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Research Article

Sustainable irrigation water and land management under multiple uncertainties: Case study of Qorveh plain, Kurdistan, Iran

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ABSTRACT- The Qorveh plain in Iran is experiencing severe groundwater depletion. This situation necessitates more efficient strategies for allocating agricultural water and land to support long-term regional sustainability. To address climatic, hydrological, and economic uncertainties, this study develops a multi-objective stochastic fuzzy programming (MOSFP) model for optimal cropping-pattern planning. The proposed framework simultaneously maximizes gross economic return and irrigation water productivity (IWP) while minimizing total cultivated area. The latter objective aims to reduce pressure on groundwater resources. The model was applied under different α-cut levels and violation risk probabilities (P). These scenarios were used to evaluate trade-offs between economic benefits and groundwater sustainability. The results indicate that sustainable agricultural management requires substantial changes in cropping patterns. Under the selected optimal scenario (α = 0.6, P = 0.20), the total cultivated area decreased by approximately 25.4% compared with the current pattern. At the same time, economically efficient and strategically important crops were prioritized. The optimized strategy substantially improved irrigation water productivity and reduced dependence on excessive groundwater extraction. Sensitivity analysis showed that increasing risk tolerance from 5% to 25% resulted in only a marginal 2.4% increase in IWP. This finding suggests that accepting higher water-shortage risk provides limited performance gains. These gains may not justify the associated environmental pressures, including potential aquifer degradation and land subsidence. Overall, the proposed framework provides an effective decision-support tool for sustainable agricultural planning under uncertainty. It can help regional policymakers balance economic objectives with long-term groundwater conservation.

INTRODUCTION

In recent decades, the development and widespread use of diesel and electric motors have enabled the extraction of groundwater from major aquifers, contributing significantly to increases in crop yields. However, growing concerns have emerged about the irreversible depletion of aquifer storage capacity, declining surface- and groundwater availability, and rising energy costs associated with water pumping (Li and Hu, 2020). These challenges highlight the importance of efficient irrigation management strategies under conditions of limited water availability. Such strategies are essential for ensuring long-term agricultural sustainability and food security. The sustainability of irrigated agriculture depends on balancing economic growth, social equity, and environmental protection. Because these three objectives can sometimes conflict, agricultural decisions should consider them simultaneously (Singh et al., 2023). In water-limited areas, the efficient and appropriate use of water and land is particularly important for maintaining food security and supporting long-term agricultural production. However, irrigated agriculture currently faces multiple challenges, including climate change, economic instability, and degradation of natural resources. Irregular rainfall, increased evapotranspiration, and extreme weather events intensified by human activities have placed additional pressure on water and land resources (Ferdous et al., 2024). At the same time, economic uncertainty poses a major challenge for agricultural planning. Fluctuations in input and output prices can cause substantial variation in farmers' incomes. Studies indicate that economic risks, particularly unstable market prices and production costs, are major sources of income instability. Research on market risk has shown that this instability is largely associated with farmers' heavy dependence on prices that frequently fluctuate (Fathi et al., 2020). This situation not only affects farm profitability but also makes it more difficult for farmers to plan and manage land and water resources efficiently and sustainably. These uncertain conditions can reduce crop yields, lower water-use efficiency, and negatively affect farmers' incomes. Moreover, their effects extend beyond farm-level production and have broader social consequences. When farmers face unstable incomes and resource shortages, their

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ability to invest in their farms declines. This can reduce agricultural productivity over time and contribute to the rural poverty, migration to urban areas, and the loss of traditional farming knowledge. At the same time, environmental degradation resulting from improper water and land management further threatens the sustainability of agricultural systems and local ecosystems (Singh et al., 2023). Addressing these challenges requires coordinated efforts among policymakers, water managers, and farmers. Such efforts should aim to ensure reasonable resource distribution, support farmers' livelihoods, and protect the environment. In response to uncertainty in climate and markets, many farmers adopt cautious or risk-averse strategies. For example, they may choose less water-demanding or lower-risk crops, reduce the use of costly inputs such as fertilizers and pesticides, or leave some land fallow to avoid potential losses (Simutowe et al., 2024; Moure et al., 2023). These risk-averse decisions are often driven by the need to secure a minimum level of income and reduce vulnerability to unpredictable shocks.

However, while such strategies can help manage short-term risks, they may also limit opportunities for higher income and improved productivity over time. Reduced input use or the cultivation of less profitable crops can result in lower yields and reduced resource efficiency. Similarly, frequent fallowing can lead to the underutilization of valuable agricultural resources (Garcia-Machado et al., 2024). Over time, these cautious approaches may also reduce farmers' ability to invest in improved technologies or diversify their production. Both are important for building resilience and supporting agricultural sustainability. In the context of mathematical optimization, it is essential to distinguish between the different types of uncertainty affecting the system. Stochastic uncertainty, also known as inherent variability, represents the random variation of physical processes. Available water resources are an example of such uncertainty. These resources can be characterized using objective probability distributions derived from historical hydrometeorological data (Kyire et al., 2025; Wang et al., 2025). Consequently, Chance-Constrained Programming (CCP) can be used to manage stochastic uncertainty. It provides a framework for decision-making under climatic risk (Zhang et al., 2023). In contrast, epistemic uncertainty refers to structural ambiguity and incomplete knowledge about technical and economic parameters, such as market prices and crop yields. These variables often lack sufficient statistical populations to support reliable probability distributions. Therefore, fuzzy set theory can be used to represent their non-probabilistic nature (Liu et al., 2023). Integrating these two types of uncertainty within a hybrid fuzzy-stochastic framework allows the optimization model to account for both the physical randomness of the environment and the volatility of the market (Shang and Xie, 2024). Research shows that risk-averse behavior is more common among smallholder farmers and those with limited access to credit, information, and extension services (Kyire et al., 2025). Improving farmers' access to reliable weather forecasts, market information, and financial support can therefore help them make more informed decisions. Such support may also enable them to adopt strategies that better balance risk and opportunity (Wang et al., 2025). In summary, understanding how farmers respond to uncertainty is crucial for designing policies and programs that promote both economic viability and sustainable resource management. Supporting farmers in moving beyond risk aversion toward more adaptive and proactive practices will be increasingly important as they face growing pressures from climate change and economic instability.

Since agricultural production depends directly on water resources, increasing water scarcity and climate change have heightened the need for intelligent and flexible water resource management. Temporal and spatial variations in hydrological parameters, such as water supply, rainfall, and evapotranspiration, together with economic fluctuations and climate-related threats, further complicate the management of agricultural water resources (Jones and Leibowicz, 2022). Climate change, particularly the projected decline in surface water availability, may increase reliance on groundwater. This situation highlights the need to develop optimal strategies for integrated water resource management (Liu et al., 2023). Many real-world problems, particularly in agriculture and water resource management, are inherently multidimensional. They often involve conflicting objectives that require accurate and comprehensive assessment. Such problems are commonly addressed through multi-objective function optimization. Concepts such as clean agricultural production and sustainable agriculture have further highlighted the importance of multi-objective programming (MOP). This importance has grown in response to the environmental and social challenges associated with climate change, global warming, and water resource pollution (Yang et al., 2024). Decision-making frameworks that incorporate uncertainty into both objectives and constraints are therefore necessary to support more resilient and equitable outcomes (Zhang et al., 2023). Fuzzy and stochastic programming methods are increasingly used to represent uncertainty in water and land allocation. Fuzzy models can account for linguistic uncertainty and expert judgment, whereas stochastic models address the randomness of key variables. Hybrid approaches, such as fuzzy-stochastic programming, provide a comprehensive method for facing multidimensional uncertainty. In addition, flexible and multi-scenario decision-making policies, mathematical modeling, Geographic Information Systems (GIS), and stakeholder participation can help mitigate the effects of uncertainty and enhance the resilience of irrigated agricultural systems (Ren et al., 2019). Recent research has made important advances in modeling agricultural resource allocation under uncertainty. Bahmanpouri and Bakhshoodeh (2017) found that incorporating climate change scenarios into cropping patterns can stabilize farm income despite fluctuations in water availability. Using the WEAP system, Abbas et al. (2022) showed that demand-side management can be more effective than supply-side expansion in water-stressed basins. Nikmehr and Zibaei (2020) emphasized that interval-parameter programming can significantly reduce the risk of overestimating available water compared with deterministic models. Liu et al. (2023) introduced innovative hybrid models that combine fuzzy sets, interval parameters, and stochastic elements to support sustainable agricultural planning. These studies demonstrate the growing recognition that uncertainty modeling is not a peripheral issue but a central

component of achieving sustainable outcomes in agricultural systems. In managing water and land resources under uncertainty, mathematical programming techniques, such as stochastic and fuzzy programming, are thus important for optimizing resource allocation and reducing risks associated with climate change. Studies in Iran provide further evidence of the relevance of these approaches. Kashiri Kolaei et al. (2020) and Fathi and Zibaei (2020) demonstrated that fuzzy programming can reduce virtual water exports by shifting cropping patterns toward crops with lower water requirements. Specifically, in multi-objective frameworks, Ren et al. (2019) and Zhang et al. (2023) reported that hybrid fuzzy-stochastic models can increase system robustness by 15-20% compared with single-method approaches.

Recent studies from 2023 to 2025 have further refined these hybrid approaches. Amaruchkul (2023) demonstrated that stochastic optimization can mitigate the "bullwhip effect" in agricultural supply chains caused by water volatility. Shang and Xie (2024) introduced advanced fuzzy-stochastic frameworks that improved the reliability of irrigation schedules by 12% under extreme weather events. Furthermore, contemporary research, including Ren et al. (2019), has shown that combining fuzzy sets with CCP allows for a more detailed analysis of risk-reward trade-offs in basin-wide water allocation. Wang et al. (2025) and Chen et al. (2023) emphasized that such integrated models are essential for identifying "tipping points" in aquifer depletion. Al Zihad et al. (2023) further showed that these methods can improve the socioeconomic equity of water distribution among competing agricultural sectors. Although these studies have effectively addressed uncertainty, relatively few have simultaneously considered multiple types of uncertainty in both objectives and constraints (Mirzaie et al., 2024). More broadly, stochastic and fuzzy programming techniques have been effective in optimizing water and land resource allocation, particularly under climate change conditions. These approaches can support optimal irrigation planning and resource management in systems characterized by multiple uncertainties. However, the present study addresses simultaneous economic and climatic uncertainties by developing a multi-objective fuzzy programming model with fuzzy variables in the objectives and stochastic parameters in the constraints. Despite recent advances in resource planning models, most existing approaches address uncertainty either in the objectives, such as maximizing profit or crop yield, or in the constraints, such as water and land availability. Few models consider uncertainty in both simultaneously. This gap is particularly important in high-risk agricultural areas such as the Qorveh plain in Kurdistan Province, Iran, where multiple sources of uncertainty occur simultaneously. Farmers in the region face several challenges, including declining groundwater levels, increasingly frequent climate extremes, unstable market prices, and environmental degradation. These combined uncertainties in water availability, climate, and economic conditions make agricultural planning particularly difficult. When planning tools do not adequately incorporate these risks, they can result in inefficient resource use and reduce the resilience of farming systems (Zhang et al., 2023; Hashemi et al., 2024).

The Qorveh plain offers a compelling case of unsustainable agricultural development under increasing resource stress. Over recent decades, this vital agricultural region has experienced a sharp decline in groundwater levels due to the recurrent droughts, excessive water withdrawals, and changing precipitation patterns. At the same time, the widespread use of chemical fertilizers has contributed to water quality degradation, while uncontrolled groundwater extraction has further compromised long-term water security. Agricultural productivity is also affected by economic uncertainty, particularly fluctuations in the prices of agricultural inputs and outputs. These fluctuations have introduced significant variability in farmers' incomes. Under these conditions, conventional resource planning approaches are insufficient. Decision-makers must address uncertainties that are both qualitative and quantitative. Qualitative uncertainties include acceptable levels of environmental impact and social equity goals, while quantitative uncertainties include variations in water supply and changes in crop prices. A robust planning framework is therefore required. Such a framework should accommodate fuzziness in objectives and randomness in constraints while also reflecting local priorities and resource limitations. This study addresses these challenges by developing a multi-objective fuzzy-stochastic optimization model for agricultural water and land allocation under multiple interacting uncertainties. The proposed model incorporates fuzzy variables into the objective functions to represent imprecise goals, such as environmental protection and economic resilience. It also incorporates stochastic parameters into the constraints to account for variability in water availability. Applied to the Qorveh plain, the model identifies optimal cropping patterns that can stabilize agricultural production, improve resource-use efficiency, and reduce vulnerability to the environmental and market risks. The framework contributes to the literature on sustainable agricultural planning under uncertainty. It also provides actionable insights for policymakers and stakeholders working in similarly resource-constrained environments.

MATERIALS AND METHODS

The hybrid stochastic-fuzzy modeling approach was deliberately chosen to address the fundamentally different nature of the key uncertainties in the water-agriculture system. This integrated methodology is well established in the environmental and water resources management literature for handling systems affected by both probabilistic and possibility-based uncertainties (van der Heijden et al., 2025). Specifically, economic uncertainties, including crop market prices and crop yields, are modeled using fuzzy set theory. This approach is appropriate for addressing epistemic uncertainty arising from incomplete knowledge and subjective forecasts. In such cases, information is imprecise and is therefore best represented using fuzzy numbers. In contrast, groundwater availability for

irrigation is subject to stochastic uncertainty arising from inherent hydrological variability. This randomness can be statistically characterized using historical probability distributions and is effectively managed through CCP. By integrating these methods, the model simultaneously accounts for probabilistic variability and fuzzy imprecision. This integration provides a more robust and realistic basis for optimization. As illustrated in Fig. 1, the modeling process begins by incorporating uncertain variables, including climatic, economic, and environmental data, into the system. Advanced uncertainty analysis techniques based on fuzzy set theory and probabilistic models are then applied to identify and evaluate the nature and intensity of these uncertainties. The fuzzy and stochastic components are subsequently integrated within a unified framework. This process combines the results of the fuzzy and stochastic analyses to ensure that the generated scenarios comprehensively represent both economic and environmental conditions. The resulting integrated multi-objective stochastic fuzzy programming (IMOSFP) model balances conflicting objectives, including improving water productivity, optimizing land allocation, and reducing risk. Relative weights are assigned to these objectives according to the decision-makers' priorities. This integrated approach facilitates the generation of optimal and practical solutions under conditions of uncertainty.

Fuzzy uncertainty in parameters and constraints

To address fuzzy uncertainties, the developed model incorporated fuzzy set theory, which is well suited to representing imprecise information. Triangular membership functions are commonly used for this purpose. A triangular fuzzy number can be defined by three values (Dubois & Prade, 1978): (1) the lowest possible value (A_{1min}), (2) the most credible values (A_{2max}), and (3) the highest possible value (A_1) as presented in Fig. 2. Under each a cut, fuzzy parameter $\tilde{A}$ can be a closed interval.

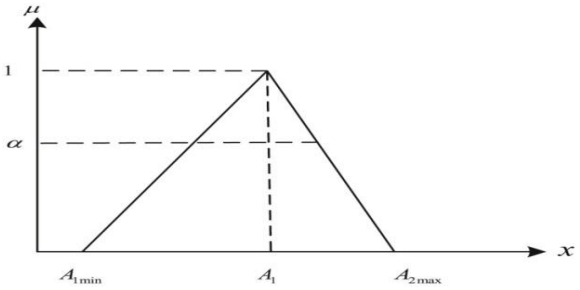


Fig. 2. A triangular fuzzy distribution function.

Mathematically, a fuzzy parameter with a triangular membership function can be defined by three values (A_{1min}, A_1, and A_{2max}). The degree of membership $\mu(x)$ for any value x is then determined by Eq. (1).

$$\alpha = \mu(x) = \begin{cases} 0 & x \le A_{1min} \\ \dfrac{A_\alpha^- - A_{1min}}{A_1 - A_{1min}} & x \ge A_{2max} \\ \dfrac{A_{2max} - A_\alpha^+}{A_{2max} - A_1} & A_{1min} < x < A_1 \\ x = A_1 & A_1 < x < A_{2max} \end{cases} \quad \text{Eq. (1)}$$

These fuzzy parameters were incorporated into the multi-objective optimization model to account for the variability in key agricultural inputs and outputs. Accordingly, water requirement, market price, and crop yield were represented as triangular fuzzy variables in this study. Table 1 summarizes the lower (L), middle (M), and upper (H) values of these parameters for the crops included in the optimization model.

Crop water requirement

The net irrigation water requirement (CWU) was treated as a fuzzy variable due to the variability of effective rainfall and climatic fluctuations. It was defined by a lower bound (CWU_{min}), a most likely value (CWU_{most}), and an upper bound (CWU_{max}), estimated based on historical data (1998-2020) for the Qorveh plain region, considering effective rainfall calculations.

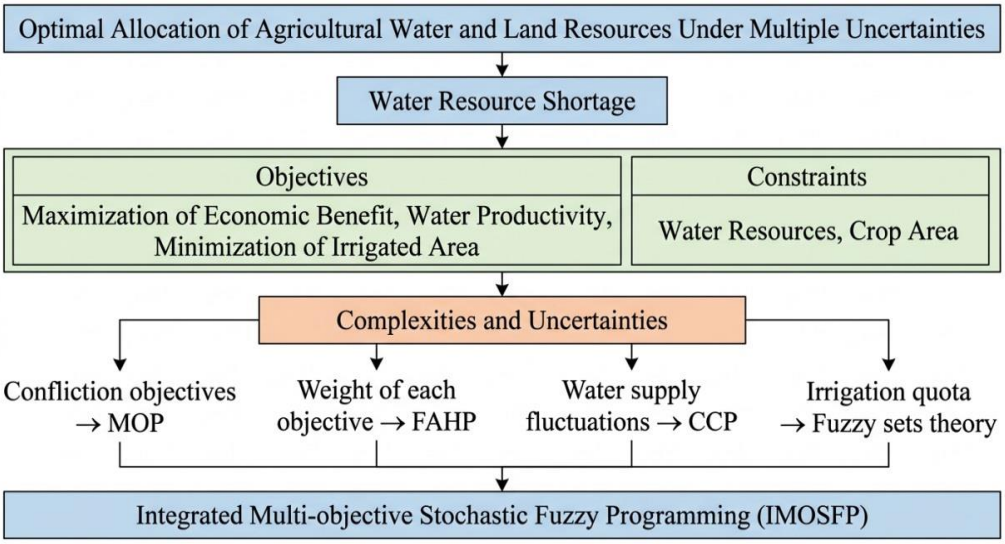


Fig. 1. The schematic diagram of the integrated multi-objective stochastic fuzzy optimal model.

Product prices

Product prices (P) were modeled as fuzzy variables using triangular membership functions, defined by a minimum price (P_{min}), a most likely price (P_{most}), and a maximum price (P_{max}). These values were determined through historical price analysis, market forecasts, and expert opinions relevant to the study area. This fuzzy representation enables the model to capture the inherent uncertainty in agricultural market dynamics.

Crop yields

Crop yields (Y) were also modeled as fuzzy variables using triangular membership functions, characterized by a minimum yield (Y_{min}), a most likely yield (Y_{most}), and a maximum yield (Y_{max}). These values were established based on experimental data, observed climatic conditions, soil quality assessments, and prevalent agronomic management practices within the Qorveh plain.

Uncertainty in constraint CCP

A key challenge in optimization models arises when parameters on the right-hand side (RHS) of constraints exhibit stochastic behavior and are therefore inherently unpredictable. When these parameters follow known probability distributions, CCP provides an effective framework for handling such uncertainty (Liu et al., 2024). The standard CCP formulation is represented by the following set of constraints, with the corresponding mathematical expressions presented in Eq. (2).

$$Pr\left[A_i(x_j) \le b_i(x_j)\right] \ge 1 - p_i \qquad \forall i = 1,2,\dots,m \qquad \text{Eq. (2)}$$

Where $A_i(x_j)\ and\ b_i(x_j)$ are random variables defined in a probability space x_j, p_i represents the allowable violation probability for the constraint i and m denotes the total number of constraints. If b_i is normally distributed and $A_i(x_j)$ is a linear function of the decision variables x_j. The chance constraint can be transformed into its deterministic equivalent form. The corresponding deterministic equivalent formulation is presented in Eq. (3) as follows:

$$\sum_{j}^{n} a_{ij}x_j \le \mu b_i - z_{p_i}\sigma_{b_i} \qquad \text{Eq. (3)}$$

Multi-objective model solution

To identify the most preferred solution for water and land resource allocation, the Compromise Programming (CP) method was employed. The mathematical formulation of the CP approach is presented in Eq. (4) as follows:

$$min\ F'^{(x)} = \sum_{i=1}^{n} w_i \left(\frac{f_i^{max} - f_i}{f_i^{max}}\right) \qquad \text{Eq. (4)}$$

Where, f_i is the value of the i-th objective function, f_i^{max} represents the ideal value (aspiration level) obtained by solving each objective individually as a single-objective model. w_i is the weight assigned to the i-th objective function. The parameter d determines the degree of importance of deviating from the optimal value. The weights of the objectives (w_1, w_2, and w_3 for the respective objectives) were determined using the Fuzzy Analytic Hierarchy Process (FAHP) method (Wongvilaisakul et al., 2023).

Optimal cropping pattern and water allocation

Following the implementation of the integrated fuzzy multi-objective mathematical programming model with a stochastic constraint, the optimal cropping pattern and water resource allocation for the study area were determined. The model was developed within a compromise framework to simultaneously maximize net profit, improve irrigation water productivity, and conserve resources by managing land-use intensity. These objectives were optimized subject to constraints on water availability and total cultivable land. To ensure food security, specific minimum and maximum limits for the cultivated areas of strategic crops were also incorporated as constraints. These thresholds were determined based on regional agricultural development priorities and consultations with agricultural economics experts. They were designed to reflect realistic production capacities within the study area.

Table 1. Estimated yield, market price, and crop water requirement of major crops under uncertainty

Crop	Average yield (1000kg/ha)	Average market price (10,000 Rials)	Average crop water requirement (1000 m³/ha)
	(L, M, H)*	(L, M, H)	(L, M, H)
Wheat	(4.12, 5.56, 7.20)	(5500, 5950, 6600)	(4.187, 5.586, 6.320)
Barley	(2.45, 3.84, 4.73)	(4000, 5450, 5750)	(3.33, 4.13, 5.09)
Potato	(24.70, 35.50, 52.10)	(10500, 37350, 73430)	(5.82, 7.15, 8.37)
Corn silage	(45, 60, 75)	(4500, 7500, 9200)	(3.40, 4.81, 6.15)
Cucumber	(20.70, 25.500, 29.400)	(70014, 80141, 100690)	(5.37, 6.01, 7.72)
Canola	(2.05, 2.80, 3.75)	(6500, 73000, 9400)	(3.29, 4.15, 5.15)

* L = Low (minimum), M = Most Likely (most probable), and H = High (maximum).
Data are based on field surveys and expert estimations for Qorveh plain (Data for 2020).

Model objectives

The model aims to achieve three primary objectives:
a) Maximize economic profit: calculated as total revenue from crop sales minus total variable costs (Eq. (5)).

$$Max\ \tilde{Z} = \sum_{j=1}^{n}\left[\left(\tilde{Y}_j \times \tilde{P}_j\right) - C_j\right] \times A_j \qquad \text{Eq. (5)}$$

Where, $\tilde{Z}$ is the gross margin of the cropping pattern, n is the number of products, A_j is cropped area of product j (hectares), C_j is production cost of the j-th product (Rials per hectare), $\tilde{Y}_j$ is fuzzy parameters for the yield of product j (kilograms per hectare), $\tilde{P}_j$ is the fuzzy parameters for the price per unit of product j (Rials) in the study area.

b) Maximize agricultural water productivity: This is defined as the ratio of crop yield to the irrigation water applied, considering irrigation efficiency and the fuzzy water requirement of each crop (Eq. 6).

$$Max\ f_2 = WUE = \frac{\sum_{j=1}^{n}(A_j\ \tilde{Y}_j)}{(\widetilde{IW}_j\ A_j/IC)} \qquad \text{Eq. (6)}$$

Where, WUE is water use efficiency, $\widetilde{IW}_j$ is the fuzzy water requirement of product j (cubic meters per hectare) and IC is the irrigation efficiency.

In this research, an average irrigation efficiency of 0.7 was assumed, reflecting the prevailing conditions in the Qorveh plain. According to regional data and expert consultations, approximately 90% of the cropped area is equipped with modern pressurized irrigation systems (sprinkler and drip), while traditional surface irrigation has been largely phased out. This high adoption rate of modern technology justifies the use of a stable and relatively high efficiency coefficient in the model.

Parameter that represents the ratio of the water effectively used by crops (i.e., actually absorbed and used for growth) to the total water applied through irrigation systems. It accounts for water losses due to evaporation, runoff, percolation beyond the root zone, and inefficiencies in the delivery and distribution systems (Eq. (7)).

$$IC = \frac{Effective\ water\ used\ by\ crops}{Total\ water\ delivered\ to\ the\ field} \qquad \text{Eq. (7)}$$

c) Minimize cropped area: This objective aims to minimize the total irrigated area, thereby reducing ecological pressure and groundwater extraction (Eq. (8)).

$$max\ f_3 = TA - \sum_{j=1}^{n} A_j \qquad \text{Eq. (8)}$$

Where TA is the total available arable land (hectares) in the study area. The objective is to minimize the total irrigated area ($\sum_{j=1}^{n} A_j$). Data related to this section were collected from the Kurdistan regional water authority and the Agricultural Jihad Organization in 2020.

Constraint conditions

a) Groundwater constraint: The total water demand for irrigation in each period cannot exceed the available groundwater resources, considering the fuzzy water requirements of crops and the stochastic nature of water availability. This metrics was calculated according to Eq. (9).

$$\sum_{j=1}^{n}\left(\frac{I\widetilde{W}R_{jm}A_j}{IC}\right) \le AGW - z \times std(AW) \qquad \text{Eq. (9)}$$

Where, $I\widetilde{W}R_{jm}$ is water required for irrigating the j-th crop in the m-th period (cubic meters per hectare), which is a fuzzy parameter. AGW is the average available groundwater (cubic meters), which is a stochastic parameter. In other words, the water requirement is limited to irrigation water and the effective rainfall during the crop growing season. This constraint indicates that crops can partially compensate for the shortage of irrigation water through rainfall. Specifically, the consumption of water resources should be less than the average available amount (AGW) minus the standard deviation of available water ($std(AW)$) multiplied by the z-statistic value at a certain probability level.

b) Cropped area constraints: Minimum and maximum limits are imposed on the cropped area of each crop, and the total area cannot exceed the total available arable land (Eq. (10) and Eq. (11)). The model operates under several constraints:

$$A_{j\,min} \le A_j \le A_{j\,max} \qquad \text{Eq. (10)}$$

$$\sum_{j=1}^{n} A_j \le TA \qquad \text{Eq. (11)}$$

In the proposed MOSFP framework, the α-cut level and probability parameter (P) were treated as independent control parameters because they represent different dimensions of uncertainty. The α parameter determines the confidence level associated with fuzzy information, whereas P represents the acceptable probability of water shortage under stochastic conditions. Treating these parameters independently allows decision-makers to explore a wider range of trade-offs between fuzzy reliability and probabilistic risk. Although more risk-averse decision-makers may simultaneously prefer higher α values and lower P values, no predefined behavioral relationship between the two parameters was imposed in this study. This approach preserves the flexibility of the analytical framework and allows the effects of each uncertainty parameter to be examined independently.

FAHP) method

The FAHP method encompasses several established approaches, including Chang's Extent Analysis Method (Chang, 1996) and Yager's Method. In this study, Chang's approach was adopted to determine the relative weights of the criteria through pairwise comparisons using fuzzy numbers.

Consistency assessment in FAHP

Following the elicitation of expert judgments through pairwise comparison matrices, the geometric mean was used to aggregate the experts' opinions and derive the weights of the criteria within the FAHP. To assess the reliability of the pairwise comparisons, the consistency ratio (CR) was also evaluated. Given the limited literature on consistency assessment in FAHP, this study adopted a procedure in which the fuzzy triangular matrix was decomposed into two matrices. The first matrix contained the median values of the triangular judgments, while the second contained the geometric means of their upper and lower bounds. The components of the fuzzy numbers were then summed, and the resulting sum was inverted and multiplied as part of the consistency assessment procedure. The Consistency Index (CI) was subsequently calculated separately for the upper- and middle-bound matrices using modified eigenvalue approaches, as presented in Eq. (12) and Eq. (13).

$$CI^m = \frac{(\lambda^m_{max} - n)}{(n-1)} \quad \text{Eq. (12)}$$

$$CI^g = \frac{(\lambda^g_{max} - n)}{(n-1)} \quad \text{Eq. (13)}$$

Where, λ^m_{max} represents the maximum eigenvalue of the upper bound matrix, λ^g_{max} represents the maximum eigenvalue of the middle matrix n the matrix size. The CR was subsequently estimated by dividing the CI by the random consistency index (RI) obtained from a standard table (Table 2) (Eq. (14) and Eq. (15)). A fuzzy matrix was considered consistent if both calculated CR values (for the upper and middle bounds) were below the threshold of 0.10. Exceeding this threshold necessitated a review of the expert judgments, with specific focus on the median values if the CR for the middle matrix was unsatisfactory (Jawad et al., 2024).

$$CR^m = \frac{CI^m}{RI^m} \quad \text{Eq. (14)}$$

$$CR^g = \frac{CI^g}{RI^g} \quad \text{Eq. (15)}$$

Study area

Kurdistan Province covers approximately 29,048.4 square kilometers, accounting for 1.7% of Iran's total land area and ranking 18th among the country's provinces (Fig. 3). The province is located in western Iran and borders Iraq. It extends from 34°45′ to 36°28′ north latitude and from 45°34′ to 48°14′ east longitude, relative to the Greenwich meridian. Qorveh County is one of the key agricultural regions of Kurdistan Province. It is located at approximately 35°6′ north latitude and 48°4′ east longitude. The county is characterized by distinctive topographical conditions and limited water resources, making it an important agricultural hub within the province. According to the Kurdistan Regional Water Authority (2020), the Qorveh plain contains 2,704 deep and semi-deep wells. The estimated annual allowable groundwater withdrawal is approximately 124 million cubic meters. The plain also contains 21,975 hectares of irrigated agricultural land (Kurdistan Regional Water Authority, 2020).

Studying cropping patterns in Qorveh County is particularly important because the region faces growing challenges related to water scarcity and climate change. Optimizing the allocation of water and land resources is essential for maintaining farmers' economic profitability while improving water productivity. Agriculture in Qorveh relies heavily on water-intensive crops, particularly potatoes. Optimizing cropping patterns under uncertain water availability can therefore improve the sustainability of agricultural production while supporting farmers' incomes. Moreover, given the impacts of climate change on water resources, analyzing and refining cropping patterns can support more informed and effective decisions on agricultural resource management. Such optimization can strengthen the region's resilience to climate variability and contribute to the long-term sustainability of its agricultural systems.

RESULTS AND DISCUSSION

Prioritization of objectives using FAHP

In this study, the FAHP method was employed to determine the relative weights of the research objectives. For this purpose, ten standardized FAHP questionnaires were completed by expert stakeholders and agricultural operators in the study area. Subsequently, the consistency matrix was examined to ensure the consistency of the pairwise comparisons. To evaluate the validity of the consistency matrix, the largest eigenvalues for the middle value matrix ($\lambda^m{}_{max}$) and the geometric mean matrix of the upper and lower bounds ($\lambda^g{}_{max}$) were estimated. Consequently, the CI was calculated for both matrices, denoted as and, using the corresponding equations. As presented in Table 2, the calculated CR values for both matrices were below the acceptable threshold of 0.1. The CR values were obtained using the average RI values reported in Table 3. These results indicate that the pairwise comparison matrices exhibited acceptable consistency, confirming the reliability and validity of the analyses.

Table 2. Pats' value of mean random consistency index (RI)

Matrix size	1	2	3	4	5	6	7	8	9
RI^g	0	0	0.18	0.26	0.36	0.38	0.41	0.42	0.44
RI^m	0	0	0.49	0.79	1.07	1.20	1.29	1.34	1.38

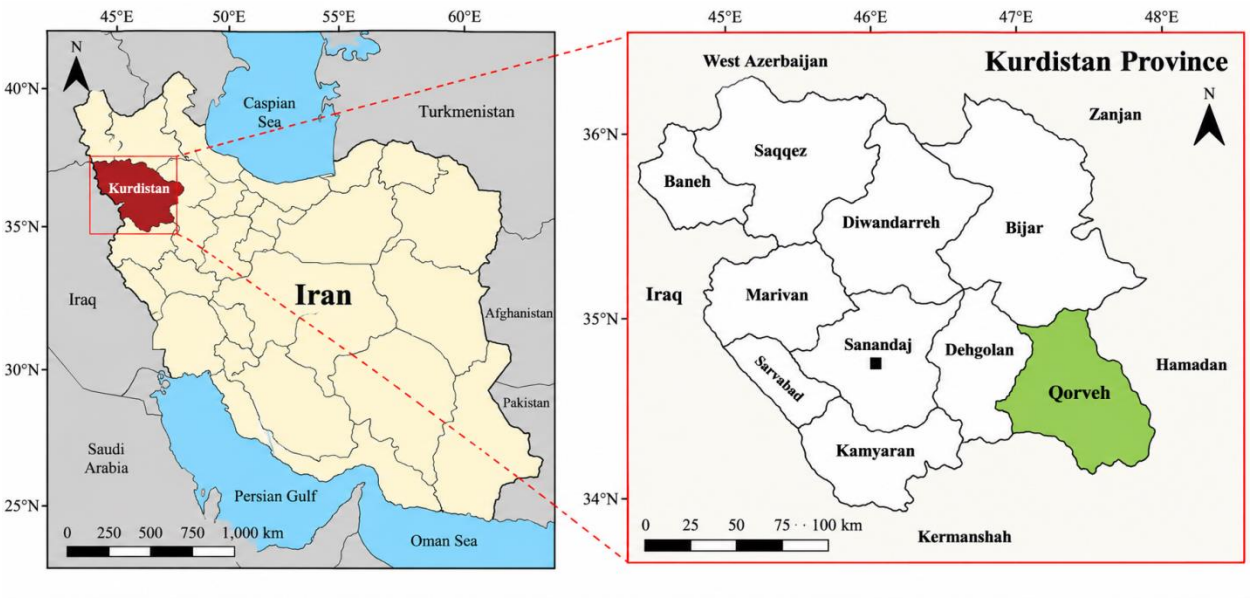


Fig. 3. Geographical location of Qorveh study areas within Kurdistan Province, western Iran.

The results obtained from the FAHP calculations are presented in Table 3. The significant weight assigned to maximizing agricultural profit (0.44) underscores the prioritization of farmers' income optimization by experts and stakeholders in the allocation of water and land resources within the study region. The substantial importance of minimizing water consumption (0.36) corroborates the water scarcity challenges prevalent in the area and the imperative for enhanced agricultural water productivity. The relatively lower weight attributed to minimizing irrigated area (0.20) suggests a tendency among farmers to maintain cultivation areas while focusing on improving efficiency and yield per unit area. These findings highlight the necessity for balanced policymaking that integrates economic profitability with optimal water resource management in the region.

These weights illustrate the preferences of local decision-makers, who prioritize increasing farmers' income and improving water use efficiency. In contrast, reducing the total cropped area is considered relatively less important, suggesting a tendency to maintain current farmland while focusing on smarter, more efficient resource use. Based on these priority weights, a multi-objective fuzzy-stochastic model was developed to improve irrigation and land use planning by accounting for multiple sources of uncertainty, including fluctuations in water availability, crop water requirements, and economic conditions.

Optimal irrigated areas: Different alpha-cuts and risk probability levels

The results of the developed fuzzy-stochastic model demonstrate that the optimal total cropped area is highly sensitive to both the alpha-cut level (α), representing data uncertainty, and the probability of water availability, representing risk. Tolerance Fig. 4 illustrates these dynamics for six alpha-cut levels (α = 0, 0.2, 0.4, 0.6, 0.8, and 1) and four risk probabilities for water availability (P_i = 0.05, 0.10, 0.20, and 0.25).

Table 3. Relative weights of the objectives derived from the fuzzy analytic hierarchy process

	Elements of the judgment matrix			**Weight by FAHP (w_i)**	
	Maximizing agricultural profit	Minimizing water consumption	Minimizing irrigated area		
Maximizing agricultural profit	(1.2, 87.3, 85.07)	(2.3, 56.3, 42.81)	(1, 1, 1)	0.44	
Minimizing water consumption	(1, 1.1, 60.6)	(1, 1, 1)	(0.1, 26, 29.39)	0.36	
Minimizing irrigated area	(1, 1, 1)	(0.1, 62.1, 62)	(0.1, 32, 35.53)	0.20	
CI^g	0.014	**RI^g**	0.262	**CR^g**	0.053
CI^m	0.046	**RI^m**	0.739	**CR^m**	0.058

A fundamental characteristic observed in the results is the monotonic convergence of the fuzzy intervals. As the alpha-cut parameter increases from 0 to 1, there is a consistent narrowing of the gap between the upper and lower bounds across all analyzed probability levels. This phenomenon signifies the transition from a state of high epistemic uncertainty (at alpha = 0) to a crisp, deterministic optimal solution (at alpha = 1). For instance, at P_i = 0.05, the initial uncertainty interval of 10.8 (10^3 ha) collapses to zero as alpha approaches unity, where the upper and lower bounds converge to 13.893 (10^3 ha). This convergence pattern is mathematically consistent across all stochastic scenarios (P_i = 0.10, 0.20, and 0.25), validating the stability of the hybrid model.

The sensitivity of the optimal area to the probability of water availability is also evident. As the risk tolerance increases (from P_i = 0.05 to P_i = 0.25), the deterministic optimal cropped area at alpha = 1 increases from 13.893 (10^3 ha) to 14.508 (10^3 ha). However, a critical finding emerges when comparing these optimal values to the current cropping area of 20.100 (10^3 ha). Even under the most favorable stochastic condition (P_i = 0.25) and maximum certainty (alpha = 1), the optimized cropped area (14.508 (10^3 ha)) shows a 27.5% decrease relative to the current cropping pattern.

This significant gap provides robust evidence that the reduction in cropped area is not primarily driven by the mathematical uncertainty or the stochastic nature of water supply. Instead, the results underscore that physical water scarcity acts as the overwhelming binding constraint in the system. The model demonstrates that even when uncertainty is eliminated, the physical lack of water necessitates a strategic reduction in cultivated land to maintain system equilibrium, thereby highlighting the urgent need for water-efficient agricultural management.

These findings align with recent studies, such as Wang et al. (2025) and Liu et al. (2023) which also emphasize the value of α-level analysis in stabilizing decisions and Chang et al. (2024), who demonstrated the importance of adjusting agricultural water allocation and cropping strategies under groundwater scarcity and fuzzy uncertainty conditions. Our model thus serves not only as an optimization tool, but also as a decision-support system that generates a range of plausible, trade-off-aware scenarios, empowering stakeholders to select strategies that best fit local priorities and constraints.

Scenario analysis and optimal scenario selection

In this study, 24 scenarios with varying levels of fuzzy cut (α) and probability of water availability (P) were evaluated to identify the optimal conditions for efficient water and land resource allocation. Based on the results, the scenario with α = 0.6 and P = 0.20 was identified as the most favorable option for achieving maximum economic profit and water productivity in the Qorveh plain.

Fig. 5 illustrates the changes in the cropped area of different crops under the optimal scenario. The cropped area of potato decreased from 3,200 hectares in the current cropping pattern to exactly 2,000 hectares in the optimal scenario (both lower and upper bounds equal to 2,000). This reduction indicates that despite its relatively high profitability, water resource constraints have led farmers to adjust its cultivation area.

The cropped area of wheat decreased from 12,625 hectares in the current cropping pattern to a range of 8,000 to 10,532 hectares in the optimal scenario. This reduction suggests that under water resource uncertainty, farmers tend to reduce wheat cultivation. However, due to its strategic role in food security, wheat remains in the cropping pattern.

The cropped area of corn silage ranged from 300 to 400 hectares in the optimal scenarios, compared with 400 hectares in the current cropping pattern. Thus, the cultivated area either remained unchanged or decreased slightly, depending on the uncertainty conditions. This result indicates that corn silage was relatively maintained in the optimal cropping pattern under water constraints.

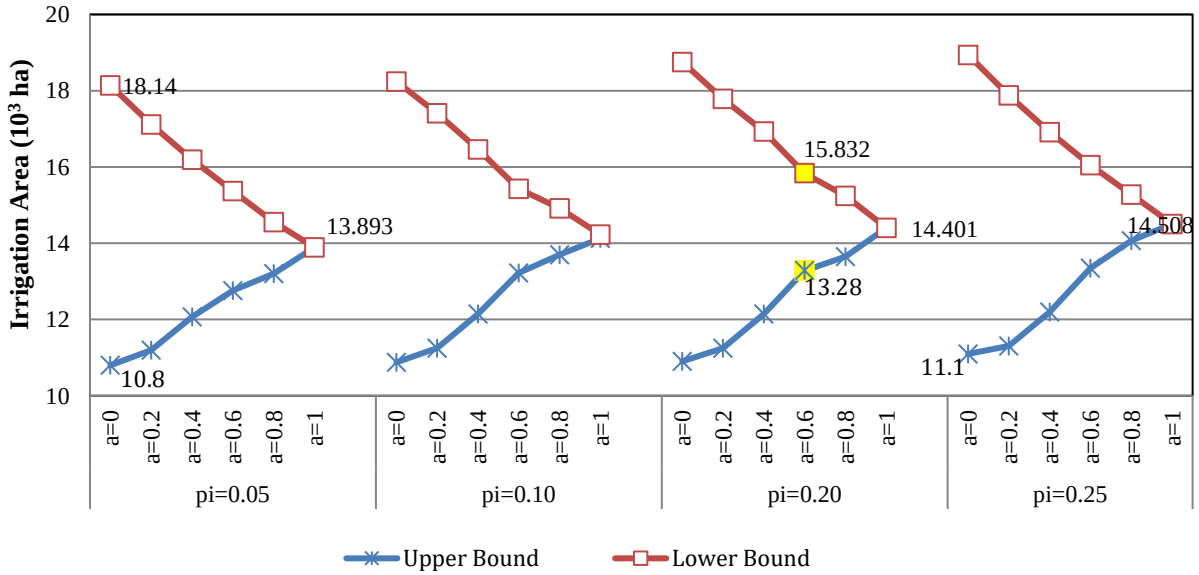


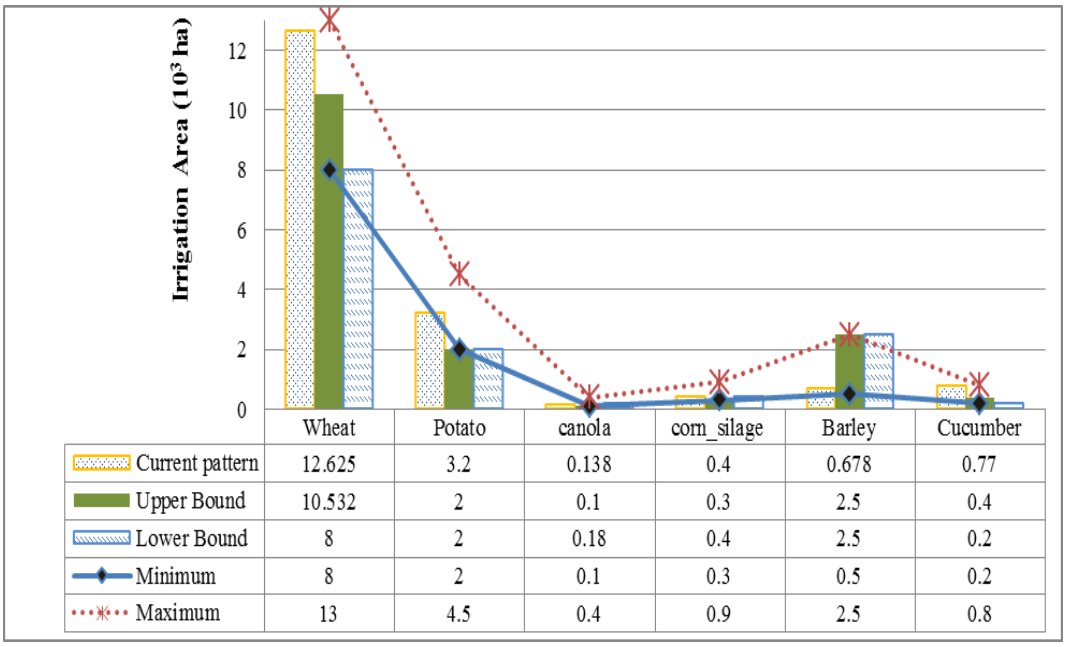
Fig. 4. Optimal irrigated area dynamics in Qorveh plain across alpha-cut levels and water availability probabilities.

The cropped area of canola ranged from 100 to 180 hectares in the optimal scenarios, compared with 138 hectares under the current cropping pattern. This relatively narrow range indicates that canola cultivation remained close to its current level, with only limited variation. In contrast, the cropped area of barley increased substantially, from 678 hectares under the current pattern to exactly 2,500 hectares in the optimal scenario, with both the lower and upper bounds equal to 2,500 hectares. This marked increase highlights the important role of barley in the regional cropping pattern under water-scarce conditions. The cropped area of cucumber decreased from 770 hectares under the current cropping pattern to 200–400 hectares in the optimal scenario. Despite its relatively low water requirement, the reduction suggests that other constraints limited the optimal allocation of land to cucumber. The quantitative assessment of percentage deviations in cropped area relative to the current cropping pattern (Table 4) indicates a strategic reallocation of land resources aimed at improving water resource sustainability. The total cropped area decreased by 11.11% and 25.44% in the upper and lower bound scenarios, respectively, compared with the status quo. This "optimization gap" indicates a substantial mismatch between current agricultural water use and the hydrological carrying capacity of the Qorveh plain. Notably, strategic but water-intensive crops such as wheat and potato underwent substantial reductions in both scenarios. In particular, wheat cultivation decreased by up to 36.63% in the conservative (lower bound) scenario, contributing to the restoration of regional water supply-demand equilibrium. High-value crops with high irrigation sensitivity, such as cucumber, experienced an even greater reduction. Its cropped area declined by 74.03% under conditions of extreme epistemic uncertainty. This result reflects the model's prioritization of system stability over short-term economic gains.

In contrast to the reduction in water-demanding crops, the optimization model identified a significant comparative advantage for barley. Its cropped area increased by 268.73% in both bounds relative to the current cropping pattern. This substantial expansion indicates that barley is a robust and water-efficient alternative under hydro-climatic stress and fuzzy uncertainty. Meanwhile, the relative stability of corn silage and the regulated variation in canola across the optimized intervals suggest that the model also seeks to preserve crop diversity and meet local production needs. Overall, the percentage deviations indicate that moving from the current cropping pattern to the optimized configuration requires a structural adjustment. This adjustment involves reducing the area allocated to crops with low marginal water productivity and reallocating land to more resilient, lower-water-demand crops. Such a shift can contribute to the long-term hydro-ecological security of the basin. The model was applied to the Qorveh plain under two distinct stages. First, single-objective optimization was performed separately for each objective to determine its respective ideal value. Second, the economic objective of maximizing net profit was integrated with the objectives of improving water productivity and conserving land within a multi-objective framework. This process was conducted across different α-cut levels P_i.

Analysis of gross economic return under different objectives and uncertainty conditions

Fig. 6 illustrates the gross economic return for farmers in the Qorveh plain under two conditions: when only the economic objective is considered (single-objective), and when economic objective maximization is integrated with other goals (multi-objective), across various alpha-cut levels and P_i. The values for the other objectives in the multi-objective model were estimated based on their respective optimal values derived from the single-objective optimizations, corresponding to the multiple uncertainties (climatic and economic) of each scenario.



	Wheat	Potato	canola	corn_silage	Barley	Cucumber
Current pattern	12.625	3.2	0.138	0.4	0.678	0.77
Upper Bound	10.532	2	0.1	0.3	2.5	0.4
Lower Bound	8	2	0.18	0.4	2.5	0.2
Minimum	8	2	0.1	0.3	0.5	0.2
Maximum	13	4.5	0.4	0.9	2.5	0.8

Fig. 5. Optimal cropped area in Qorveh plain under scenario α = 0.6((α-cut level for fuzzy uncertainty) and Pi = 0.20 (probability of violating the groundwater availability constraint)

Table 4. Current cropping pattern vs. optimal cropping pattern with percentage changes

Crop	Current cropping pattern	Upper bound in optimal cropping pattern	Deviation (%)	Lower bound in optimal cropping pattern	Deviation (%)
Wheat	12.625	10.532	-16.58	8	-36.63
Potato	3.2	2	-37.5	2	-37.5
Canola	0.138	0.1	-27.54	0.18	30.43
Corn silage	0.4	0.3	-25	0.4	0
Barley	0.678	2.5	268.73	2.5	268.73
Cucumber	0.77	0.4	-48.05	0.2	-74.03
Total	17.811	15.832	-11.11	13.28	-25.44

α = 0.6 (α-cut level for fuzzy uncertainty) and Pi = 0.20 (probability of violating the groundwater availability constraint)

The findings indicate that the inclusion of environmental and resource-based objectives in the multi-objective configuration leads to a reduction in economic benefits compared to the single-objective approach. For instance, at P_i = 0.20 and α = 0.6, the lower-bound and upper-bound of economic benefits in the single-objective model are 233.6 and 281.26 (10 billion Rials) respectively, whereas these values decrease to 143.98 and 189.50 (10 billion Rials) in the multi-objective model, reflecting the trade-off between profit and water sustainability.

The analysis reveals that decreasing uncertainty, reflected by increasing α-cut levels, leads to convergence between the upper and lower bounds in both models, thereby narrowing the range of potential economic outcomes. Furthermore, as the risk probability (P_i) increases, indicating greater tolerance for potential water shortages, the overall gross economic return in the multi-objective model increases. Specifically, at α = 1, the return rises from 158.43 at P_i = 0.05 to 162.08 at P_i = 0.25, representing an increase of approximately 2.3%. These results demonstrate that the proposed model provides a flexible decision-making framework for balancing risk-averse and risk-taking strategies. This flexibility can support targeted policies, such as tiered water pricing and the reallocation of subsidies, to protect farmers' livelihoods in water-constrained regions. The observed economic gap between the single- and multi-objective scenarios can be interpreted as an "environmental premium" associated with improving the long-term hydrological security of the Qorveh plain. Bridging this gap may require policy interventions that encourage farmers to adopt the optimized cropping pattern rather than relying solely on traditional input subsidies. In particular, establishing local value-added industries for water-efficient crops such as barley and developing "water-saving credit" systems could help compensate for the initial 27% reduction in cropped area. Such measures could strengthen the practical applicability of the model by linking optimization results with the socio-economic mechanisms required for regional water governance.

Irrigation water productivity (IWP) under uncertainty conditions

Fig. 7 presents the IWP obtained from the multi-objective optimization model across different α and P_i levels. Because crop water requirements and yields are represented as fuzzy parameters, IWP follows a triangular distribution and is sensitive to both data uncertainty and water-availability risk. The results indicate that IWP generally increases as P_i increases. This pattern suggests that the model tends to allocate resources toward more water-efficient crops when greater water-shortage risk is accepted. For example, at α = 0.6, the lower bound of IWP increases from 17.02 kg/m^3 at P_i = 0.05 to 17.89 kg/m^3 at P_i = 0.25. Over the same range, the upper bound increases from 18.36 to 18.79 kg/m^3. These changes represent improvements of approximately 5.1% and 2.3%, respectively. As expected, higher α-cut levels reduce the uncertainty range of IWP. At P_i = 0.20, for example, the difference between the upper and lower bounds decreases from 3.13 kg/m^3 at α = 0 (19.32-16.19) to 0.43 kg/m^3 at α = 0.8 (18.51-18.08). At α = 1, the two bounds converge at 18.31 kg/m^3. This convergence indicates that increasing the precision of the underlying fuzzy information produces more stable IWP estimates. However, α = 1 represents the limiting case of the fuzzy analysis and should not necessarily be interpreted as complete certainty in real agricultural systems. Even under this condition, IWP remains dependent on the uncertainty associated with crop water requirements and yields. At α = 1, the upper and lower bounds converge for each P_i level. As shown in Fig. 7, IWP increases from 17.95 kg/m^3 at P_i = 0.05 to 18.38 kg/m^3 at P_i = 0.25. This represents an increase of 0.43 kg/m^3, or approximately 2.4%, across the examined P_i range. Thus, under the limiting α = 1 condition, increasing the acceptable probability of water shortage from 0.05 to 0.25 results in only a modest improvement in IWP of 0.43 kg/m^3.

The 2.4% increase indicates that, at α = 1, IWP is relatively insensitive to changes in P_i. In practical terms, increasing the acceptable risk of water shortage from 5% to 25% improves water productivity by less than 2.5%. This suggests that, in the Qorveh plain, greater tolerance for water-shortage risk produces only marginal gains in water-use efficiency. Overall, these findings provide a quantitative assessment of how uncertainty and risk preferences influence irrigation water productivity. The results can support policymakers in developing adaptive water management strategies that account for local risk attitudes and the reliability of available data.

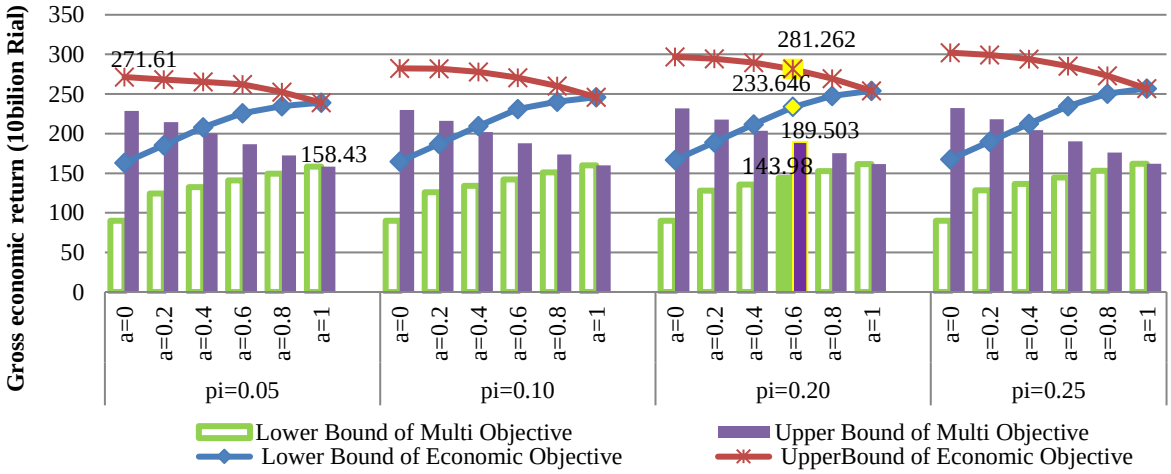


Fig. 6. Gross economic return of economic objective and multi-objective under different alpha-cuts levels of different risk probabilities (10 billion Rial).

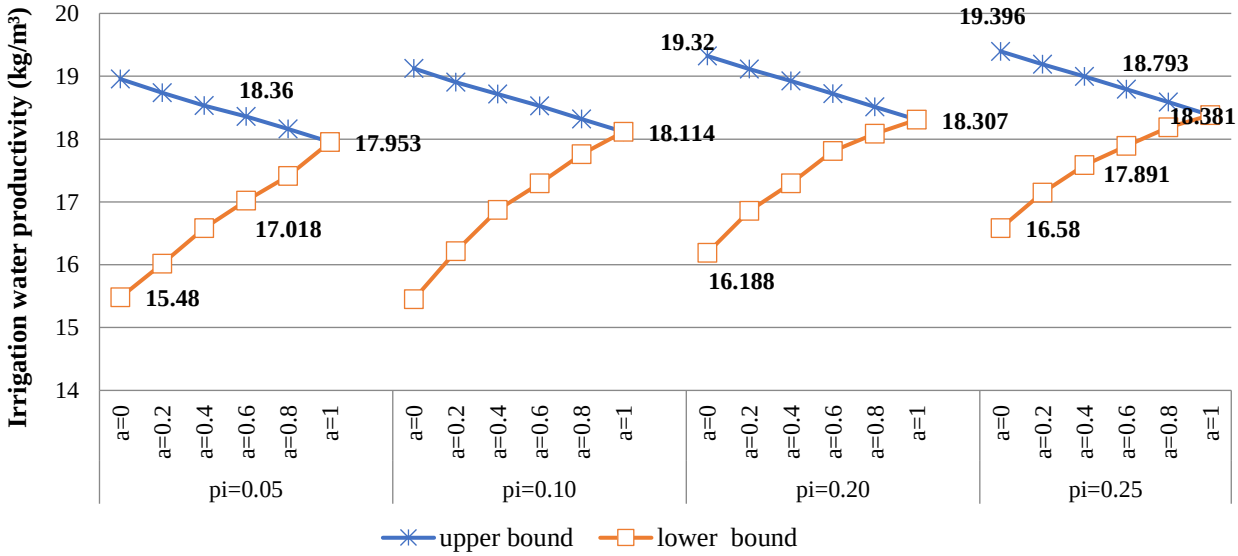


Fig. 7. Irrigation water productivity under different fuzzy uncertainty levels (α) and probability levels of constraint violation (Pi)

CONCLUSION

This study developed a multi-objective stochastic fuzzy optimization model for allocating agricultural water and land resources in the Qorveh plain under uncertainty. The results showed that increasing α-cut levels progressively narrows the uncertainty intervals for cropped area, gross economic return, and irrigation water productivity, confirming the stability of the model. More importantly, even under the most favorable water-availability scenario (P_i = 0.25), the optimal cropped area remained 18.5% below the current level. This indicates that the reduction is primarily associated with the physical limitations of water resources rather than model uncertainty and suggests that current agricultural development has exceeded the plain's hydrological capacity. The optimized cropping pattern involved substantial reductions in water-intensive crops, including cucumber (−74.03%) and potato (−37.5%), while barley emerged as a more water-efficient alternative. Although the multi-objective model produced lower economic returns than the single-objective profit-maximization scenario, it improved the balance between economic performance, water productivity, and resource conservation. At α = 1, increasing the acceptable water-shortage risk from 5% to 25% improved IWP by only 2.4%, indicating that greater risk tolerance provides limited gains in water-use efficiency. The optimal scenario identified in the analysis (α = 0.6 and P_i = 0.20) therefore provides a practical basis for balancing economic returns with water-resource sustainability. Overall, the findings demonstrate the importance of incorporating both stochastic and fuzzy uncertainties into agricultural water planning. The results support a transition from expansion of cultivated area toward higher value generation per unit of water, particularly through value-added activities associated with water-efficient crops.

Incentive mechanisms such as water-saving credits and risk-based support could facilitate farmers' adoption of the optimized cropping pattern. Future studies should integrate the proposed framework with dynamic aquifer models to assess the long-term effects of climate change and agricultural decisions on groundwater levels.

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CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Conceptualization: Susan Ganji, Fatemeh Fathi, Mohammad Bakhshoodeh, and Mansour Zibaei; Methodology: Susan Ganji and Fatemeh Fathi; Software: Susan Ganji and Fatemeh Fathi; Formal analysis: Susan Ganji, Fatemeh Fathi, and Mansour Zibaei; Writing—original draft: Susan Ganji; Writing—review and editing: Fatemeh Fathi, Mohammad Bakhshoodeh, and Mansour Zibaei.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial or personal interests that could have appeared to influence the work reported in this article.

ETHICAL STATEMENT

This study did not involve human participants, human subjects, or human data and therefore did not require ethical approval.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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