index and Two phase IFO MOFLP (TPIFO MOFLP), has been applied considering the three conflicting objectives i.e., maximization of Net irrigation benefits (NIB), minimization of cost of cultivation (CC) and maximization of revenue generation from municipal and industrial supplies (MI). Results obtained from the IFO MOFLP model was compared with the MOFLP model and it shows that TPIFO MOFLP model gives better results in terms of irrigation intensity, objective function values along with the extra parameters degree of rejection and hesitation index with degree of acceptance.

The previous investigations in the water resources domain could not address the implementation of IFO multi-objective fuzzy linear programming (IFO MOFLP) with contemplation of degree of acceptance, degree of rejection, and degree of hesitation index, particularly, for an intricate problem of a multipurpose water resources project. The minimization of the degree of rejection and hesitation index along with maximization of the degree of acceptance is considered as the objective function in the proposed framework. The estimation of additional parameters like the degree of rejection and hesitation index may likely instill more confidence in the decision-makers for the implementation of the proposed model in their respective command areas.

The present study is aimed to address the following research objectives: -

i. Develop multi-objective intuitionistic fuzzy optimization (IFO) approaches for solving, an intricate water resources real-world problem.
ii. Analyse sensitivity of degree of acceptance, degree of rejection, and hesitation index with scaling factor which would facilitate the decision-makers in taking a proper decision on implementation of the IFO model.
iii. Compare and demonstrate the merits of the proposed IFO solution with previous multi-objective fuzzy linear programming (MOFLP) solutions for the same study area.

2.0 Study Area

The Ukai-Kakrapar water resources project is the second-largest multipurpose reservoir in the Gujarat state in India. Fig.1 shows the index map of the Ukai-Kakrapar water resources project which has three canal command areas in the system. The Ukai left bank main canal (ULBMC), originates from Ukai Reservoir itself, and has a command of area 66,168 ha. The Kakrapar right bank main canal (KRBMC) and Kakarapar left bank main canal (KLBMC), originate from Kakrapar weir, which is located on the Tapi river 30 km downstream of Ukai reservoir. The

KRBMC and KLBMC encompass the command areas of 1, 13,123 ha and 1, 45,335 ha respectively. The planned cropping pattern of each command area is included in Table-1.

Historical monthly inflows of 36 years into the Ukai reservoir were analyzed (Mirajkar and Patel, 2016) and it was reported that the monthly flow pattern follows the lognormal distribution. The fitted probability distribution, in turn, was adopted to compute the monthly inflows corresponding to a 75% probability of exceedance. The modified Penman method was adopted for computation of water requirements of the crops wherein due allowance was given to the effective rainfall in the command areas for arriving the net irrigation requirements of different crops.

Table 1. Principal Crops in the Ukai Command Areas

Crop index (i)	**ULBMC**	**KLBMC**	**KRBMC**
1	Paddy (k)	Paddy (k)	Paddy (k)
2	Vegetables (k)	Juwar/Bajri/other (k)	Juwar/Bajri (k)
3	Other (k)	Vegetables (k)	Vegetables (k)
4	Wheat (r)	Wheat (r)	Wheat (r)
5	Vegetables (r)	Vegetables (r)	Vegetables (r)
6	Juwar/Bajri/other (r)	Juwar/Bajri/other (r)	Juwar/Bajri (r)
7	Paddy (r)	Pulses and other (r)	Paddy (hw)
8	Pulses and other (r)	Paddy (hw)	Groundnuts (hw)
9	Groundnuts (r)	Groundnuts (hw)	Cotton (ts)
10	Vegetables (hw)	Vegetables (hw)	Vegetables (ts)
11	Groundnuts (hw)	Sugarcane (p)	Sugarcane (p)
12	Other (hw)	Bananas (p)	Bananas (p)
13	Paddy (hw)	-	-
14	Bananas and other (p)	-	-
15	Sugarcane (p)	-	-

Note: k, r, hw, and p represent the Kharif, rabi, hot weather, and perennial crops, respectively

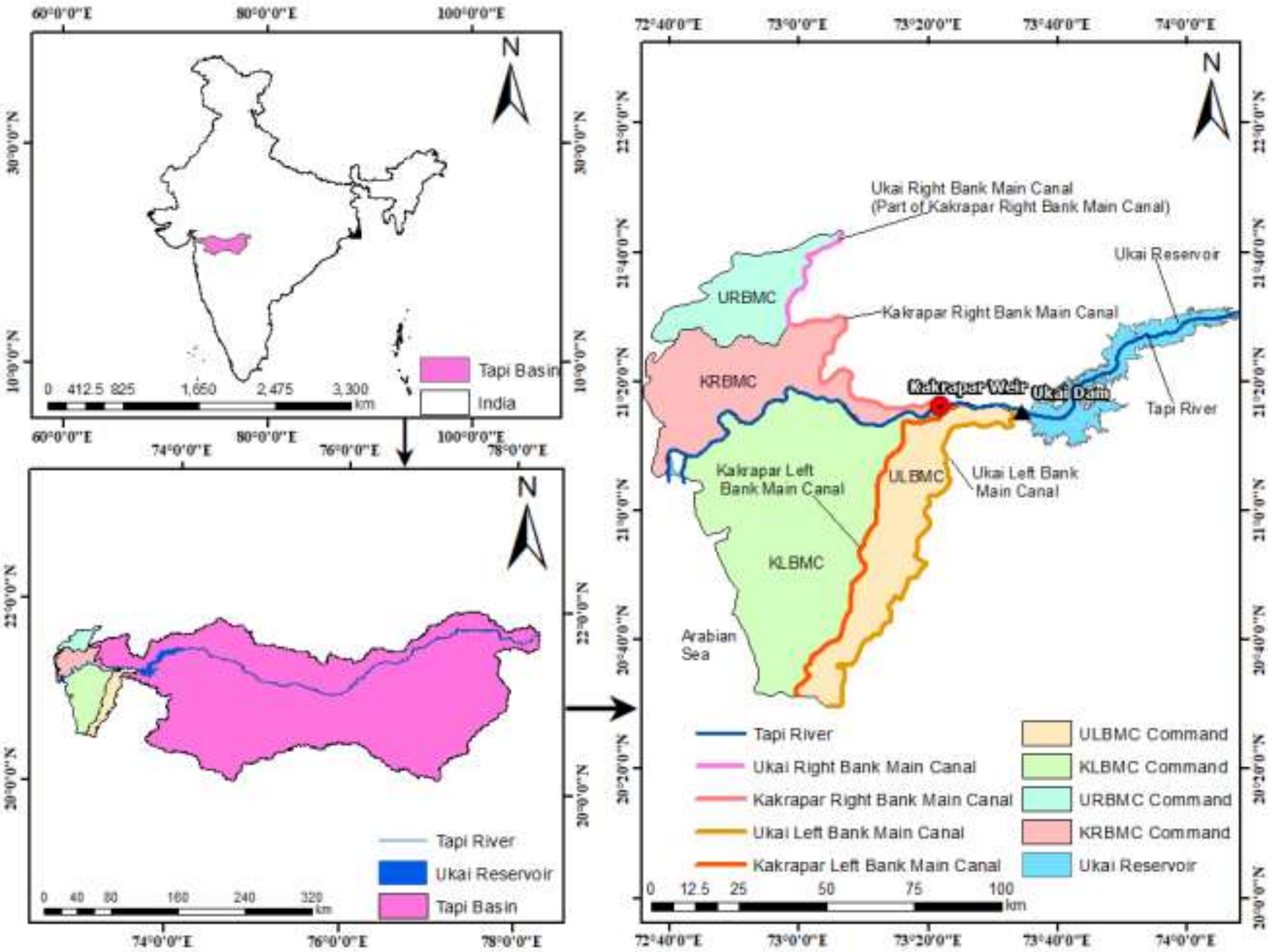

Fig.1 Index map of the Ukai–Kakrapar water resources project, Gujarat, India

3.0 Methodology and Model Development

The detailed descriptions of each objective and constraint, are described in Mirajkar and Patel (2016). However, briefs descriptions of objective functions and relevant constraints are given in the following paragraphs.

3.1 Objective functions and constraints

Four objective functions, namely, maximization of net irrigation benefits (Z_1), employment generation (Z_2), minimization of cost of cultivation (Z_3), and maximization of revenue generation from municipal and industrial supplies (Z_4), were used to obtain the optimal cropping pattern in the command areas of Ukai-Kakrapar Water resources project. The individual Linear Programming (LP) solutions of each objective were obtained using the *Modified Simplex method* in LINGO version 18.0 under relevant constraints, i.e., water allocation constraint, maximum sowing area constraint, socioeconomic constraint, canal capacity constraint, reservoir storage capacity constraint, continuity constraint, overflow constraint, and releases to municipal and industrial supplies and labor constraint. In the present study, individual LP solutions of selected objectives functions were, in turn, used to develop a multi-objective IFO model to obtain the cropping pattern in the command areas of the Ukai-Kakrapar Water resources project.

3.2 Intuitionistic Fuzzy Optimization

Intuitionistic fuzzy optimization (IFO) is a recent approach in defining fuzzy sets. The IFO is useful for solving the problems wherein available knowledge is insufficient and impreciseness is associated with the solutions. In ordinary fuzzy sets, there is only consideration of membership (degree of satisfaction) whereas Intuitionistic fuzzy sets consider both membership (degree of acceptance), non-membership functions (degree of rejection), and hesitation index. In the present study, the multipurpose Ukai-kakrapar water resources project has been considered for obtaining the optimal cropping pattern and release from the reservoir.

The algorithm for Intuitionistic fuzzy optimization multiobjective problem (IFO MOFLP), is described in the following paragraphs: -

(a) The solutions of individual objective functions, **m** (four), were obtained using a linear programming approach along with corresponding decision variables.

(b) The solutions obtained from step (a) above for individual objective functions, the pay-off-matrix was prepared as shown in Table-2.

(c) From step (b) (Table-2), the lower ($\min(Z_m(x))$ and upper values $(\max(Z_m(x))$ for all objective functions were obtained.

(d) For the maximization type objective function, the membership and non-membership functions are estimated using Eqs. (1) and (2),

$$\mu_m(x) = \begin{cases} 0 & if \quad Z_m(x) \le L_m^{\mu} \\ \dfrac{Z_m(x) - L_m^{\mu}}{U_m^{\mu} - L_m^{\mu}} & if \quad L_m^{\mu} \le Z_m(x) \le U_m^{\mu} \\ 1 & if \quad Z_m(x) \ge U_m^{\mu} \end{cases} \tag{1}$$

$$v_m(x)=\begin{cases}0 & if \quad Z_m(x)\geq U_m^{v}\\ \frac{U_m^{v}-Z_m(x)}{U_m^{v}-L_m^{v}} & if \quad L_m^{v}\leq Z_m(x)\leq U_m^{v}\\ 1 & if \quad Z_m(x)\leq L_m^{v}\end{cases} \tag{2}$$

Here, $\mu_m(x)$ is membership function, $v_m(x)$ is non-membership function, $Z_m(X)$ is the objective function, $U_m^{\mu}=\max(Z_m(X))$, $L_m^{\mu}=\min(Z_m(X))$, $L_m^{v}=L_m^{\mu}$, $U_m^{v}=U_m^{\mu}-S_f(U_m^{\mu}-L_m^{\mu}), 0<S_f<1$. Here, S_f is a scaling factor, indicated on a scale of 0 to 1.

Table 2. "Pay-off Matrix from LP solutions of four Objective Functions for Inflows corresponding to 75% Probability of Exceedance" (Mirajkar and Patel, 2016).

Nature of objective functions	Objective Functions	NIB (Z_1)	EG (Z_2)	CC (Z_3)	MI (Z_4)
Max	Net benefits (NIB) in million Rs	13,897.83^{max}	13834.22	7275.48	7187.73^{min}
Max	Employment generation (EG) in a thousand workdays	38,204.09	39,334.4^{max}	21,425.57	21,425.57^{min}
Min	Cultivation cost (CC) in million Rs	7,082.31^{min}	7,033.76	3841.07^{max}	3928.43
Max	Revenue generation due to municipal and industrial supply (MI) in million Rs	1,065.86^{min}	1,065.86	1,154.44	2,686.86^{max}

"Note: **max** and **min** are the upper and lower bounds (maximum and minimum values) of an objective function"

(e) For the minimization type objective function, the membership function along with non-membership functions are estimated using Eqs. (3) and (4),

$$\mu_m(x)=\begin{cases}0 & if \quad Z_m(x)\geq U_m^{\mu}\\ \frac{U_m^{\mu}-Z_m(x)}{U_m^{\mu}-L_m^{\mu}} & if \quad L_m^{\mu}\leq Z_m(x)\leq U_m^{\mu}\\ 1 & if \quad Z_m(x)\geq L_m^{\mu}\end{cases} \tag{3}$$

$$v_m(x)=\begin{cases}0 & if \quad Z_m(x)\leq L_m^{v}\\ \frac{Z_m(x)-L_m^{v}}{U_m^{v}-L_m^{v}} & if \quad L_m^{v}\leq Z_m(x)\leq U_m^{v}\\ 1 & if \quad Z_m(x)\geq U_m^{\mu}\end{cases} \tag{4}$$

Here, $U_m^{\mu}=\max(Z_m(X))$, $L_m^{\mu}=\min(Z_m(X))$, $U_m^{v}=U_m^{\mu}$, $L_m^{v}=L_m^{\mu}+S_f(U_m^{\mu}-L_m^{\mu})$.

(f) Under IFO, the multi-objective fuzzy linear optimization problem (MOFLP), for *p* objectives under *q* sets of constraints, using linear membership and non-membership functions without considering the hesitation index, the objective function and constraints can be expressed using Eqs. (5-11) as per the mathematical concept given by Bharti and Singh (2014).

Maximize $(\alpha - \beta)$ (5)

Subject to $\alpha \leq \mu_m(x),$ (6)

$\beta \geq v_m(x),$ (7)

$\alpha + \beta \leq 1,$ (8)

$\alpha \geq \beta,$ (9)

$\beta \geq 0,$ (10)

$g_j(x) \leq b_j, x \geq 0,$ (11)

$m = 1, 2, ...p; j = 1, 2, ...q$.

Here, α signifies the degree of acceptance of objective functions, and β indicates the degree of rejection of objective functions under sets of constraints, **m** is m^th^ objective function, *p* is the total number of objective functions; *p* =4.0 and j represents the j^th^ constraint.

Here, $g_j(x)$ are constraints, b_j are resources available and q is a number of constraints.

(g) On the other hand, IFO MOFLP with hesitation index, as per the concept given by Garai and Roy (2013), for maximization of the degree of acceptance (α), minimization of the degree of rejection (β), and minimization of the degree of hesitation *(π)*, the objective function and constraints can be expressed using Eqs. (12-15) along with the constraint set from Eqs. (8-11).

Maximize $(\alpha - \beta - (1 - \alpha - \beta))$ (12)

Here, $(1 - \alpha - \beta)$ represents the degree of hesitation, (π) .

Subject to $\alpha \leq \mu_m(x),$ (13)

$\beta \geq v_m(x),$ (14)

$1 - \alpha - \beta \geq 1 - \mu_m(x) - v_m(x),$ (15)

The objective functions expressed using Eq. (5) and Eq. (12), are solved under sets of constraints, using the modified simplex method.

(h) The Two-Phase IFO MOFLP can upgrade the efficiency of IFO MOFLP with hesitation index solution by giving suitable weights to the individual objective functions. Here, w_m, weight of the m[th] objective function which is selected by the decision-maker such that $\sum_{m=1}^{4} w_m = 1$. The values of w_m of the m[th] objective function are selected suitably by the decision-maker to obtain feasible solutions corresponding to different values of scaling factors (S_f). The TPIFO MOFLP solutions are improved by considering the optimal values of degree of acceptance (α_m) and degree of rejection (β_m) of IFO MOFLP with hesitation index as the initial values (lower limit) of corresponding parameters of the latter. (Eqs. 17 and 18). A Series of trial values are required for different values of S_f ranging from 0 to 1, to achieve the best feasible solution. The relevant objective function for TPIFO MOFLP is expressed using Eq. (16):

$$\text{Maximize} \sum_{m=1}^{4} w_m(\alpha_m - \beta_m - (1 - \alpha_m - \beta_m)) \tag{16}$$

Here, the values of W_m are chosen by the decision-maker on a priority basis to obtain feasible solutions of the objective function with sets of constraints defined as per Eqs. (17-21).

$$\alpha_m^l \le \alpha_m \le \mu_m(x) \tag{17}$$

$$\beta_m^l \ge \beta_m \ge \nu_m(x) \tag{18}$$

$$1 - \alpha_m - \beta_m \ge 1 - \mu_m - \nu_m, \tag{19}$$

$$\alpha_m \ge \beta_m,\ \beta_m \ge 0, \alpha_m + \beta_m \le 1, \tag{20}$$

$$w_m > 0 \text{ and } \sum_{m=1}^{4} w_m = 1 \tag{21}$$

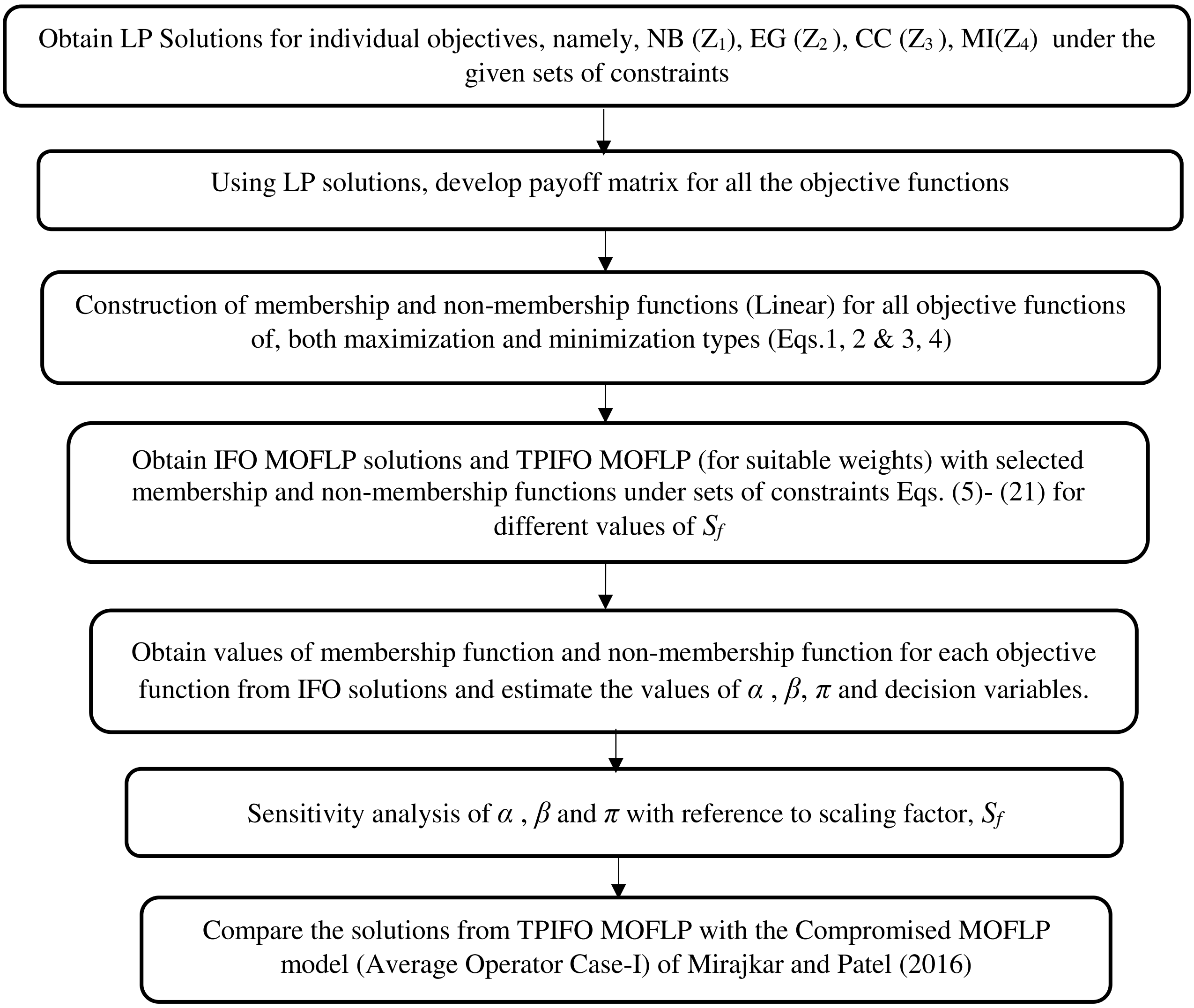

Fig.2 Flow chart for the evolution of IFO MOFLP solutions

The complete methodology, involving the optimal LP solutions of individual objective functions (Z_1, Z_2, Z_3, and Z_4), IFO MOFLP, IFO MOFLP with hesitation index (Eqs.5,12), and TPIFO MOFLP (Eq.16) subjected to sets of relevant constraints using *LINGO 18.0* (extended version), for different scaling factors (S_f), is explained using a flow chart as shown in Fig.2.

4. Results and Discussions

The complete analyses of IFO MOFLP, IFO MOFLP with hesitation index, and Two-phase IFO MOFLP, for the chosen study area, i.e., Ukai-Kakrapar water resources project, as per the approach discussed in Sub-section 3.2 is included in the **Supplementary material** at **Appendix A**.

The relative performance of IFO models, sensitivity analysis of performance parameters (α , β, and π) with scaling factor, comparison of proposed IFO MOFLP model with Compromised MOFLP

(Average Operator Case-I) model (Mirajkar and Patel, 2016), corresponding cropping pattern from best IFO MOFLP model and rule curve of the reservoir are included in following subsections:-

4.1 Relative performance of IFO models

The optimal solution of selected objective functions [Eq. (5)], [Eq. (12) and [Eq. (16)]] under sets of constraints, i.e., Eqs. (22)-(29), Eqs. (30)-(37) and Eqs. (38)-(56), were obtained for IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP respectively along with the values of corresponding decision variables (X^o) of individual objective functions (Z_1-Z_4). The solutions of individual objective function [$Z_m(x)$], after IFO solutions, are substituted in Eqs. (1), (3) and (2), (4) to get the membership function and non-membership function values for the maximization and minimization type objective function respectively. Hence, the overall degree of acceptance and rejection is obtained by using Eqs. (5), (12), and (16) for IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP models. The degree of hesitation (π) was obtained as, (π = 1- α -β) for IFO MOFLP with hesitation index and TPIFO MOFLP. Table 1 shows the principal crops in the command area of ULBMC, KLBMC, and KRBMC of the Ukai Kakrapar irrigation project.

A Series of trials were used for different values of scaling factor (S_f) ranging from 0.01 to 0.95, for all the three approaches, i.e., IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP, and corresponding values of α, β and π were obtained. The IFO MOFLP and IFO MOFLP with hesitation index gave feasible solutions for all the selected trial values of S_f while TPIFO MOFLP resulted in feasible solutions only for some typical S_f values, i.e., 0.19, 0.2, 0.21, 0.22, and 0.23. Further, the sensitivity of overall degree of acceptance (α), degree of rejection (β), and degree of hesitation (π) with reference to different values of scaling factor (S_f) are shown in Fig.3 and Fig. 4 for IFO MOFLP and IFO MOFLP with hesitation index respectively. From Fig.3 and Fig. 4, it is seen that the degree of acceptance (α) is invariant with change in scaling factors. However, the degree of rejection (β) decreases while degree of hesitation (π) increases with increase in scaling factor. The planner has to strike the right balance between β, and π, depending upon the degrees of rejection and uncertainty desired in the selection of the suitable value of S_f. The sensitivity analysis of TPIFO MOFLP models could not be accomplished due to availability of limited values of S_f for feasible solutions.

Finally, the best values of S_f, for IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP, have been chosen by making the right balance between β and π *(Fig.3) and (Fig.4)* to achieve the maximum irrigation intensity and the corresponding values of objective functions. The selected trial values of S_f and their respective optimum solutions, i.e., irrigation intensity and objective function values are included in Table 3. The S_f = 0.32, 0.27, and 0.23 have arrived for IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP respectively based on the above criteria. Incidentally, from Fig.3 and Fig.4 and Table-3, it is seen that S_f values corresponding to point of intersections of β and π lines give the optimal solution of IFO MOFLP (S_f=0.32) and IFO MOFLP with hesitation index (S_f=0.27).

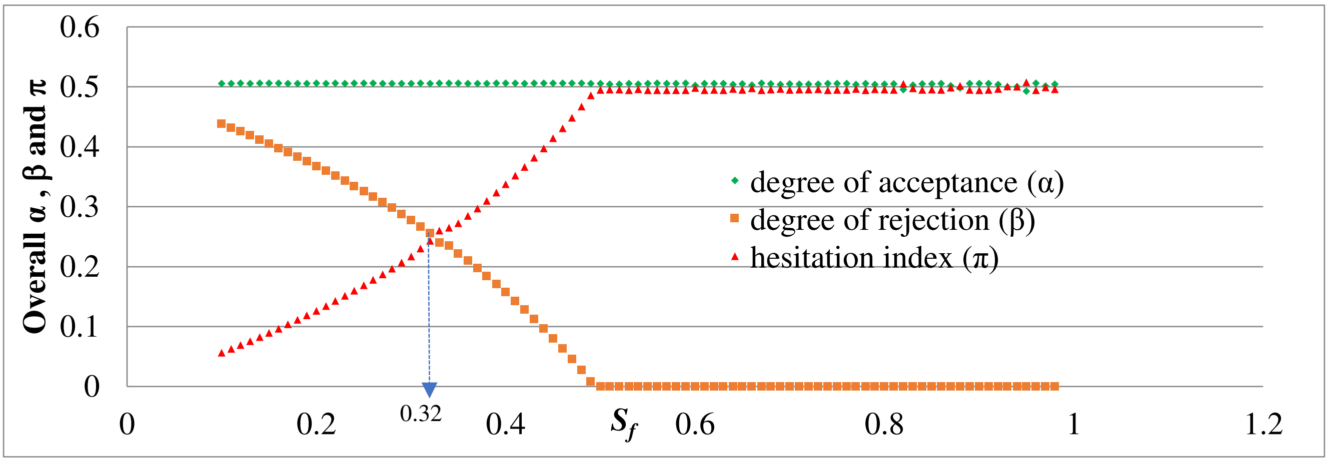

Fig.3 Sensitivity of α, β, and π with scaling factors for IFO MOFLP

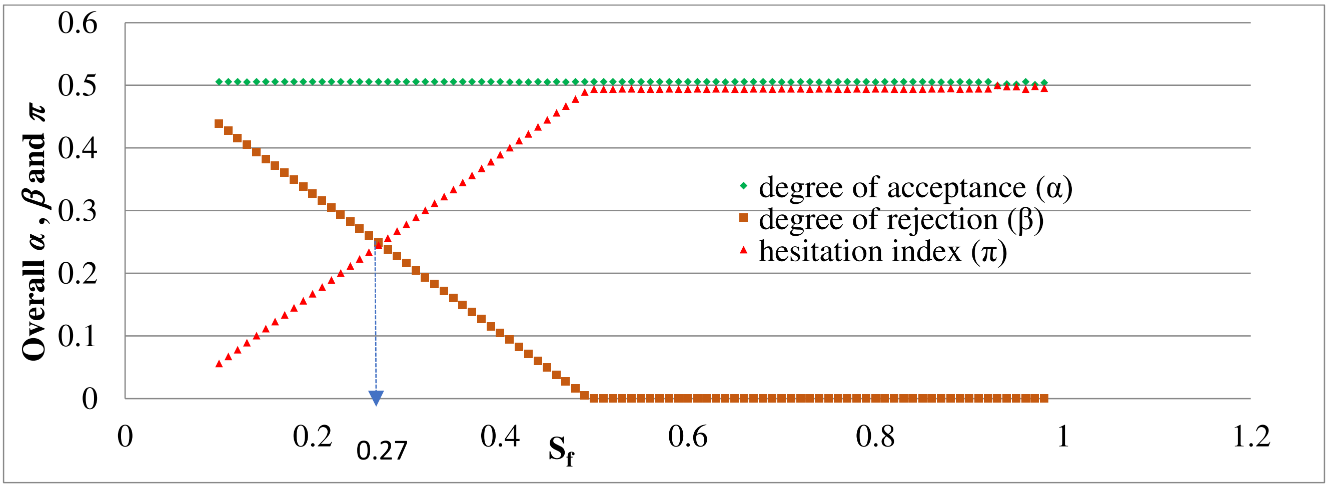

Fig.4 Sensitivity of α, β, and π with scaling factors for IFO MOFLP with hesitation index

The optimal solutions of individual objective functions, i.e., NIB, EG, CC, and MI, obtained from the IFO MOFLP approach for S_f =0.32, are Rs. 10580.33 million, 32396.47 thousand workdays, Rs.5443.55 million, and Rs. 1918.77 million respectively (Table 3) and, corresponding values for overall α and β, estimated from Eqs. (5), are 0.51 and 0.26 respectively. The irrigation intensities obtained using the IFO model, for S_f = 0.32, for ULBMC, KLBMC and, KRBMC are 134.67%, 100.18% and, 86.71% respectively (See Table-4) while the irrigation intensity for the whole command area is 102.52% (Table-4).

Similarly, the optimal solutions of individual objective functions, i.e., NIB, EG, CC, and, MI, using IFO MOFLP with hesitation index model, are Rs. 10581.12 million, 31922.65 thousand workdays, Rs. 5443.17 million and 1991.69 million respectively (Table 3) for the value of S_f =0.27. The irrigation intensity for the whole catchment has been estimated to be 102.09%, and corresponding values of ULBMC, KLBMC, and KRBMC, are 135.44%, 104.83%, and 79.07% respectively for S_f =0.27.

The results of the objective functions obtained by IFO with hesitation index have been found to improve marginally as compared to the IFO MOFLP model. The solutions of individual objective functions from IFO solutions with hesitation index, for S_f = 0.27, were substituted in Eqs. (1), (3) and (2), (4) to get the membership function and non-membership function values for the maximization and minimization type objective function respectively. Hence, the overall degree of acceptance, rejection, and hesitation index is obtained by using Eqs. (12) for IFO MOFLP with hesitation index. The overall values of α, β and π for S_f = 0.27 obtained using Eqs.(12) are 0.51, 0.25 and 0.24 respectively.

The optimal TPIFO solution gives the improvement in results of all the objective functions, i.e., NIB, EG, CC, and MI, 10836.19 million Rs, 34980.4 thousand workdays, 5672.28 million Rs, and 2314.03 million Rs respectively. Also, degree of acceptance α, degree of rejection β, and, degree of hesitation π have been estimated to be 0.68, 0.19, and 0.13 respectively. The degree of acceptance obtained by TPIFO MOFLP (for S_f=0.23.) has been found to improve significantly as compared to IFO MOFLP and IFO MOFLP with a hesitation index (See Table-4).

Table-3. Performance of IFO MOFLP models for different scaling factors

S_f	Methodology	Overall α, β, π values	Z_1	Z_2	Z_3	Z_4	Irrigation Intensity (%)
(Scaling Factors)			NB (million Rs.)	EG (thousand workdays)	CC (million Rs.)	MI (million Rs.)	
0.10	IFO MOFLP	0.51,0.44,0.05[@]	10580.6	32389.69	5443.41	1885.5	102.52
	IFO MOFLP with hesitation index	0.51,0.44,0.05	10580.3	32396.47	5443.56	1885.43	102.52
0.19	IFO MOFLP	0.51,0.38,0.11[@]	10580.3	32396.47	5443.55	1885.43	102.52
	IFO MOFLP with hesitation index	0.51,0.38,0.11	10581.1	31922.65	5443.17	1885.62	102.09
	TPIFO MOFLP	0.62,0.28,0.10	10830.2	31031.53	5631.81	2378.87	100.08
0.20	IFO MOFLP	0.51,0.37,0.12[@]	10581.1	31922.64	5443.17	1885.62	102.09
	IFO MOFLP with hesitation index	0.51,0.37,0.12	10581.1	31922.65	5443.17	1885.6	102.09
	TPIFO MOFLP	0.66,0.23,0.11	10897.6	33505.73	5641.76	2362.66	106.43
0.21	IFO MOFLP	0.51,0.36,0.13[@]	10579.4	31921.48	5443.99	1885.21	102.09
	IFO MOFLP with hesitation index	0.51,0.36,0.13	10581.1	31922.65	5443.17	1885.62	102.09
	TPIFO MOFLP	0.68,0.20,0.12	10793.9	34905	5651.82	2346.45	111.88
0.22	IFO MOFLP	0.51,0.35,0.14[@]	10581.1	31934.67	5443.19	1885.61	102.17
	IFO MOFLP with hesitation index	0.51,0.35,0.14	10581.1	31934.68	5443.19	1885.61	102.17
	TPIFO MOFLP	0.68,0.19,0.13	10814.9	34942.49	5661.99	2330.24	112.04
0.23	IFO MOFLP	0.51,0.34,0.15[@]	10580.6	32389.69	5443.41	1885.5	102.52
	IFO MOFLP with hesitation index	0.51,0.34,0.15	10583	32201.06	5442.26	1886.08	101.10
	TPIFO MOFLP	0.68,0.19,0.13	10836.2	34980.4	5672.28	2314.03	112.19
0.27	IFO MOFLP	0.51,0.31,0.18[@]	10580.3	32396.47	5443.55	1920.65	102.52
	IFO MOFLP with hesitation index	0.51,0.25,0.24	10581.1	31922.65	5443.17	1991.69	102.09
0.30	IFO MOFLP	0.51,0.28,0.21[@]	10580.6	32389.69	5443.41	1987.06	102.52
	IFO MOFLP with hesitation index	0.51,0.28,0.11	10581.1	31922.65	5443.17	1991.69	102.09
0.31	IFO MOFLP	0.51,0.27,0.22[@]	10581.1	31922.64	5443.17	1984.01	102.09

	IFO MOFLP with hesitation index	0.51,0.27,0.22	10581.1	31922.65	5443.17	1991.69	102.09
0.32	**IFO MOFLP**	0.51,0.26,0.23[@]	10580.3	32396.47	5443.55	1918.77	102.52
	IFO MOFLP with hesitation index	0.51,0.26,0.23	10581.1	31922.65	5443.17	1991.69	102.09
0.40	IFO MOFLP	0.51,0.16,0.33[@]	10582.3	32176.11	5442.63	1931.14	101.54
	IFO MOFLP with hesitation index	0.51,0.49,0.00	10580.6	32426.21	5443.41	1933.48	102.83
0.50	IFO MOFLP	0.51,00,0.49[@]	10578.5	32425.04	5444.43	1884.97	102.83
	IFO MOFLP with hesitation index	0.51,0.00,0.49	10583	32201.06	5442.26	1886.06	101.10
0.60	IFO MOFLP	0.50.00,0.50[@]	10558.2	31693.05	5454.27	1880.05	100.00
	IFO MOFLP with hesitation index	0.51,0.00,0.49	10582.4	32704.52	5442.57	1885.90	101.84
0.70	IFO MOFLP	0.51,00,0.49[@]	10576.4	32115.91	5445.45	1884.46	102.38
	IFO MOFLP with hesitation index	0.51,0.00,0.49	10579.8	32376.76	5443.81	1885.29	103.03
0.80	IFO MOFLP	0.50,00,0.50[@]	10573.6	31806.66	5446.79	1883.79	102.22
	IFO MOFLP with hesitation index	0.51,0.49,0.00	10580.1	32345.47	5443.69	1885.34	102.80
0.90	IFO MOFLP	0.51,00,0.49[@]	10579.8	32352.25	5443.83	1885.27	102.79
	IFO MOFLP with hesitation index	0.51,0.00,0.49	10579.8	32376.76	5443.81	1885.29	103.03

[@] Calculated values i.e. $\pi = (1-\alpha-\beta)$

Table 4. Summary of solutions from Average Operator Case-I (Mirajkar and Patel, 2016), IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP Models for 75% exceedance probable inflow condition

Model description	Irrigation intensity in %				λ	S_f	α	β	π	Objective function values			
	ULBMC	KLBMC	KRBMC	TOTAL						NIB (million Rs)	EG (thousand workdays)	CC (million Rs)	MI (million Rs)
Average Operator Case-I*	133.66	105.30	87.48	104.60	0.75	-	-	-	-	11058.27	33414.62	5622.20	2686.25
IFO MOFLP #	134.67	100.18	86.71	102.52	-	0.32	0.51	0.26	-	10580.33	32396.47	5443.55	1918.77
IFO MOFLP with hesitation index #	135.44	104.83	79.07	102.09	-	0.27	0.51	0.25	0.24	10581.12	31922.65	5443.17	1991.69
TPIFO MOFLP$ #	132.44	116.05	95.41	112.19	-	0.23	0.68	0.19	0.13	10836.19	34980.4	5672.23	2314.03

Note: λ=overall satisfaction level; S_f = Scaling factor; α=degree of acceptance; β=degree of rejection; π=degree of hesitation; CC=cultivation cost; EG=employment generation; MI=municipal and industrial supplies; NIB=net irrigation benefits

* (Mirajkar and Patel, 2016) # Present study $ minimum (α_m^l) and maximum (β_m^l) are as obtained in the IFO with hesitation index

4.2 Performance of TPIFO model vis-à-vis MOFLP model

The IFO models cited in the preceding sections [IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP], were solved for 75% probable inflow conditions into the Ukai reservoir. The respective values of degree of acceptance (α), degree of rejection (β), degree of hesitation (π), and objective function values are shown in Table 4. The TPIFO MOFLP model, as described in Subsection 4.2.1, has been found to perform significantly better vis-à-vis other IFO models. Apart from this, it was also felt worthwhile to compare the best performing IFO model, i.e., TPIFO MOFLP, with the best performing MOFLP model, i.e., Compromised MOFLP (Average Operator Case-I) as proposed by Mirajkar and Patel (2016).

The TPIFO MOFLP resulted in a degree of acceptance (α), degree of rejection (β), and degree of hesitation index (π) as 0.68, 0.19, and 0.13 respectively with the values of individual objective functions, i.e., NIB, EG, CC and MI, as Rs. 10836.19 million, 34980.4 thousand workdays, 5672.28 million Rs and 2314.03 million Rs respectively. Further, the irrigation intensity of the TPIFO MOFLP model of the whole command area is 112.19% (see Table-4).

On the other hand, the values of individual objective functions, i.e., NIB, EG, CC, and MI, obtained from Compromised MOFLP (Average Operator Case-I) were Rs. 11058.27 million, 33414.62 thousand working days, Rs.5622.20 million, and Rs. 2686.25 million respectively with irrigation intensity of 104.60 %. The degree of satisfaction (λ), for Compromised MOFLP (Average Operator Case-I), was found to be 0.75.

With cited results as above, it is apparent that both approaches give similar values of individual objective functions except revenue generation from the municipal and industrial supply (MI) is higher for Compromised MOFLP (Average Operator Case-I) than TPIFO MOFLP. On the other hand, TPIFO MOFLP gives higher irrigation intensity vis-à-vis Compromised MOFLP (Average Operator Case-I). The merit lies in TPIFO MOFLP is that, apart from giving the degree of acceptance, it gives the degree of rejection and hesitation index in the proposed solution. The inclusion of a hesitation index in the solution would give more confidence to the decision-maker to adopt the TPIFO solution in the command area. The Compromised MOFLP (Average Operator

Case-I), though gives marginally better results in some of the objective functions, However, it does not give any uncertainty measure in the optimal solutions for taking the robust decision by the decision-maker. Thus, TPIFO MOFLP models can be recommended for obtaining the optimal solutions for a water resources system with the inclusion of a degree of acceptance, degree of rejection, and hesitation indices.

4.3 Cropping Pattern in Subcommand areas from IFO MOFLP models

The comparison of the recommended cropping patterns in the command area based on IFO MOFLP models and the Compromised MOFLP (Average Operator Case-I) model is included in Table-5 for 75% probable inflow conditions for ULBMC, KLBMC, and KRBMC respectively. From Table-5, it is seen that TPIFO MOFLP models invariably give lesser irrigation intensity in the ULBMC subcommand area vis-à-vis other IFO MOFLP models and Compromised MOFLP model (Average Operator Case-I) due to lesser area suggested in the TPIFO MOFLP model for the sugar cane crop. Such a decrease in the area of sugarcane from the model is partially compensated by allocated larger areas for Juwar/Bajri/other rabi crops, pulses/other similar rabi crops, and groundnuts crops from the TPIFO model. For the KLBMC subcommand area, the TPIFO MOFLP model gives higher intensity (ref. Table 5) vis-à-vis other IFO MOFLP models and Compromised MOFLP (Average Operator Case-I) due to the allocation of larger areas for Juwar/Bajri/other rabi crops, groundnuts and hot weather vegetables. Similarly, the TPIFO model gives higher irrigation intensity in the KRBMC command area (95.41%) vis-à-vis other IFO MOFLP models due to higher cropped area for Juwar/bajri (in rabi season), groundnut (during hot weather), cotton and banana. It is important to note that groundnut, cotton, banana, and sugarcane are the cash crops in the command area. The sowing of cash crops in the command area will improve the prosperity in the region of the Ukai-kakrapar water resources project.

Table 5 Areas distributed to different Crops (in ha) by IFO MOFLP models for ULBMC, KLBMC and KRBMC compared with Average Operator Case-I under inflows having 75% Probable of Exceedance

Crop (i)	Models → / Crop ↓	(Average Operator Case-I) *	IFO MOFLP #	IFO MOFLP with hesitation index #	TPIFO MOFLP $ (weights-0.3,0.3, 0.2,0.2) #	Models → / Crop ↓	(Average Operator Case-I) *	IFO MOFLP #	IFO MOFLP with hesitation index #	TPIFO MOFLP $(weights-0.3,0.3, 0.2,0.2) #	Models → / Crop ↓	(Average Operator Case-I) *	IFO MOFLP #	IFO MOFLP with hesitation index #	TPIFO MOFLP$ (weights-0.3,0.3, 0.2,0.2) #
	ULBMC					**KLBMC**					**KRBMC**				
1	Paddy (k)	19850	19850	19850	19850	Paddy (k)	30513	30513	30513	30513	Paddy (k)	16965	16965	16965	16965
2	Vegetables (k)	3310	3310	3310	3310	Juwar/Bajri/other (k)	16786	16786	16786	16786	Juwar/Bajri (k)	11310	11310	11310	11310
3	Other (k)	1323	305	305	1323	Vegetables (k)	2906	2906	2906	2906	Vegetables (k)	1131	1131	1131	1131
4	Wheat (r)	662	662	662	662	Wheat (r)	1163	1163	1163	1163	Wheat (r)	3654	3654	3654	3654
5	Vegetables (r)	3310	3310	3310	3310	Vegetables (r)	7265	7265	7265	7265	Vegetables (r)	1131	1131	1131	1131
6	Juwar/Bajri/other (r)	662	662	662	11055	Juwar/Bajri/other (r)	11624	11624	11624	24373	Juwar/Bajri (r)	10091	10091	10091	16965
7	Paddy (r)	1985	1985	1985	3310	Pulses and other (r)	0	0	0	0	Paddy (hw)	8145	8145	8145	8145
8	Pulses and other (r)	5928	5928	5928	9930	Paddy (hw)	13037	13037	13037	13037	Groundnuts (hw)	192	192	192	1131
9	Groundnuts (r)	2648	2648	2648	3755.55	Groundnuts (hw)	7265	7265	7265	10135.13	Cotton (ts)	860	860	860	1131
10	Vegetables (hw)	1324	1324	1324	1324	Vegetables (hw)	5812	2529	2529	5812	Vegetables (ts)	5655	5655	1335	5655
11	Groundnuts (hw)	3970	3970	3970	3970	Sugarcane (p)	17436	17436	18302.51	17436	Sugarcane (p)	10179	10179	10179	10179
12	Other (hw)	3972	3972	3972	3972	Bananas (p)	1453	68	1453	1453	Bananas (p)	633	633	633	1131
13	Paddy (hw)	1985	1985	1985	1985	-					-				
14	Bananas and other (p)	662	662	662	662	-					-				
15	Sugarcane (p)	11841.1	12403.3	12574.6	5962.82	-					-				
	Total	88438.4	89106.9	89620.8	74381.38			148883	152354.5	130879.1			98085	89445	78528
	Irrigation Intensity %	133.65	134.67	135.44	132.44			102.44	104.83	116.05			87.48	79.07	95.41

* (Mirajkar and Patel, 2016) # Present study **(refer to Table-2) $ minimum (α_m^l) and maximum (β_m^l) are as obtained in the IFO with hesitation index

4.4 Proposed rule curve and release pattern in the command area

The optimized releases from the reservoir for meeting the requirement of irrigation and municipal and industrial supplies from the proposed TPIFO MOFLP model are included in Table-6 for ULBMC, KLBMC, and KRBMC subcommand areas. Invariably, the optimal irrigation releases from the proposed model are very less during the Monsoon (July-August and September) months due to heavy rainfall in the command area. While observing the reservoir levels derived from the TPIFO MOFLP model (Fig.5), it is seen that reservoir is at 104.24 m (October) which is very close to the full reservoir level (FRL) (105 m) of the Ukai reservoir for 75% dependable inflow condition at the end of monsoon. Further, it is seen that reservoir would have a 98.99 (June) m level just before the start of the monsoon which is quite adequate for infilling the reservoir just after the end of the monsoon. On the other hand, the optimal releases are on the higher side for the January, February, March, and April months as Rabi crops are in their mature stage and require more water for meeting their high evapotranspirational requirements. Further, the releases from the TPIFO MOFLP model for different subcommand areas are lesser than those obtained from Compromised MOFLP (Average Operator – Case I). The estimated reservoir levels and optimized releases from the Ukai reservoir would help the irrigation authorities to plan out the regulation of water level in the reservoir and release adequate quantity of water in each sub-command area of Ukai reservoir (Table-6 and Fig.5).

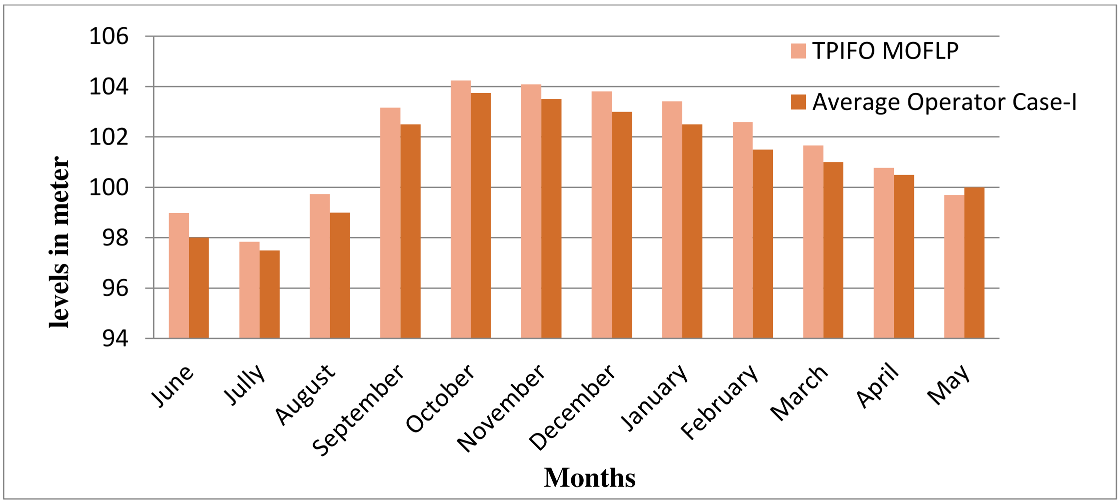

Fig.5 Comparison of Reservoir levels for inflows with 75% (TPIFO MOFLP and Average Operator Case-I)) probable inflow condition.

Table 6 Comparison of releases for irrigation from the recommended TPIFO MOFLP model and Average Operator Case-I (Mirajkar and Patel, 2016)

Monthly Releases (Mm^3)								
	ULBMC		**KLBMC**		**KRBMC**		**Total**	
Month	**TPIFO MOFLP**	**Average Operator Case-I**	**TPIFO MOFLP**	**Average Operator Case-I**	**TPIFO MOFLP**	**Average Operator Case-I**	**TPIFO MOFLP**	**Average Operator Case-I**
June	31.22	31.86	57.69	66.88	43.18	50.88	132.08	149.62
July	7.00	1.48	2.00	16.99	10.00	7.97	19.00	26.44
August	11.15	12.29	27.69	39.00	16.13	29.11	54.97	80.40
September	32.75	34.15	62.61	71.73	35.34	44.08	130.71	149.96
October	61.68	61.60	108.38	117.40	75.97	87.08	246.04	266.08
November	25.44	26.00	52.52	62.11	55.66	65.27	133.63	153.38
December	35.65	36.37	71.75	89.26	61.78	70.22	169.17	195.85
January	65.99	66.92	172.55	186.96	111.52	136.39	350.05	390.27
February	81.93	82.55	211.66	245.22	87.50	99.38	381.09	427.15
March	77.61	78.65	166.77	189.95	84.43	97.21	328.81	365.81
April	88.38	89.23	199.61	215.77	106.16	106.49	394.15	411.49
May	53.96	53.02	108.56	107.28	59.18	56.93	221.70	217.23
Total	572.76	574.12	1241.80	1408.55	736.85	851.01	2551.41	2833.68

4.5 Optimized crop area in proposed model vis-à-vis Actual crop area

The optimized crop areas in the present study are compared with actual crop areas in the command area of the UKai-Kakrapar water resources project, to demonstrate the relative significance of the proposed optimization model. The annual 75% dependable inflow condition was obtained by using the historical data of 36 years which corresponds to the actual inflow into the reservoir for the year 2008-09. The actual cropping pattern for ULBMC and KLBMC command area are compared with the cropping pattern obtained from the TPIFO model for the aforesaid flow condition. The actual cropping pattern of KRBMC could not be compared due to the non-availability of the data in that command area.

From Table 7, it is seen that crop area allocated to each crop from the TPIFO model for 75% probable inflow condition is found to be higher in terms of irrigation intensity than the actual cropping pattern during the year 2008-09. The area allocated to individual crops in actual cropping patterns in ULBMC and KLBMC are different than those allocated from the TPIFO model (see

Table 7). This difference is due to non-compliance with constraints conditions while releasing water for the actual cropping pattern. From Table 7, for ULBMC, it is observed that NIB derived from the proposed TPIFO model, even for 75% exceedance probable inflow condition, is higher than NIB values derived from the actual cropping pattern for the years 2008-09. A similar trend is also observed for employment generation (EG) in the command area.

Table 7 Comparison of actual cropping pattern with optimized cropping pattern from TPIFO model for ULBMC and KLBMC command areas

Crop index (i)	**ULBMC**	**Actual crop area for 2008-09 (75% dependable year) ULBMC**	**(75 % exceedance probable inflow condition, (TPIFO) ULBMC**	**KLBMC**	**Actual crop area for 2008-09 (75% dependable year) KLBMC**	**(75 % exceedance probable inflow condition, (TPIFO) KLBMC**
1	Paddy (k)	1801	19850	Paddy (k)	126	30513
2	Vegetables (k)	2	3310	Juwar/Bajri/other (k)	5094	16786
3	Other (k)	302	1323	Vegetables (k)	8923	2906
4	Wheat (r)	115	662	Wheat (r)	236	1163
5	Vegetables (r)	264	3310	Vegetables (r)	68	7265
6	Juwar/Bajri/other (r)	193	11055	Juwar/Bajri/other (r)	425	24373
7	Paddy (r)	1464	3310	Pulses and other (r)	7326	0
8	Pulses and other (r)	9559	9930	Paddy (hw)	0	13037
9	Groundnuts (r)	3156	3755.55	Groundnuts (hw)	3829	10135.13
10	Vegetables (hw)	232	1324	Vegetables (hw)	19	5812
11	Groundnuts (hw)	4025	3970	Sugarcane (p)	19797	17436
12	Other (hw)	5576	3972	Bananas (p)	559	1453
13	Paddy (hw)	1803	1985	-	-	-
14	Bananas and other (p)	162	662	-	-	-
15	Sugarcane (p)	15559	5962.82	-	-	-
Total		**44213**	**74381.38**	-	**46402**	**130879.1**
Irrigation Intensity in %		**114.34**	**132.44**	-	**59.94**	**116.05**
NIB in Million Rs.		**2665.42**	**2790.97**	-	**3502.76**	**5645.32**
EG in Thousand Man-days		**6941.21**	**9448.53**	-	**8151.9**	**16490.00**
CC in Million Rs.		**1157.83**	**1180.47**	-	**1505.66**	**2372.22**

Also, the cropping pattern obtained from the TPIFO model for the KLBMC command area is compared with the actual cropping pattern for the year 2008-09 which leads to an increase in the irrigation intensity from 59.94 % to 116.05% while using the proposed TPIFO model. This increase in irrigation efficiency also leads to a higher NIB and EG in the KLBMC command area.

4.6 Performance Assessment of the Water Resource System

The optimal cropping pattern and releases obtained for the inflows with 75% probability of exceedance from the TPIFO MOFLP, are chosen to simulate the reservoir system using 36 years of historical inflow data (1975-2010) and 100 years (2010-2109) of synthetically generated inflow data for the Ukai reservoir. The 100 years of monthly inflow data were generated using Monte Carlo simulations. The statistical parameters, such as the mean and standard deviation of the generated data, were the same as those of the historical data. The simulations were performed using *LINGO 18.0* (extended version). The releases from the reservoir in a chosen year were obtained for the actual inflow conditions in the reservoir for the cropping pattern suggested by the recommended TPIFO MOFLP model. The releases obtained from the simulation for different months with actual flow data were compared with those from the recommended TPIFO MOFLP model for the inflows with a 75% probability of exceedance.

A specific year is considered a deficit if any of the months of that year have less release associated with the actual inflow than the release obtained from their recommended TPIFO MOFLP model. A similar procedure was adopted for all 36 years to obtain the monthly and annual irrigation deficits. The performances of the optimized cropping pattern and operation policy from the model were analyzed using the following performance indices: monthly frequency of irrigation deficit (MFID), the annual frequency of irrigation deficit (AFID), annual average irrigation deficit (AAID), and percentage annual irrigation deficit (PAID). The description of these performance indices is included in Mirajkar and Patel (2016).

The computed performance indicators for the historical (36 years) and generated (100 years) data sets are presented in Table 8. The analyses show that the irrigation deficit will increase from 12.26×10^6 m^3 for the past 36 years to 29.89×10^6 m^3 over the next 100 years. The monthly frequency irrigation deficit (MFID) and annual frequency irrigation deficit (AFID) will rise from 6.48 % (past) to 24.17% (in the next 100 years) and 47.22 % (past) to 84 % (in the next 100 years), respectively.

The percentage annual irrigation deficits for the past and future data sets are 22.12% and 15.17 %, respectively. The maximum deficit months obtained from the simulation were March, April, and May for both the historical and generated data sets.

Table 8 Performance indices for irrigation Deficit calculations

Sr No	Data type	MFID	AFID	AAID($\times 10^6 m^3$)	PAID (%)
1	**Historical data (36 years) (1975-2010)**	28/432 (6.48%)	17/36 (47.22%)	12.26	22.12
2	**Generated data (100 years) (2010-2109)**	290/1200 (24.17%)	84/100 (84%)	29.89	15.17

5.0 Conclusions

The intuitionistic fuzzy optimization (IFO) approach has been applied to address the socio-economic issues in the Ukai-Kakrapar water resources system in India. The intuitionistic fuzzy optimization multi-objective fuzzy linear programming models give additional decision-making parameters like degree of acceptance (α), degree of rejection (β), and hesitation index (π) vis-à-vis the earlier model proposed by Mirajkar and Patel (2016). Further, the proposed TPIFO MOFLP model gives better irrigation intensity, a higher degree of acceptance, a lower degree of rejection, and hesitation index, and comparable values of optimized objective functions for the system. The application of the proposed model in the command area would help better regulation of water and releases from the reservoir and improve the prosperity in the command area. The key conclusions drawn from forgoing are summarized as follows: -

(a) Three Intuitionistic fuzzy optimization-based models have been developed for Ukai-Kakrapar Water Resources Project to optimize net irrigation benefit (NIB), maximize Employment generation (EG), minimize the cost of cultivation (CC), and maximize municipal and industrial revenues (MI) in the command area. Out of three IFO models, i.e., IFO MOFLP, IFO MOFLP with hesitation index, and TPIFO MOFLP, the TPIFO model is proposed for the whole command area of the project due to a higher degree of acceptance, lower values of degree of rejection, and hesitation index; higher irrigation intensity and better values of objective functions.

(b) The sensitivity analysis of performance measures with scaling factors indicated that the degree of acceptance (α) is invariant with scaling factors while the degree of rejection (β) decreases and hesitation index (π) increases with scaling factors. Further, it is noticed that optimal solutions of IFO MOFLP and IFO MOFLP with hesitation index are obtained corresponding to the point of intersections of degree of rejection (β) line and degree of hesitation (π) lines for respective models.

(c) The proposed TPIFO model has been found to be the robust model vis-à-vis the MOFLP model proposed by Mirajkar and Patel (2016) for the same system. Former gives higher irrigation intensity and additional performance measures, viz. α, β, and π, which would help the decision-makers to decide on its implementation in a particular system.

(d) The proposed TPIFO MOFLP model with a degree of acceptance (α) of 0.68, degree of rejection (β) of 0.19, and hesitation index (π) of 0.13, provide net Irrigation Benefit (NIB), Employment generation (EG), Cost of cultivation (CC) and Revenue generation from the municipal and industrial supply (MI), as Rs. 10836.19 million, 34980.4 thousand workdays, 5672.28 million Rs and 2314.03 million Rs respectively, with irrigation intensity of whole command area as 112.19%.

(e) The proposed TPIFO MOFLP model provides the releases for ULBMC, KLBMC, and KRBMC sub-command areas of the Ukai Kakrapar water resources project (as per Table 6 and Fig.5) with irrigation intensity of 132.44 %, 116.05 %, and 95.41% respectively.

(f) The reservoir levels in the Ukai reservoir for different months (Fig.5) and releases for three subcommand areas in different months (Table 6), would help the decision-maker in the field to regulate the releases from the reservoir to fulfill the proposed objectives in the command area.

(g) The proposed TPIFO MOFLP model, developed for 75% probable inflow condition, has been simulated for the historical flows (36 years) and synthetically generated data of 100 years. The monthly frequency irrigation deficit (MFID) and annual frequency irrigation deficit (AFID) of

6.48 %, 24.17% and 47.22%, 84% for historical flows and synthetically generated data sets respectively. Similarly, the Annual average irrigation deficit (AAID) and Percentage annual irrigation deficit (PAID) for historical flows and synthetically generated data sets were found to be 12.26 Mm^3, 29.89 Mm^3, and 22.12%, 15.17% respectively. These irrigation deficits were invariably observed in March, April, and May months due to severe reduction of flows in these months in recent years.

(h) The cropping pattern obtained from the TPIFO model have been compared with the actual cropping pattern for the 75% dependable flow condition in the command area and significant improvements in net irrigation benefit and employment generation are reported due to the implementation of the proposed model.

The methodology presented in the current investigation is generic in nature, the same can be applied to other water resources systems to develop IFO models for deciding the management of water resource systems.

The present study has been developed for the available data of the year 1975-2010, which is an extension of the Compromised MOFLP (Average Operator Case-I) model proposed by Mirajkar and Patel (2016). The same can be updated by incorporating the data of recent years for the system in the future.

Data Availability Statement

All the data, models, or codes that support the findings of the current study are available with the corresponding author. The data can be shared on the public portal only, after getting the approval from data providing agency.

Appendix-A Supplementary Material

The supplementary material to this article can be found as Online Resource 1 at Springer Library.

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Ethical Declarations

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