



Development of a Fuzzy Multi-Objective Heuristic Model for Optimum Water Allocation

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Received: 26 April 2017 / Accepted: 12 July 2019 /
Published online: 27 July 2019
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Abstract

A challenging issue in optimal allocating water resources is uncertainty in parameters of a model. In this paper, a fuzzy multi-objective model was proposed to maximize the economic benefits of consumers and to optimize the allocation of surface and groundwater resources used for optimal cropping pattern. In the proposed model, three objective functions were optimizing farmer's maximum net profit, groundwater stability and maximizing the reliability of water supply considering uncertainties in water resources and economic parameters in a basin. The optimal Pareto trade-off curves extracted using Non-dominated Sorting Genetic Algorithm- II. The best point on the Pareto trade-off curves was determined by using five decision-making approaches which combined by Breda aggregation method. Then, analyzing the credibility level of the optimization parameters and nonlinearity condition of objective functions revealed that by non-linearization of objective functions and increasing the fuzziness of the water demand and economic parameters, the model achieves more desirable values. Having been applied under uncertain conditions of objective functions and the input parameters, the results indicate an average increase of 17% and 54% in the allocation of agriculture and urban sectors, respectively. According to the annually optimal allocation results, the groundwater resources show higher sensitivity rather than surface water resources to the uncertainties in the parameters. Moreover, the optimal operation policies are more efficient than the deterministic model. Consequently, the suggested model can facilitate optimizing water resources allocation policies, providing the optimal cropping pattern under uncertainty conditions, and can be used for the similar uncertain condition in other basins.

Keywords Non-dominated sorting genetic algorithm-ii · Multi-objective optimization · Optimal crop pattern · Uncertainty · Credibility level · Conjunctive use

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1 Introduction

Water demands in urban, industry and agriculture sectors will significantly increase in the near future and water supply for irrigated agriculture will be restricted regarding the competition between the economic sectors in obtaining more water. Specially, sustainable management of water resources in arid regions requires optimal use of agricultural water resources (Banihabib et al. 2017). By restricting the water supply in the agricultural sector, foodstuffs production will face difficulties (Rosegrant et al. 2002). Moreover, the future of water and food are severely confronted with uncertainty. Some of these uncertainties result from some uncontrollable factors such as weather conditions. Furthermore, there are several other critical factors being affected by humans including: population growth, investment in water infrastructures, water allocation to different sectors, water management strategies and employing technology in the agricultural sector. Therefore, uncertainties in the optimization of water resource allocation is an unavoidable part of water resource management. The uncertainties can rise from various causes like climate condition, available water volume, cropping area, demand rate and economic factors. In this regard, taking the uncertainties into account by a developed optimization model can play an effective role in more realistic water allocation for irrigation.

Optimal cropping pattern is one of the effective strategies for agricultural water management which applies optimum allocation of land and water resources. In optimal cropping pattern, some questions as the following can be addressed: what type of crops should be replaced by the existing ones? What percentage of the area should be assigned to each crop? Since planners and decision-makers can not neglect the variation of cropping pattern, decisions and behaviors of farmers and managers, uncertainty in irrigation management requires attention. Therefore, considering uncertainties and flexibilities in planning and policy-making in the agriculture sector will lead to more realistic and acceptable outcomes.

In recent decades, numerous uncertain optimization methods were developed. For instance, Sahoo et al. (2006) expanded linear programming and fuzzy optimization for planning and management of the land-water-product system for Mahanadi-Kathajodi River's delta in the east of India. The models were used for optimization of economic revenues, workforce, cropping pattern, fertilizer and limited water resource. According to the results, the model facilitated conjunctive use of surface and groundwater. Abolpour and Javan (2007) developed a model for optimum water allocation within application of probabilistic fuzzy dynamic planning in Karosivand basin, Fars Province, Iran. The results of their research showed that the reliability of reservoir operation could increase up to 51% during drought years. Lu et al. (2010) applied fuzzy linear planning method for agricultural water resource management and showed that the interval fuzzy collections could state dual uncertainties in model parameters, and the solution can make valid decisions for decision-makers' priorities and practical conditions. Tabari (2015) developed a model for conjunctive use of water with considering uncertainty in the input parameters of groundwater simulation. Based on this model, the optimal water allocations from surface and groundwater resources specified with combination of fuzzy logic theory and direct search optimization tools. The results showed that applying uncertainty in the optimization process can lead to the improvement of the performance of water supplying and sustainability of system in order to have available water resources for a long-term planning. Niu et al. (2016) developed an interactive two-stage fuzzy stochastic method to optimize the cropping pattern. The economic penalty function was also considered for the deviating problem from rational mode into the irrational mode. In proposed model, water resource allocation investigated under uncertainty conditions. The results showed that

the proposed optimization model is suitable and useful for arid and semi-arid regions. In another research, Yousefi et al. (2018) proposed a multi objective model to optimize farmers' benefits, the use of water resources and decrease nitrogen leaching from drainage networks. This research displayed how significant the multi objective optimization of agricultural water use is for sustainable management of water resources.

The literature review reveals that the use of fuzzy concept in order to apply uncertainty of water resource parameters in management models can lead to enhanced operation policies (Banihabib and Shabestari 2017). In addition, due to the complexity of demands and water resources system in the study areas, applying several objectives in the process of developing optimal allocation policies can lead to more realistic rules for operation of surface and underground water than single-objective models (Yousefi et al. 2018). With the aim of improving the results of water allocation models, this research attempted to consider uncertainty of economic parameters and demands of several study areas simultaneously. In this approach, not only the economic benefits of operating water resources in the short-term achieved, but also the sustainability of the aquifer system for its long-term operation as the main source of water supply demands have been considered. This idea, which has not been previously considered to model demands and water resource system, has been developed in this study and its various aspects have been investigated.

In this research, a multi-objective optimization algorithm called Non-dominated Sorting Genetic Algorithm- II (NSGA-II) was proposed to determine the optimum water allocation and cropping pattern, maximum reliability, and making a stability in the groundwater system simultaneously.

The purpose of the model is to determine optimal allocation from surface and groundwater resources for agriculture and domestic demands in order to maximize benefits resulted from cropping in five separate studied sub-areas, to make stability in groundwater level and to maximize the reliability of water supply in the condition of applying uncertainty on the demands and the economic coefficients parameters. It should be noted that the uncertainty in both objective functions and constraints was considered. Furthermore, in order to increase the speed of achieving global optimal solution, the NSGA-II algorithm used, and the best scenario on the optimal trade-off curves was selected based on Borda aggregation method. The major contributions of this study are as follows:

- Applying uncertainty due to the demands and economic coefficients in the process of optimal allocation of surface and ground water resources using fuzzy theory,
- Development of a stochastic multi-objective conjunctive use approach of surface and groundwater resources with priority in their use,
- Using multiple decision making methods and aggregating their results with Breda, Aggregation Method (BAM) to determine the best scenario for extracting optimal allocation values.

2 Material and Methods

2.1 Study Area

Zarrinehrud basin located in three provinces (East Azerbaijan, West Azerbaijan and Kordestan Provinces, Iran) in latitude $36^{\circ} 45'$ to $38^{\circ} 20'$ and longitude $44^{\circ} 50'$ to 46°

10°. Zarrinehrud Sub-basin has significant contribution in supplying water for drying lake, Urmia Basin. Restoration of Lake Urmia is a national goal, therefore, sustainable management of water resources in Lake Urmia basin is required for optimal use of agricultural water management (Azarnivand and Banihabib 2017). Zarrinehrud Sub-basin's area is more than 12025 km², and its main river has 300 km length and originated from Chehel-Cheshme mountains of Kordestan Province and it reaches Urmia Lake from southeast direction. Average discharge of this river is estimated 139.5 Million Cubic Meter (MCM) monthly. A storage dam, called Zarrinehrud dam, was built in 1350 on the Zarrinehrud River. The dam is located in West Azerbaijan Province and a distance of 35 km to the southeast of Bukan City. Norouzlou diversion dam was built in 70 km of downstream of storage dam, and it supplies the water for Miandoab plain and parts of Bonab and Malekan plains. Zarrinehrud River is comprised of four main sub-basins. The geographical location of this area is given in Fig. 1 (Ministry of energy, 2010a).

The agricultural area of Zarrinehrud equals 64670 ha and about 58171 ha of it is irrigable. In addition to agricultural water supply, Zarrinehrud supplies more than 40% of urban water for Tabriz City. Regarding agricultural lands' position out of the basin and the considerable difference in climatic and topography conditions, we divided the basin into study sub-areas. For that, according to the position of Zarrinehrud storage dam, hydrometric stations, and rivers existing in the area, Zarrinehrud basin has been divided into five study sub-areas: Saqqez, Takab, Sainqaleh, Miandoab-1 and Miandoab-2. Based

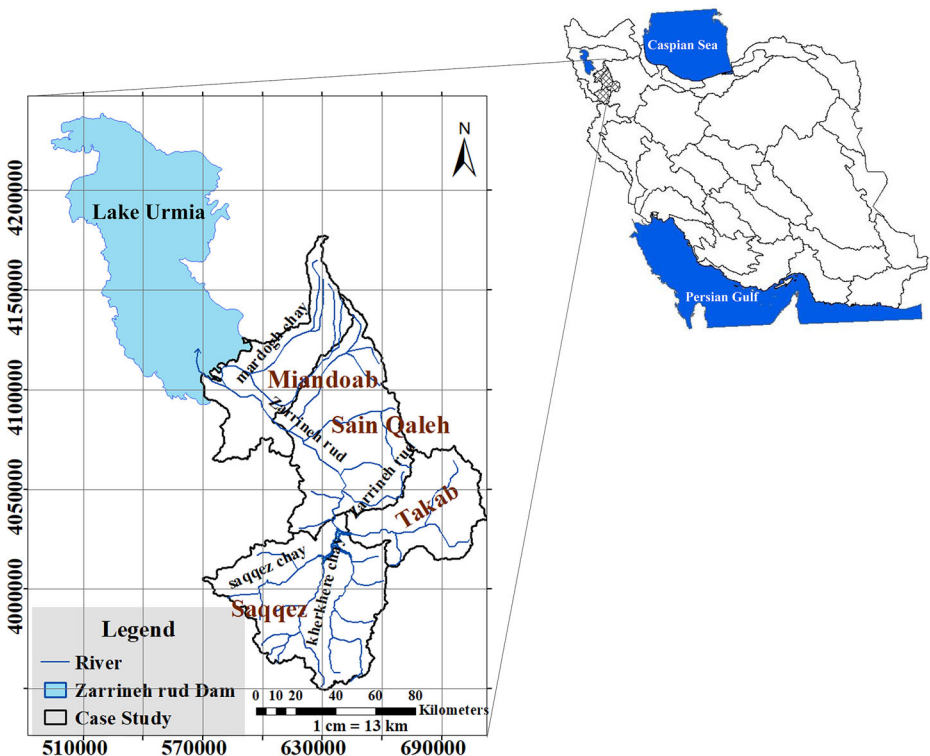


Fig. 1 Location of Zarrinehrud water resources

on collected agricultural information and data from the study area, the crops of wheat, alfalfa, beans, sunflower, potato, tomato, corn, maize, peas, onion and watermelon are being cultivated in the study area. Moreover, the study area includes orchards such as apricot, peach, grapes, apple, cucumber, almond, walnut, and cherry (Ministry of energy, 2010b).

2.2 The Structure of Proposed Model

In the proposed model, three objective functions were considered in order to maximize benefits obtained from agricultural activities, to make stability in groundwater level and to maximize the reliability of water supply under conditions of applying uncertainty in parameters of water demands and economic factors. According to Kishor et al. (2009), Zeng et al. (2010), and Li et al. (2013) studies, the mathematical form of the objective functions based on membership function developed as follows:

- **First objective function:** Maximizing the economic benefits obtained from cropping (Eqs. 1–3).

$$\text{Maximize } \mu_{Z_1} = \begin{cases} 0 & , Z_1 \leq Z_1^L \\ \left(\frac{Z_1 - Z_1^L}{Z_1^U - Z_1^L} \right)^{\beta_1} & , Z_1^L < Z_1 < Z_1^U \\ 1 & , Z_1 \geq Z_1^U \end{cases} \quad (1)$$

$$Z_1 = \sum_{i=1}^{nz} \sum_{j=1}^{nc} \left[\alpha_{ij} A_i \left(Y_{ij} \widetilde{B}_{ij} - \widetilde{C}_{ij} \right) \right] - PF_t \quad (2)$$

$$Y_{ij} = Y_j^{max} \times \prod_{t=1}^{12} \left[1 - K_{jt} \left(1 - \frac{TAWA_{ijt}}{\widetilde{AD}_{ijt}} \right) \right] \quad (3)$$

where, i is counter of studied sub-areas numbers, j is counter of product numbers, nz is number of all studied sub-areas, nc is the total number of examined products, α_{ij} is percentage of sub-area covered by product j in sub-area i (dimensionless and as decision variable), A_i is the total cultivable land in sub-area i (ha), \widetilde{B}_{ij} (as $[B_{ij}^L, B_{ij}^U]$) is sale price of product j in sub-area i (IRR/kg), \widetilde{C}_{ij} (as $[C_{ij}^L, C_{ij}^U]$) is the total cost (cropping, harvest and etc.) of product j in sub-area i (IRR/ha), Y_{ij} is the yield of product j in sub-area i (kg/ha), Y_j^{max} is the maximum yield of product j kg/ha, K_{jt} is sensitivity ratio of product j in month t , $TAWA_{ijt}$ is total water allocated to product j in sub-area i and in month t (millimeter and as decision variable), \widetilde{AD}_{ijt} (as $[AD_{ij}^L, AD_{ij}^U]$) is water need of product j in month t (millimeter). In this study, μ_{Z_1} , μ_{Z_2} and μ_{Z_3} are the membership function for first, second and third objective function., Z_1^L, Z_2^L, Z_3^L and Z_1^U, Z_2^U, Z_3^U are the maximum and the minimum feasible solution of the objective functions, and determination based on deterministic multi-objective model.

In this research, the cost coefficients, the sale price of agricultural products, and water needs for each of the sub-areas were considered as parameters with uncertainty and in fuzzy form by using credibility level as proposed by Liu et al. (2013) (Fig. 2). In this figure, values of b^L , b^U , and b are lower limit, upper limit and median (mid limit) of each uncertainty parameters, respectively. In addition, 10% of variations in the existing values were considered for each of uncertainty parameters as variation interval of fuzzy values. It means that if the credibility level of a fuzzy event equals zero, the event will not happen, and under the conditions that the credibility level equals one, the fuzzy incident will definitely occur. According to studies conducted by Li et al. (2013) and Liu et al. (2013), it is usually assumed that a significant credibility level shall not be less than 0.5.

- **Second objective function:** Stability of aquifer’s system by controlling its withdrawal (Eqs. 4–5).

$$\text{Minimize } \mu_{Z_2} = \begin{cases} 1 & , Z_2 \leq Z_2^L \\ \left(\frac{Z_2^U - Z_2}{Z_2^U - Z_2^L}\right)^{\beta_2} & , Z_2^L < Z_2 < Z_2^U \\ 0 & , Z_2 \geq Z_2^U \end{cases} \quad (4)$$

$$Z_2 = \left(\frac{\sum_{t=1}^{12} \sum_{i=1}^{n_z} [TGAW_{it} - Per_i \times (\sum_{j=1}^{n_c} ((1 - efd_i) \times TAWA_{ijt}) + PW_i \times TAWD_{it})]}{\sum_{t=1}^{12} \sum_{i=1}^{n_z} Per_i \times ((1 - efd_i) \times \sum_{j=1}^{n_c} TAWA_{ijt} + PW_i \times TAWD_{it})} \right)^2 + PF_i \quad (5)$$

Where $TGAW_{it}$ is total groundwater allocated to sub-area i and in month t (mcm), $TAWD_{it}$ is total water allocated to urban sector of sub-area i and in month t (mcm), efd_i is the efficiency of water usage in sub-area i , Per_i is infiltration percent of water into groundwater in sub-area i , PW_i is conversion percent of domestic water to sewage in sub-area i .

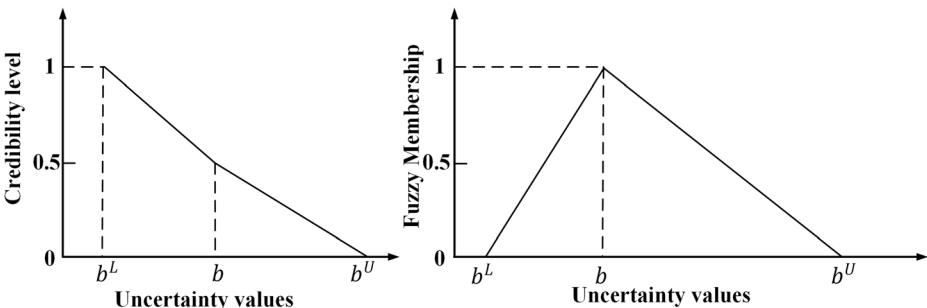


Fig. 2 Fuzzy membership function and credibility level considered for uncertainty parameters (Liu et al. 2013)

Third objective function: minimizing the rate of lack of water supplying (Eqs. 6–7).

$$\text{Minimize } \mu_{Z_3} = \begin{cases} 1 & , Z_3 \leq Z_3^L \\ \left(\frac{Z_3^U - Z_3}{Z_3^U - Z_3^L}\right)^{\beta_3} & , Z_3^L < Z_3 < Z_3^U \\ 0 & , Z_3 \geq Z_3^U \end{cases} \quad (6)$$

$$Z_3 = \sum_{i=1}^{nz} \left[\sum_{j=1}^{nc} \left(\frac{(TAWA_{ijt} - \widetilde{AD}_{ijt})^2}{\widetilde{AD}_{ijt}} \right) + \left(\frac{(TAWD_{it} - \widetilde{DD}_{it})^2}{\widetilde{DD}_{it}} \right) \right] + PF_t \quad (7)$$

where, \widetilde{DD}_{it} (as $[DD_{it}^L, DD_{it}^U]$) is water demand rate of urban sector in sub-area i and in month t (MCM). Since the resources of surface water, groundwater and lands in the sub-areas are limited, the following limitations were considered in the optimization model (Eqs. 8–20):

$$TAWD_{it} \leq DD_{it} + (1-2\delta)(DD_{it} - DD_{it}^L) \quad (8)$$

$$TAWA_{ijt} \leq AD_{ijt} + (1-2\delta)(AD_{ijt} - AD_{ijt}^L) \quad (9)$$

$$\sum_{j=1}^{nc} \alpha_{ij} = 1, \quad i = 1, 2, \dots, nz \quad (10)$$

$$TAW_{it} = TAWA_{it} + TAWD_{it} \quad (11)$$

$$TSAW_{it} = \min(TAW_{it}, SW_{it}^{max}) \quad (12)$$

$$TGAW_{it} = \max(TAW_{it} - SW_{it}^{max}, 0) \quad (13)$$

$$S_{t+1} = S_t + \sum_{i=1}^2 I_{it} - Env_t - \sum_{i=1}^{2,5} TSAW_{it} - Ev_t \times \bar{A}_t \quad (14)$$

$$\bar{A}_t = \frac{A_t + A_{t+1}}{2} \quad (15)$$

$$A_t = 5 \times 10^{-8} S_t^3 - 0.0001 S_t^2 + 0.1168 S_t + 2.443 \quad (16)$$

$$SP_t = \max(S_{t+1} - S_{max}, 0) \tag{17}$$

$$S_{min} \leq S_t \leq S_{max} \tag{18}$$

$$S_1 \leq S_{T+1} \tag{19}$$

$$PF_t = K \times (\max(1 - S_{t+1}/S_{min}, 0) + \max(1 - S_{T+1}/S_1, 0)) \tag{20}$$

where, β_1 , β_2 and β_3 are indicators of membership function shape. If these values equal one, membership functions are linear, otherwise the membership function of each objective in optimization process are considered nonlinear (Sasikumar and Mujumdar 1998). Accordingly, membership function of each objective can be presented on the basis of β_1 , β_2 , β_3 values as Fig. 3.

The $TSAW_{it}$ is total surface water allocated to sub-area i and in month t (MCM), δ is credibility level, SW_{it}^{max} is maximum surface water allocated to sub-area i and in month t (MCM), I_{it} is surface inflow into sub-area i and in month t (MCM), Env_t is environmental water need of Zarrinehrud in month t (MCM), Ev_t is evaporation rate from reservoir surface in month t (meter), A_{t+1} , A_t are reservoir water sub-area at the beginning and the end of month t (square kilometer), \bar{A}_t is average reservoir water sub-area in month t (square kilometer), S_t is reservoir volume in month t (MCM), S_{max} , S_{min} are maximum and minimum of reservoir volume (MCM), SP_t is volume of water overflow from reservoir spillway in month t (MCM), PF_t is penalty function related to dam reservoir when the limitations related to eqs. 18 and 19 is not observed, it will be added to minimum objective functions and it will be reduced from maximum objective functions. K is the constant of penalty function and was considered as 10^{20} (a big number) in this study.

According to the objective functions, all urban and agricultural water allocation in each month were considered as decision variables. Thus, the number of multi-objective decision variables equals $((18 + 1) \times 12 + 18) \times 5 = 1230$ by considering 18 cropping sub-areas, 19 water users (1 urban and 18 agriculture) in 12 months and five sub-areas. It should be noted that, in this study, water needs in the industry sector was not considered in optimization due to its insignificance. The priority of allocation in this area (like other similar studies) is surface water resources and in shortage

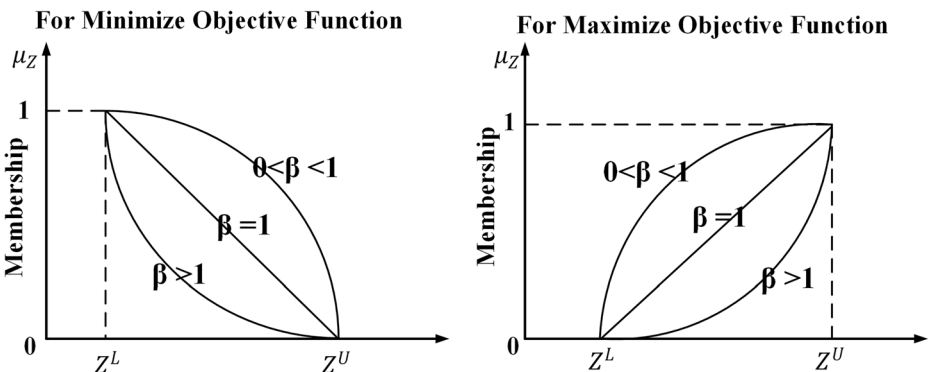


Fig. 3 The membership function considered for each suggested objective function (Liu et al. 2013)

condition, thus, according to eq. 12, if the allocated water is less than whole available surface water, total allocated water is withdrawn from surface water by the optimization algorithm.

However, when total allocated water is more than available surface water in each sub-area, the surplus is supplied from groundwater resources (Eq. 13). Moreover, the continuity equation (Eq. 14) was used to optimize water release from Bukan Dam. Equation 20 was used for applying a penalty to unjustifiable responses which are found in the process of searching global optimum. According to this equation, if in a water release, the reservoir volume offends the determined maximum and minimum values, the penalty will be applied to each of objective functions which lead to non-reselection of it in the optimization model.

The flowchart for determining uncertain optimal values was presented in Fig. 4. As shown in this figure, it is necessary to determine first the data of resources, consumptions, cropping area and cropping water needs in the studied sub-area. Then, objective functions were optimized by programming a multi-objective optimizer algorithm NSGA-II in MATLAB using the uncertain parameters in this study (agriculture and urban water demands and economic coefficients (including sale price and products' cost)), fuzzy concept and credibility level,. In this study, due to the complexity of the model and for a high number of decision variables and for increasing the speed of optimization, the multi-objective heuristic NSGA-II algorithm was used which was suggested by Deb et al. (2000).

Since in the obtained Pareto trade-off curves, using NSGA-II algorithm, each point is a scenario for water allocation, the decision-maker can select one of the scenarios considering the entire three determined objectives to allocate optimal values for water users and cropping

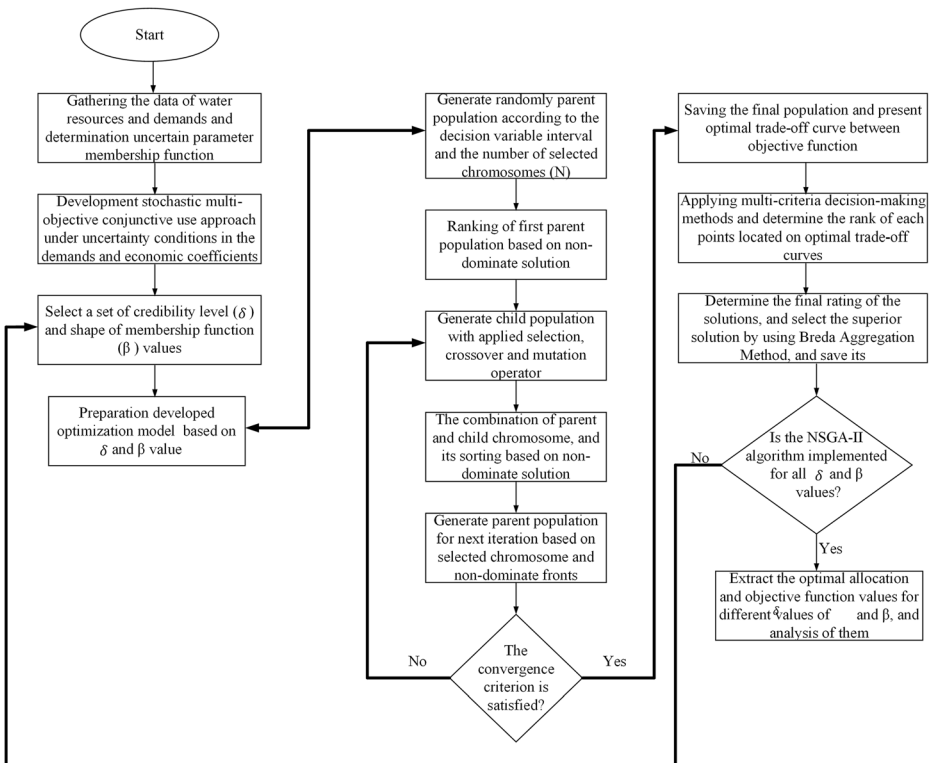


Fig. 4 Flowchart of the optimization model for water resource allocation under uncertainty condition

pattern. For selecting a proper point on Pareto trade-off curves, multi-criteria decision-making methods (MCDM) can be used (Bozdağ 2015; Bozorg-Haddad et al. 2016). Since using each MCDM method leads to a different result, in this study, Breda aggregation method was offered to integrate the results of several MCDMs. For this purpose, five MCDM methods were employed including Compromising Programming (CP), Complex Proportional Assessment (COPRAS), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Modified- TOPSIS (M-TOPSIS), and Weighted Aggregate Sum Product Assessment (WASPAS). Using Breda Aggregation Method, the final integrated ranking of each point located on Pareto trade-off curves was determined for each δ value (indicator of credibility level rate and certainty degree of uncertain parameter) and β_1 , β_2 and β_3 (indicator of linearity or non-linearity of objective functions). Having looked into the optimum points on Pareto trade-off curves, determined by the different conditions of objective functions and uncertainty of parameters, the affectivity rate of uncertain conditions on each of decision variables and objective function can be investigated and analyzed. In fact, the output of presented approach can denote the water allocation policies from surface water and groundwater also optimal cropping pattern in each studied sub-area for the effective water resources management in uncertainty conditions.

3 Results and Discussion

By using information gathered from Zarrinehrud basin and implementing the proposed model, the optimum water allocation to urban and agriculture sections and also optimal cropping pattern were determined under uncertainty conditions. The initial selection of chromosome population within the NSGA-II algorithm plays an important role in run-time of the optimization model and distribution of points on Pareto trade-off curves. Accordingly, the most appropriate initial chromosome population was determined as 150 by trial and error in this study. Considering the selected population, the NSGA-II algorithm was examined for four credibility level (δ) of 0.5, 0.65, 0.8, 1 and for seven β_1 , β_2 and β_3 of 0.3, 0.5, 0.8, 1, 2, 5, 10 in order to attain global optimum. Suggested approach (Fig. 4) was applied to examine and determine selected chromosome for optimum decision variables and objective functions (Table 1). Since shape of objective function and interval of allowable variations of limitations varies, various chromosomes were determined under various uncertainty conditions. Then, chromosomes from Pareto trade-off curves selected in order to be analyzed and be extracted as best results (Table 1).

The objective functions values under various uncertainty conditions and also in different fashions of linearity or non-linearity were examined, and the behavior of three objectives functions (economic benefit, aquifer stability index and the total sum of non-supplying demands) are displayed in Fig. 5. According to the figure, it is clear that the increasing non-linearity of the objective functions and the fuzziness of water-demand parameters and economic coefficients led to more desirable values of three objective functions and experienced a significant difference with the linear mode of the functions (especially second and third objective functions). This result indicates an average increase of 54% and 17% in allocation to urban and agriculture sectors, respectively, using optimization under uncertain conditions of objective functions and the input parameters as well. Moreover, this shows better optimum water allocation policies than linear mode of objective functions and applying the crisp (non-fuzzy) input parameters (β_1 , β_2 and β_3 equals 1 and δ equals 0.5). This result is in line with the results of Zeng et al. (2010)

Table 1 Selected chromosomes under uncertainty conditions

Optimal chromosome number	β_3	β_2	β_1	δ	Optimal chromosome number	β_3	β_2	β_1	δ	Optimal chromosome number	β_3	β_2	β_1	δ
67	0.5	1	1	0.8	39	1	0.3	1	0.65	18	1	1	0.3	0.5
67	0.8	1	1	0.8	43	1	0.5	1	0.65	85	1	1	0.5	0.5
18	2	1	1	0.8	83	1	0.8	1	0.65	93	1	1	0.8	0.5
41	5	1	1	0.8	100	1	2	1	0.65	123	1	1	1	0.5
107	10	1	1	0.8	40	1	5	1	0.65	144	1	1	2	0.5
37	1	1	0.3	1	34	1	10	1	0.65	103	1	1	5	0.5
42	1	1	0.5	1	62	0.3	1	1	0.65	48	1	1	10	0.5
127	1	1	0.8	1	102	0.5	1	1	0.65	65	1	0.3	1	0.5
41	1	1	1	1	87	0.8	1	1	0.65	110	1	0.5	1	0.5
57	1	1	2	1	17	2	1	1	0.65	27	1	0.8	1	0.5
74	1	1	5	1	49	5	1	1	0.65	33	1	2	1	0.5
106	1	1	10	1	70	10	1	1	0.65	67	1	5	1	0.5
73	1	0.3	1	1	93	1	1	0.3	0.8	47	1	10	1	0.5
20	1	0.5	1	1	86	1	1	0.5	0.8	125	0.3	1	1	0.5
32	1	0.8	1	1	71	1	1	0.8	0.8	115	0.5	1	1	0.5
51	1	2	1	1	29	1	1	1	0.8	141	0.8	1	1	0.5
80	1	5	1	1	24	1	1	2	0.8	37	2	1	1	0.5
138	1	10	1	1	47	1	1	5	0.8	81	5	1	1	0.5
58	0.3	1	1	1	79	1	1	10	0.8	10	10	1	1	0.5
54	0.5	1	1	1	91	1	0.3	1	0.8	14	1	1	0.3	0.65
34	0.8	1	1	1	88	1	0.5	1	0.8	142	1	1	0.5	0.65
59	2	1	1	1	31	1	0.8	1	0.8	71	1	1	0.8	0.65
126	5	1	1	1	118	1	2	1	0.8	10	1	1	1	0.65
130	10	1	1	1	26	1	5	1	0.8	42	1	1	2	0.65
					26	1	10	1	0.8	28	1	1	5	0.65
					48	0.3	1	1	0.8	124	1	1	10	0.65

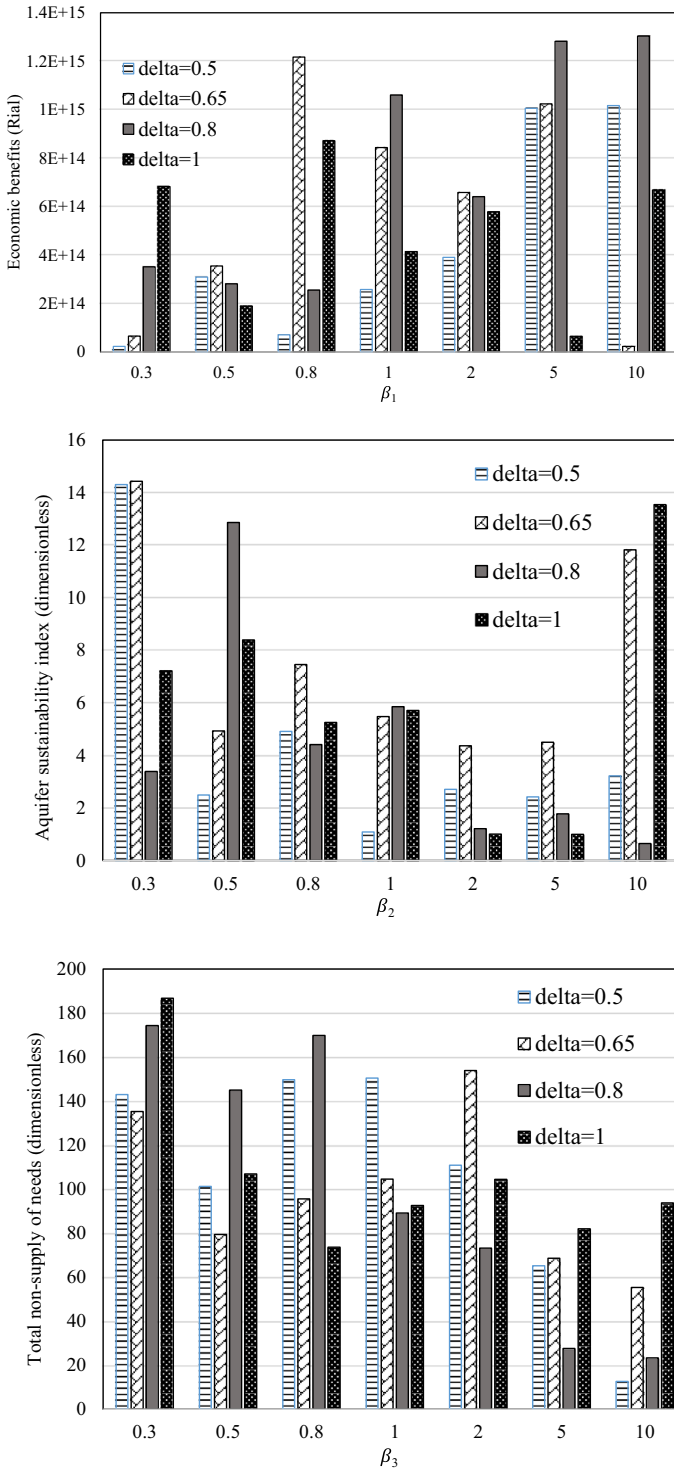


Fig. 5 Behavior of objective functions for applying uncertainty of input parameters and the nonlinear condition

in which the use of fuzzy multi-objective programming can lead to the development of more efficient operation policies and better options for land-use planning and optimal water allocation. In this regard, Li et al. (2013) also emphasized that the use of uncertain models towards crisp deterministic models can be very effective in providing better decisions for allocating water from surface and groundwater resources for water demands.

Table 2 shows the optimal values of the objective functions obtained under certain and uncertain conditions. By comparing the obtained results for the mentioned conditions, it can be found that the certain values of the first and the second objective functions are out of optimal interval presented for each objective function under uncertain conditions. This fact indicates the high complexity of examined system in satisfying three objective functions concurrently when the uncertainty of input parameters are applied to the optimization of land and water allocation.

Assessment of the optimum values of annual allocation for the sub-areas demonstrates that applying uncertainty of the parameters for allocation of groundwater is more sensitive in comparison with the surface water allocation (Fig. 6). For instance, in Takab sub-area, average variation of optimum annual allocation from this plain's groundwater (17.6 million cubic meters) is 7.5 times greater than the value of surface water resources (2.07 million cubic meters). These variations achieved under conditions in which three fuzzy parameters experienced 10% of variations compared to the crisp (non-fuzzy) model. This consequence is confirmed by other studied sub-areas. In other words, in the condition of applying uncertainty in water resource management, the optimum allocation of groundwater in the sub-areas tolerates more changes, and have higher sensitivity than surface water allocation.

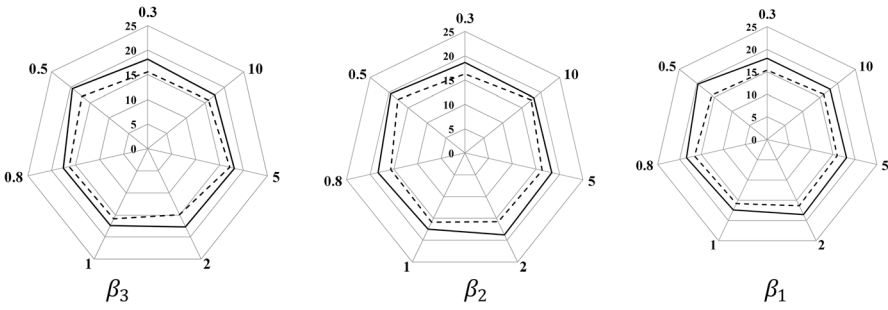
Table 3 provides a comparison of the optimum water allocation values under three conditions: current condition, under the certain and uncertain conditions. According to the table, it is clear that the optimum water allocation related to certain condition is more than optimum water allocation interval in uncertain condition. This fact shows the significant impact of uncertain parameters on optimal policies for water resources allocation, which is not possible to be estimated accurately in a crisp model of water allocation optimization. Consequently, without applying uncertain conditions to the water resource parameters, a great deviation happens in optimum water allocation policies in real conditions.

Table 4 shows optimal values of cropping pattern, values of objective functions and total allocated water (MCM) in certain and uncertain conditions. It can be noted that in credibility level of 0.8 and total nonlinearity conditions of objective functions, objective functions of the developed model have a higher value than other uncertain conditions (Fig. 5). Hence, the results related to values $\delta = 0.8$ and $\beta = 10$ were selected for the comparison.

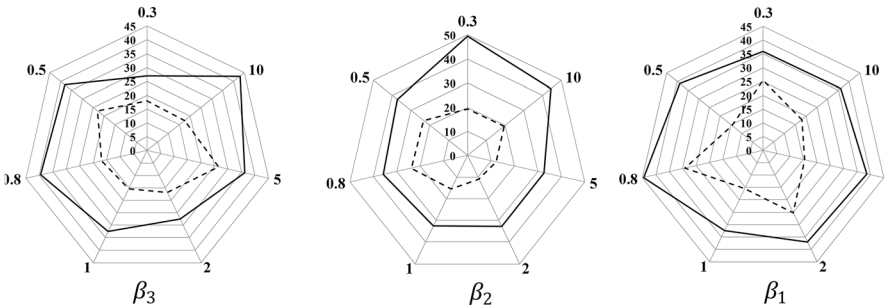
According to Table 4, applying uncertainty and nonlinearity in water-demand parameters, economic coefficients, and objective functions can lead to generating the better scenarios for water resource management rather than crisp optimization model. This is has also been considered in the study of Li et al. (2013) in which the results of uncertain model have led to an improved water use for irrigation of agricultural lands and saving water consumption. For example, if the second objective function is completely considered nonlinear ($\delta = 0.8$), then in

Table 2 Comparison of objective functions of suggested structure under certain and uncertain conditions

Objective function	Uncertain conditions	Certain conditions
Economic benefits ($10^{14} \times \text{IRR}$)	[1.54–8.34]	12.9
Aquifer sustainability index (dimensionless)	[1.87–9.38]	5.03
Total non-supply of needs (dimensionless)	[73.87–136]	50.08



Annual variation interval optimal allocation of surface water to studied area of Takab



Annual variation interval optimal allocation of ground water to studied area of Takab

Fig. 6 Variation of the annual optimum allocation of surface water resources and groundwater under uncertainty condition in studied sub-area of Takab (MCM)

spite of 8.5% and 47.3% saving in water compared to certain and present condition, respectively, the net benefit of system will not have considerable changes and the state of aquifer improves significantly with almost 87% reduction in water withdrawal. Under this conditions, despite more than twice increase in the non-supply index compared to crisp optimization model, the water intra-year distribution for different users and crops in five sub-areas were properly provided, which it led to an ignorable change in net benefit. It should be noted that the developed approach is similar to the study of Li et al. (2013) and these two approaches are very suitable for arid and semi-arid areas with severe water shortages for irrigation. Moreover, similar to Yang et al. (2015) study, this model can simultaneously focus on several water resources; multiple regions and products during the optimization process, and considered uncertainties from the input parameters of the model.

Table 3 Comparison between optimum annual groundwater and of surface water allocation to studied sub-areas under present conditions, certain and uncertain (MCM)

Sub-area name	Allocation of groundwater			Allocation of surface water		
	Uncertain conditions	Certain conditions	Current conditions	Uncertain conditions	Certain conditions	Current conditions
Saqqez	[18.98–33.23]	36	74.23	[19.45–24.55]	30.7	7.2
Takab Area	[19.13–36.77]	40.5	2.22	[16.18–18.26]	18	59.97
Sainqaleh	[10.64–16.74]	16.92	0.03	[12.78–16.01]	18.37	41.48
Miandoab-1	[40.43–103.4]	85.8	111.7	[14.21–20.78]	21.22	159.15
Miandoab-2	0	0	125.72	[159.73–226.84]	246.38	311

Table 4 Comparison of allocation optimum parameters and sub-area under cropping of products under certain and uncertain conditions in all reviewed sub-area

Cropping	Curtain conditions	$\delta = 0.8$ $\beta_3 = 1.0$, $\beta_1 = \beta_2 = 1$	$\delta = 0.8$ $\beta_2 = 1.0$, $\beta_1 = \beta_3 = 1$	$\delta = 0.8$ $\beta_1 = 1.0$, $\beta_2 = \beta_3 = 1$
Wheat	7168.93	8439.943	2349.377	6372.413
Alfalfa	1364.85	4262.97	2560.735	4635.066
Apple	2544.82	5666.09	4775.075	5425.459
Grapes	5075.22	9411.659	3172.005	5623.59
Onion	1580.68	6132.716	4589.456	6530.204
Walnut	5441.65	7235.581	4890.971	2458.339
Tomato	4417.35	3768.052	12743.5	8342.896
Watermelon	5091.34	6429.524	4192.349	5638.118
Apricot	4121.36	7289.413	4561.102	9075.749
Corn	5419.42	10396.15	2831.4	12204.07
Potato	2475.26	8735.062	3433.487	6267.063
Almond	5922.58	2248.635	4304.782	4588.41
Peas	5475.92	8669.153	5144.157	6268.78
Cucumber	4045.04	6753.6	4892.196	6439.314
Peach	45033	6439.949	34792.2	12912.97
Sunflower	1189.26	3364.558	5265.346	2782.493
Maize	3129.93	4337.359	3328.685	4944.363
Cherry	3549.36	3465.588	5219.174	2536.709
Total allocated water (MCM)	513.87	361.36	470.33	429.14
Net benefit (IRR)	1.29×10^{15}	7.36×10^{14}	1.18×10^{15}	1.3×10^{15}
Groundwater sustainability (dimensionless)	5.03	2.6	0.64	5.49
Non-supply index of needs (dimensionless)	50.08	23.37	112.45	90.7

4 Conclusion

In the present study, a fuzzy multi-objective heuristic model for optimal water resources allocation using credibility level concept under uncertainty of system parameters was developed and applied on Zarrinerud basin. This study revealed that nonlinearity of objective function and increase in fuzziness of water demand parameters and economic coefficients leads the objective functions to more desirable values. In addition, the results confirm that the groundwater resources have higher sensitivity rather than surface water resources to applying uncertainty. Based on results, it can be concluded that the optimum values of decision variables associated with deterministic conditions are generally out of the optimal allocation interval provided in uncertain conditions. This indicates the considerable effectivity of uncertain parameters on optimum water resources planning, and it is not possible to be accurately estimated by a crisp optimization model. Finally, it concluded that the proposed model enhances our capability in optimal water resources management, especially in integrated water and land resource planning. Therefore, this model can be offered for determining optimum policies for water withdrawal from water resources and optimal cropping pattern in uncertainty conditions in other similar areas.

Compliance with Ethical Standards

Conflict of Interest None.

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Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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