Development of Multipurpose Single Reservoir Release Policy with Fuzzy constraints—A Case Study

S. V. Pawar, P. L. Patel, and A. B. Mirajkar

Abstract The study aims to present a fuzzy linear programming approach using fuzzy technological coefficients for optimal function of a reservoir system. This comprises a model that takes into account the water resource system's inherent uncertainty, which includes lack of adequate data, subjectivity, imprecision, and fuzziness. A single objective function, i.e., maximization of irrigation releases, is considered to solve the problem. The model is run for 75% dependable inflow into the reservoir while using fuzzy linear programming (FLP) approach. Here, uncertainty in reservoir operation parameters, including irrigation demand, reservoir storages, and irrigation releases, is taken into consideration by considering them as fuzzy sets. Construction of membership functions for the objective function and the constraints are included in the model development processes. The Khadakwasala reservoir in Maharashtra State, India, has been used as a case study to demonstrate the methodology. Optimizing the fuzzy objectives and constraints leads to a compromised solution for the suggested FLP model. The resulting degree of truth (λ) for the chosen objective function is 0.48. Also, the monthly release pattern has been obtained in the command area which can be used by the users in the command area.

Keywords Fuzzy linear programming problem · Fuzzy technological coefficient · Khadakwasala reservoir

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1 Introduction

The fuzzy logic method can offer a potential option to the techniques considered for reservoir operation modeling in fuzzy decision-making problems, according to Russell et al. [1]. This approach is further adaptable and allows for the inclusion of expert opinions, which may make it more suitable to operators. To determine the best reservoir operating strategies for the Karanjwan reservoir in Maharashtra State, India, Balve and Patel [2] used fuzzy linear programming (FLP). The obtained truth level is 0.5058, and the related optimal irrigation releases are 88.51 Mm^3. Comparisons between FLP's reservoir release policy and linear programmings (LPs) are presented. Regulwar et al. [3] used three different models to determine the best operating strategy. By creating three models, i.e., when the resources and technological coefficients are fuzzy and when both technological coefficients and resources are fuzzy, then fuzzy set theory was utilized to explain ambiguity in a variety of parameters. Yeh [4] studied models for reservoir operation and management. Computer modeling techniques are necessary for the synchronization of reservoir systems to offer information for intelligent management and operational decisions. The most recent research on multireservoir system optimization was reviewed by Labadie [5]. Panigrahi and Mujumdar [6] advanced a fuzzy rule-based model for the management of a single-purpose reservoir. The "if–then" assumption governs how the model behaves, with "if" denoting a vector of fuzzy premises and "then" denoting a vector of fuzzy consequences. Using genetic algorithms, Oliveira and Loucks [7] established operating principles for multireservoir systems. By utilizing fuzzy membership functions, Fontane et al. [8] gave the vague and non-commensurable objectives for planning reservoir operation and investigated the applicability of the method in dynamic programming. According to Shreshtha et al. [9], fuzzy relations could be used to represent both the inputs (such as storage, inflows, and demands) and the outputs (historical releases) of reservoir operating principles. To get crisp output, these fuzzy inputs were combined and defuzzified. The approach for solving the FLP problem by utilizing a linear membership function was described by Gasimov et al. [10]. With the use of FLP with technology coefficients, FLP with technological coefficient, and fuzzy right-side numbers, a FLP problem has been resolved and methodology is illustrated through a numerical example. The idea of maximizing and minimizing sets was used to propose a novel fuzzy ranking algorithm by Anand Raj et al. [11]. The Ranking Fuzzy Weight's (RANFUWs) approach is easy analytically and simple to use. The suggested approach (RANFUW method) was used to solve a planning and management issue for a river basin. To determine the most appropriate planning for the reservoirs and their related purposes, the technique was used to the Krishna River basin. Using three conflicting objectives, Raju and Kumar [12] used the Multi-Objective Fuzzy Linear Programming (MOFLP) technique in irrigation planning. For the Sri Ram Irrigation Project in India, the study was carried out. The degree of truth (λ) of the compromised solution for these three objective functions was calculated to be 0.69. With the use of a multi-objective constrained linear programming problem, Thakre et al. [13] presented the solution to a FLP problem where the cost coefficients and constraint matrix were both fuzzy. Additionally, they demonstrated that the solutions proposed by them were independent of weights. Singh et al. [14] developed a LP model to suggest the best cropping strategy for the maximum net return at various water availability levels, including 100, 70 and 50% dependability levels. It was discovered that the water in the command area may support the best cropping strategy for the maximum net return.

In the current study, the formulation of a FLP model is used to apply the fuzzy set theory to a water resources system in order to maximize reservoir release rates. Here, the LP model's technological coefficients are considered as having a fuzzy nature. The Khadakwasala reservoir in Pune, Maharashtra State, India, is used as a case study to demonstrate the methodology. LINGO 19 is used to develop and solve the FLP model.

2 Methodology

In this model, the technological coefficients are fuzzy numbers and resources are crisp in nature. A membership function represents the level of truth (λ) of a certain value of the parameter within the fuzzy set. Figure 1 shows the flowchart for solving LP problem with fuzzy technological coefficients. Formulation of FLP model is explained as discussed in following sub-sections:

2.1 LP Problems with Fuzzy Technological Coefficients

A LP problem with fuzzy technological coefficients is given as [3]

$$\max \sum_{j=1}^{n} c_j x_j$$

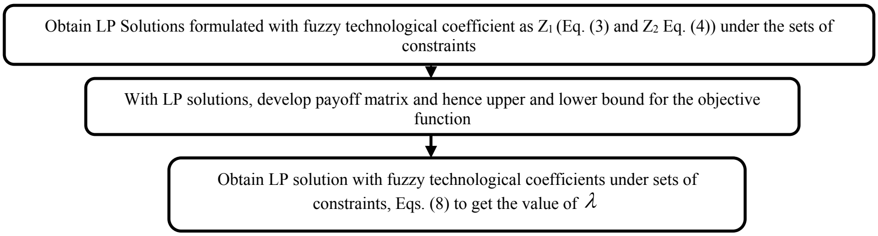

Fig. 1 Flowchart for development of LP solution with fuzzy technological coefficient

$$\text{s.t.} \sum_{j=1}^{n} a_{ij}\, x_j \le b_i \quad 1 \le i \le m$$

$$\text{where,} \quad x_j \ge 0, \quad 1 \le i \le n \tag{1}$$

2.2 Assumptions

Assumption 1. a_{ij} is a fuzzy number and consider the following linear membership function:

$$\mu_{a_{ij}}(x) = \begin{cases} 1 & \text{if}\, x < a_{ij} \\ (a_{ij} + d_{ij} - x)/d_{ij} & \text{if}\, a_{ij} \le x \le a_{ij} + d_{ij}, \\ 0 & \text{if}\, x \ge a_{ij} + d_{ij}, \end{cases} \tag{2}$$

where $x \varepsilon R$ and $d_{ij} > 0$. Initially, fuzzify the objective function in order to defuzzify this problem. This is accomplished by first determining the optimal values' minimum and maximum bounds. Solving the basic LP problem gives the best values, Z_l and Z_u.

$$\begin{aligned} z_1 &= \max \sum_{j=1}^{n} c_j\, x_j \\ \text{s.t.} &\sum_{j=1}^{n} a_{ij}\, x_j \le b_i, \quad i = 1, \ldots, m, \\ x_j &\ge 0, \quad j = 1, \ldots, n, \end{aligned} \tag{3}$$

and

$$\begin{aligned} z_2 &= \max \sum_{j=1}^{n} c_j\, x_j \\ s.t. &\sum_{j=1}^{n} (a_{ij} + d_{ij})\, x_j \le b_i, \quad i = 1 \ldots m, \\ x_j &\ge 0, \quad j = 1 \ldots n, \end{aligned} \tag{4}$$

The objective function takes values between Z_1 and Z_2' while technological coefficients vary between a_{ij} and $a_{ij} + d_{ij,}$ where $Z_l = \min\,(Z_1, Z_2)$ and $Z_u = \max\,(Z_1, Z_2)$. Then, Z_l and Z_u are called the minimum and maximum bounds of the optimal values, respectively.

Assumption 2 The solutions to the linear crisp problems are finite. The fuzzy set of optimum values in this situation, G, which is a subset of R^n, is defined as.

$$\mu_G(x) = \begin{cases} 0 & \text{if } \sum_{j=1}^{n} c_i x_j < z_1 \\ (\sum_{j=1}^{n} c_i x_j z_l)/(z_u - z_l) & \text{if } z_l \le \sum_{j=1}^{n} c_i x_j < z_u, \\ 1 & \text{if } \sum_{j=1}^{n} c_i x_j \ge z_u \end{cases} \tag{5}$$

The fuzzy set of the ith constraint, C_i, which is a subset of R^m, is defined by,

$$\mu_{c_i}(x) = \begin{cases} 0, & b_i < \sum_{j=1}^{n} a_{ij} x_j \\ (b_i - \sum_{j=1}^{n} a_{ij} x_j)/\sum_{j=1}^{n} d_{ij} x_j, & \sum_{j=1}^{n} a_{ij} x_j \le b_i < \sum_{j=1}^{n} \left(a_{ij} + d_{ij}\right) x_j \\ 1, & b_i \ge \sum_{j=1}^{n} \left(a_{ij} + d_{ij}\right) x_j \end{cases} \tag{6}$$

Accordingly, the problem (1) becomes to the subsequent optimization problem

$$\begin{aligned} & \max \lambda \\ & \mu_G(x) \ge \lambda \\ & \mu_{C_i}(x) \ge \lambda, \quad 1 \le i \le m \\ & x \ge 0, \quad 0 \le \lambda \le 1 \end{aligned} \tag{7}$$

By using (5) and (6), the problem (7) can be written as

$$\begin{aligned} & \max\ \lambda \\ & \lambda(z_1 - z_2) - \sum_{j=1}^{n} c_j\, x_j + z_2 \le 0, \\ & \sum_{j=1}^{n} (a_{ij} + \lambda\, d_{ij})\, x_j - b_i \le 0,\ 1 \le i \le m \\ & x_j \ge 0, \quad 1, \ldots n, \quad 0 \le \lambda \le 1. \end{aligned} \tag{8}$$

3 Case Study

In the Pune region of Maharashtra State, India, a dam was built across the Mula-Mutha River to form the Khadakwasala reservoir, a multipurpose project considered as a study area. The reservoir has an 86 Mm^3 total storage capacity, 56 Mm^3 of live storage, and a 62,146 Ha irrigable command area. The index map of the Khadakwasala command area is shown in Fig. 2. Table 1 presents the reservoir's monthly 75% dependable inflows.

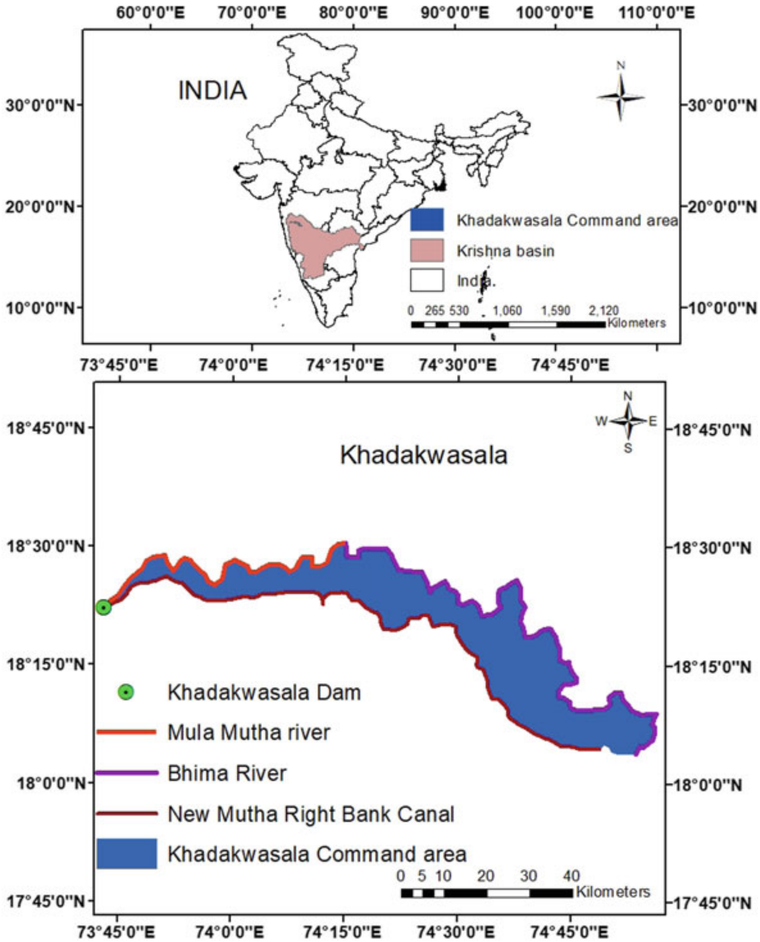

Fig. 2 Index map of Khadakwasala command area

Table 1 Monthly inflows of Khadakwasala reservoir

Month	Inflows in Mm^3	Month	Inflows in Mm^3
June	82.48	December	56.82
July	156.25	January	145.51
August	190.48	February	63.47
September	178.52	March	123.87
October	65.82	April	131.17
November	143.03	May	106.95

4 Fuzzy Linear Programming Model

The FLP model is developed for the reservoir's monthly operation. Here, the constraints are considered as crisp, or non-fuzzy, and the objective functions as fuzzy. Assuming stationary inflows throughout the course of a water year, the following generalized LP model is developed for monthly operation of the reservoir. The following generalized LP model incorporates FLP formulations as described in the methodology.

4.1 *Objective Function*

Maximization of irrigation releases has been considered as an objective function with a relevant set of constraints.

The objective considered in the model is

$$\text{Max } Z = \sum_{t=1}^{12} RIr \tag{9}$$

4.2 *Constraints*

Industrial release constraint

Releases for industry in each month (RIn_t) should be less than the maximum industrial releases ($RIn_{t(\max)}$). Releases in each month also should be greater than the minimum industrial releases ($RIn_{t(\min)}$).

$$RIn_t < RIn_{t(\max)} \quad \forall t = 1 \text{ to } 12, \tag{10}$$

$$RIn_t > RIn_{t(\min)} \quad \forall\, t = 1 \text{ to } 12. \tag{11}$$

Irrigation release constraint

Irrigation releases in each month (RIr_t) should be less than maximum irrigation demand ($IrD_{t(\max)}$). Irrigation releases also should be greater than minimum irrigation demand ($IrD_{t(\min)}$).

$$RIr_t < IrD_{t(\max)} \quad \forall\, t = 1 \text{ to } 12, \tag{12}$$

$$RIr_t > IrD_{t(\min)} \quad \forall\, t = 1 \text{ to } 12. \tag{13}$$

Domestic water supply constraint

Releases for domestic in each month (RDw_t) should be less than maximum domestic water demand ($RDw_{t(\max)}$). Releases for domestic also should be greater than minimum domestic water demand ($RDw_{t(\min)}$).

$$RDw_t < RDw_{t(\max)} \quad \forall\, t = 1 \text{ to } 12, \tag{14}$$

$$RDw_t > RDw_{t(\min)} \quad \forall\, t = 1 \text{ to } 12. \tag{15}$$

Reservoir storage constraints

Reservoir storage in each month should be less than maximum reservoir storage. Reservoir storage also should be greater than minimum reservoir storage.

$$S_t < S_{t(\max)} \quad \forall\, t = 1 \text{ to } 12, \tag{16}$$

$$S_t > S_{t(\min)} \quad \forall\, t = 1 \text{ to } 12. \tag{17}$$

Reservoir storage continuity constraint

Reservoir storage, inflows, irrigation releases, industrial releases, domestic water supply, evaporation losses from the reservoir during the time period t for all months are considered in volume units, and overflows are all subjected to this constraint.

$$S_t + I_t - RIr_t - RIn_t - RDw_t - E_t - O_t = S_{t+1} \quad \forall\, t = 1 \text{ to } 12. \tag{18}$$

Overflow Constraint

$$O_t > S_t + I_t - RIr_t - RIn_t - RDw_t - E_t - S_{t(\max)} \quad \forall\, t = 1 \text{ to } 12. \tag{19}$$

5 Results and Discussions

In the present study, model of FLP has studied and it has applied to Khadakwasala reservoir. Data used (inflow, irrigation, domestic and industrial water requirement, evaporation) to formulate aforementioned methodology have been procured form the Sinchan Bhavan, Pune. The objective considered in FLP model is maximization of irrigation releases (*RIr*). As stated in the methodology, the model initially takes into account the uncertainty associated with resources (b_i), i.e., irrigation demands and reservoir storage in any time period t are considered to be fuzzy resources, while technological coefficients are considered to be crisp in nature. For fuzzy technological coefficients, such as irrigation releases, the FLP model is solved (RIr). In this model using Eqs. (3) and (4), the model is solved for upper and lower bounds of irrigation releases, and maximum value of the objective is considered as upper bound (Z_u) and minimum value is considered as lower bound (Z_l) for the objective function. These values are given in Table 2. Equations (5) and (6) have been used to establish a linear membership function for the objective and constraints. Finally, a model is solved using Eq. (8) to maximize the truth level (λ). Table 3 displays the release policy for the maximized value of degree of truth (λ).

Table 3 presents optimal operating policies for the FLP model as described in the methodology section. When the uncertainty in the technological coefficients of the model is taken into account, the annual release for irrigation obtained is 515.63 Mm^3, and the degree of truth (λ) is 0.48.

By this model, in the month of June—90.84%, July—87.76%, October—38.54%, November—62.31%, January—4.41%, February—84.92%, March—40.15%, April—43.14%, May—44.85%, the releases in terms of percentage demand are satisfied, and in the months of August, September, and December, the releases

Table 2 Maximum and minimum bounds of the objective function for b_i

Objective function	
Bounds	Irrigation releases in Mm^3
Upper	593.495
Lower	578.42

Table 3 Release strategy for fuzzy technological coefficients (a_{ij})

Months	Irrigation releases (Mm^3)	Months	Irrigation releases (Mm^3)
June	3.51	December	73.17
July	11.91	January	45.21
August	12.57	February	77.86
September	66.59	March	38.83
October	54.72	April	43.96
November	48.69	May	38.61

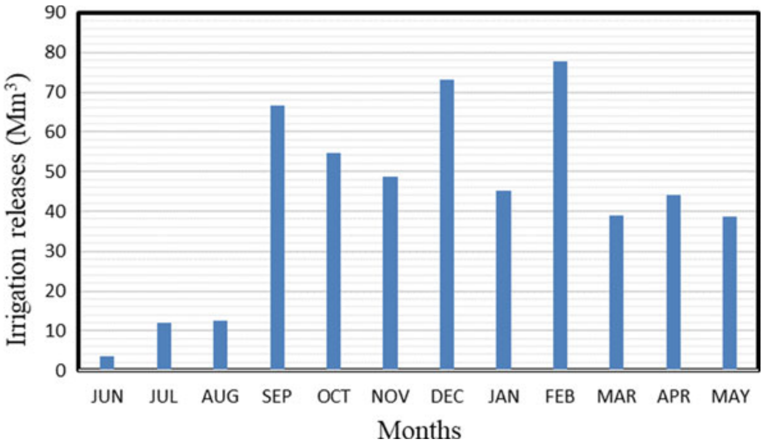

Fig. 3 Irrigation releases

in terms of percentage demand satisfied are 91.29%. As a result, it is observed that the best operating strategy derived by the current methodology taking into account the fuzziness involved in technological coefficients provides more precise results (Fig. 3).

6 Conclusions

The optimal reservoir operation with fuzzy technological coefficients is described as a fuzzy linear programming problem with a single objective. With respect to determine the optimal monthly operation strategy, this model is used for the case study of the Khadakwasala reservoir, which is located on the Mutha River in Maharashtra State, India. Maximizing irrigation releases is the objective function taken into consideration. Within a context of linear modeling, this methodology addresses uncertainty in demands, storages, and releases. The modeling process verified that how uncertainty in different parameters of reservoir operation model can be included progressively in resources, in technological coefficients of the model with fuzzy objective. The key findings of the present study are:

(i) The fuzzy logic model has the benefit that its computations are simple and its structure makes it simple for the operator to understand.
(ii) The model achieves an overall truth level (λ) of 0.48; however, it is up to the operations' manager to understand the sensitivity of the optimal results.

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