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Developing Strategies for Agricultural Water Management of Large Irrigation and Drainage Networks with Fuzzy MCDM

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Abstract

Sustainable water resources management aims at increasing the efficient use of water and achieving food security. This work proposes a generalized novel spatial fuzzy strategic planning (SFSP) in combination with multi-criteria decision making (MCDM) and a conceptual agricultural water use model for determining sustainable agricultural water management strategies. The proposed framework is applied to an irrigation and drainage network in Iran, which constitutes a large-scale water resource system. A spatial strength, weakness, opportunity, and threat (SWOT) analysis of internal and external factors related to agricultural water management is applied in this work. Possible water management strategies were ranked with the MCDM approach that combines the Analytic Hierarchy Process (AHP) and the Fuzzy technique for order-preference by similarity to ideal solution (TOPSIS). The AHP estimates the criteria weights and the TOPSIS model prioritizes the agricultural water management strategies. The results of SWOT analysis show that the final scores of the internal and external factors are equal to 2.9 and 2.73, respectively. Accordingly, the most attractive strategic type is a SO (aggressive) strategy, and a combination of structural and non-structural strategies (SO, ST, and WO strategies) are the top-ranked ones. Proposed strategies for water supply and demand management are the development and rehabilitation of the physical structure of water resources system of irrigation network, improvement of operation management and maintenance of water resources system, wastewater management, and inter-basin water transfer within the irrigation network. The results indicate that the total annual volume of agricultural water under normal conditions is about 1.8 billion cubic meters, of which about 1707 million cubic meters (95%) issue from surface water sources and 90 million cubic meters (5%) from groundwater sources. The proposed model and the calculated results provide viable and effective solutions for the implementation of sustainable management of water resources and consumption in large-scale water resources systems.

Keywords Irrigation and drainage network · Agricultural water management · SWOT analysis · Fuzzy strategic planning · Multi-criteria decision making

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1 Introduction

Previous pertinent studies were reviewed and categorized as pertaining to sustainable water resources management, strategic planning approach, and multi-criteria decision-making models. The review of previous studies provides an insight into existing research gaps and the innovation contributed by this work.

The spatiotemporal variation of precipitation, fluctuations in river flow during the growth period, and the water scarcity during the dry season pose challenges for agricultural water management (Li et al. 2020; Hughes and Farinosi 2020). The increasing population and economic growth may lead to worsening water supply and demand management. Integrated Water Resources Management (IWRM) provides a viable approach to meet water demand and supply management through sustainability concept. The Global Water Partnership defines IWRM as a process which promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems. (Garcia 2008). Crop diversification, crop pattern management, and conjunctive (i.e., surface water and groundwater) water management can be effective in improving agricultural water supply (Conrad et al. 2020; Portoghese et al. 2020). Baccour et al. (2021) analyzed water allocation and agricultural pollution for sustainable water management in the Ebro river basin (Spain).

The management of today's complex water supply and demand systems relies on assessment models that combine climatic, social, economic, and environmental factors. Yadeta et al. (2020) examined the climate change posed drought and potential of rainy season in Kesem sub-basin, Awash basin, Ethiopia. The latter authors examined the rainfall variability using statistical indicators. The results showed that policy-makers must consider supplementary irrigation for crops in the study area because of the high probability of drought. A participatory modelling based on the system dynamics approach was implemented by Nyam et al. (2021) in the Breede River Catchment, South Africa. The results showed the major causal-relationships that determine the usefulness of the participatory approach in solving challenges related to water management and agricultural development in the catchment. Kim et al. (2021) developed a model using the concept of risk by identifying hazards, exposure, and vulnerability. The vulnerability was classified into two domains, sensitivity and adaptive capacity, and two spheres, natural/built environment and human environment. Water allocation rules among water user groups were evaluated by Rouillard and Rinaudo (2020) considering environmental, economic, and social criteria involving 54 agricultural water user groups across France.

A hydro-economic framework for sustainable water resources management in irrigated agriculture was evaluated by Alamanos et al. (2020), who developed two hydro-economic models for the analysis analysis of challenges regarding data limitations, spatial analysis, and scenario-based problems. The results indicated that the developed model can achieve a balance between simplicity, flexibility, accuracy and robustness. Drisya and Sathish Kumar (2022) applied three water management strategies, i.e., water harvesting, demand reduction, and soil management. In addition, hydrological modeling was carried out to analyze the hydrological responses. All the scenarios showed improvement in the water yield and the soil moisture storage in the study watershed. Climate adaptation alternatives were identified by Acharjee et al. (2020) with stakeholder consultation. The latter authors applied multi-criteria analysis to evaluate and prioritize the proposed options. The researchers recommended that short-term and medium-term planning must focus on opportunities to implement achievable adaptation measures within the local agricultural system. A risk-based two-stage stochastic robust programming model was applied to an agricultural-ecological system to manage agricultural-ecological water resources system in the Heihe River Basin in China. The results showed that the combination of these models can be effective for the optimal water allocation (Youzhi et al. 2021). Robust adaptable plans under climate uncertainties in the agricultural sector were evaluated by Babaeian et al. (2021) using a combination of the Adaptation Pathways (AP) approach and the Soil and Water Assessment Tool (SWAT) to evaluate management strategies under climate uncertainties in the Hablehroud river basin, Iran. Thaler et al. (2020) analyzed two strategic planning approaches in Austrian flood risk management by identifying background conditions to facilitate scaling and replication of catchment regional planning tools in flood-prone areas. A raster-based regional conservation action planning tool was developed for prioritizing local and regional scale conservation actions in heterogeneous landscapes (Thomson et al. 2020). Baskent (2021) proposed a methodology for the assessment of an integrated land management plan. The plan involved a governance option allowing each organization to prepare and implement its own activities according to the rights and responsibilities defined in legal agreements. The water-energy-food nexus index was applied by Karamian et al. (2021) at the farm level for agricultural water management. Psomas et al. (2021) developed an integrated framework combining methods of environmental analysis with multi-criteria decision making for agricultural water management in river basins. The proposed framework combines the driving forces–pressures–state–impacts–responses model with the water–energy–land–food nexus model. The framework recommended strategies for selection by the decision makers and was applied to the Pinios river basin in Greece.

Achieving sustainability in basins with existing irrigation and drainage networks requires a strategic planning approach according to sustainable development principles (Loucks 2000). The pillars of sustainable development include economic, social and environmental components. Three dimensions of strategic management are process, content, and context that encourage the integration of sustainability into corporate activities and strategies (Baumgartner and Rauter 2016). Strategic planning defines an organizational mission, prioritizes plans, and maximizes potential opportunities and benefits in management (David 2011). SWOT (strengths, weaknesses, opportunities, and threats) analysis is a framework used to evaluate competitive alternatives and to develop strategic planning. SWOT analysis assesses internal and external factors, as well as current and future potential. SWOT analysis was applied to develop strategies for renewable-resources based industries and most suitable approaches (Yang et al. 2018). Petousi et al. (2017) reported SWOT analysis of water resources management, and the results were shared by users, water managers, planners and policy makers. Tziritis et al. (2014) proposed a strategic planning approach at the river basin scale to groundwater quality assessment and evaluation. Abdallah et al. (2020) reported an optimization model for solid waste management strategies. Non-linear mathematical modeling was implemented in the form of a systematic optimization framework to identify the beneficial set of waste to energy management strategies. SWOT analysis was performed to promote the renewable energy sector in Pakistan. The results identified the strategies to develop the renewable energy sector towards sustainability in Pakistan (Kamran et al. 2019).

The analytic hierarchy process (AHP) and Analytic Network Process (ANP) are structured techniques for organizing and analyzing complex decisions (Saaty 1996). Multi-criteria decision making allows the systematic evaluation of SWOT factors (Kajanus et al. 2012). SWOT analysis can be improved by combining it with MCDM (Svekli et al. 2012; Amin et al. 2011). The Analytic Hierarchy Process (AHP) and the Analytical Network Process (ANP) analysis have been combined with SWOT analysis (Kahraman et al. 2007). The risk of floods was assessed using a fuzzy approach in the Kalu-Ganga River basin in Sri Lanka. Prato (2009) reported a study on fuzzy adaptive management of social and ecological capacities in flood protected areas. The main goal of their study was to find suitable strategies for basin management. A multi-criteria approach was reported by Sadr et al. (2020) to assess the relative performance of two types of adaptation strategies: (a) stand-alone strategies (green or grey strategies only), and (b) hybrid strategies (combined green and grey strategies). The results illustrated that the trade-off between adapting to short term pressures and addressing long term challenges. Wang et al. (2020) applied a combination of AHP and SWOT to analyze the growth factors of various energy sources. Their results showed that the economic and socio-political criteria were the dominant factors that influence the growth of renewable energy.

Previous works have demonstrated that a framework based on SWOT analysis in combination with MCDM approach can be effective in assessing the sustainability of agricultural water management strategies in irrigation drainage networks. It is imperative to include sustainability indices within MCDM ranking techniques to achieve sustainability.

Despite numerous studies on sustainable water management and research on sustainability principles, it is factual that sustainable water management at the local scale has received less attention. Studies which have been done by the Organization for Economic Co-operation and Development (OECD) on water sustainability indicators show that analysis at the local levels and scales is necessary to demonstrate the effectiveness of the principles of water sustainability.

The analysis of large-scale water resource systems regarding the resources, stakeholders, reservoirs, small irrigation reservoirs, and water transfer schemes requires the consideration of the interactions between several components (Bozorg-Haddad et al. 2009; Akbari-Alashti et al. 2014). This work develops sustainable strategies for agricultural water management of irrigation and drainage networks. Specifically, this study employs spatial fuzzy strategic planning (SFSP) with MCDM and a conceptual agricultural water use model. This paper poses the management of agricultural water as a spatial analysis of internal and external factors related to agricultural water management. This paper contributes to agricultural water management as follows:

- Identification and evaluation of the current status of water resources and agricultural water management, and provides a spatial analysis of the strengths, weaknesses, opportunities and threats (SWOT) of irrigation and drainage networks.
- Development of agricultural water management strategies to ensure efficient use of scarce water in irrigation and drainage networks.
- Assessment and ranking of water-management strategies in the form of structural and non-structural measures in irrigation and drainage networks.

2 Methodology

2.1 Formulation of the Strategic Planning Framework

This paper presents a generalized novel three-stage framework that blends strategic planning with SWOT analysis (Stage 1), a conceptual agricultural water-use model (Stage 2), and fuzzy AHP TOPSIS techniques (Stage 3). Figure 1 depicts the three-stage approach employed in this work. The components of the model are explained next.

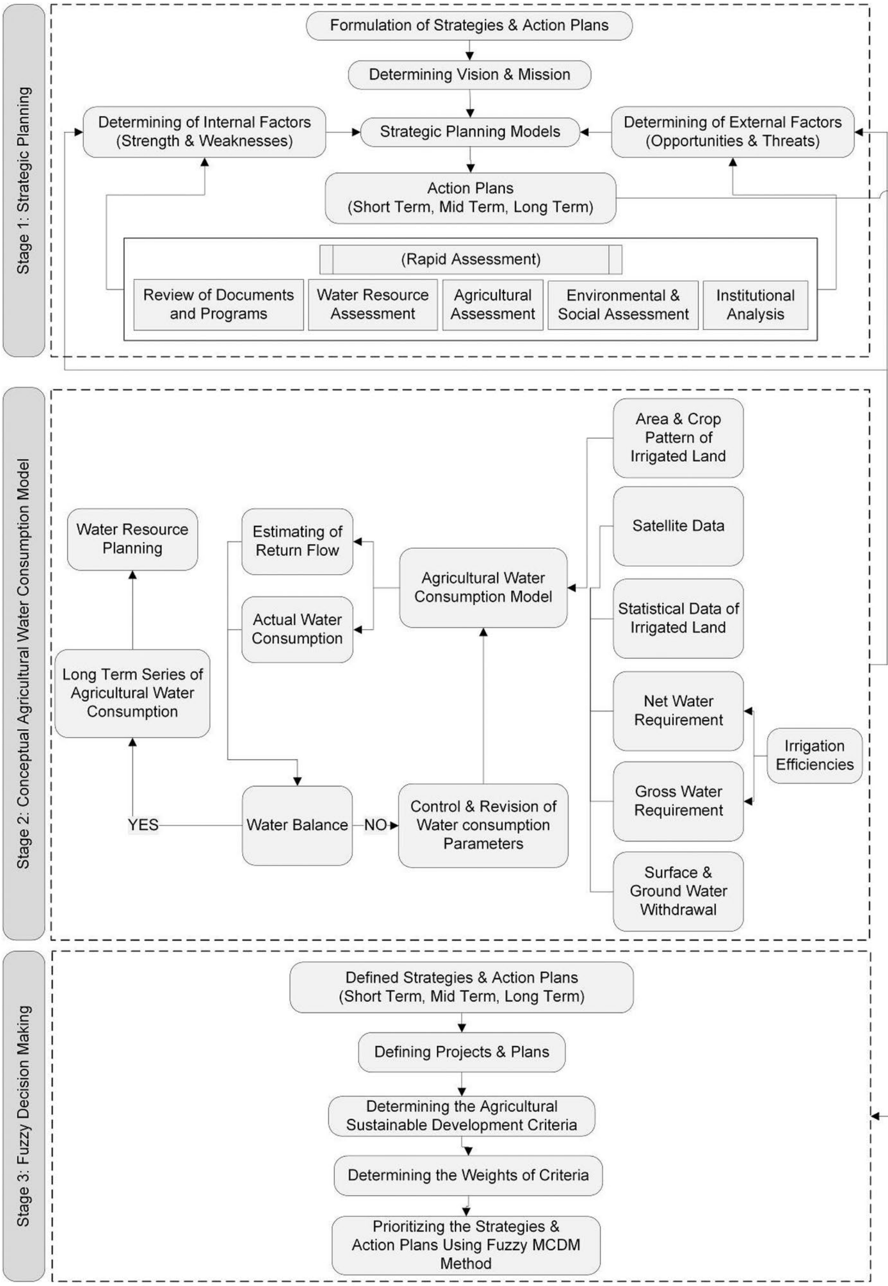


Fig. 1 Strategic planning framework developed in this work

2.1.1 SWOT Analysis

A vision for agricultural water management requires a thorough understanding of social, environmental, economic, institutional, and water resources factors. This work identifies internal (strengths and weaknesses) and external (opportunities and threats) factors from the perspective of sustainable agricultural development by applying SWOT analysis. Several data sources are used in the SWOT analysis, including national databases and programs, field visits, and interviews with local and provincial water managers and irrigation water users in the irrigation network. This information was used to develop the internal factor evaluation (IFE) and the external factor evaluation (EFE) matrices. The SWOT matrices are used in conjunction with the space matrix to identify the type of development strategies for sustainable agricultural development It should be noted that the space matrix analysis functions upon two internal and two external strategic dimensions in order to determine the strategic posture (Srinivas et al. 2018). This work's goal is assisting planners and decision makers in developing sustainable strategies for agricultural water management.

The SWOT analytical matrix provides four general categories of strategies (Babaesmailli et al. 2012). The strategies may overlap, or may be implemented concurrently with each other. The categories are (a) strength-opportunities (SO) strategies that use internal strengths to achieve external opportunities, (b) strength—threats (ST) strategies that use the strengths of the system to maximize strengths and minimize threats, (c) weakness- threats (WT) strategies that reduce internal weaknesses to prevent external threats, and (d) weaknesses-opportunities (WO) strategies that reduce internal weaknesses to take advantage of external opportunities.

2.1.2 Conceptual Model of Agricultural Water Use

The type of available water resources including dam and irrigation network, local rivers, drainage, small irrigation reservoirs and groundwater resources, the crop pattern and quality of soil and water sources vary throughout the study area. Therefore, a database of water-use statistics was prepared to estimate the water use by agricultural lands within the study area. The water use in the agricultural lands is a function of various factors such as the type of water resources, the method of water conveyance and distribution, the irrigation method, the type of crop products, climatic conditions, soil type, management practice, and others. Therefore, estimating the amount of water use in agricultural areas in the study area is beset by complexity. The inputs to the agricultural water use model are the cultivated area and crop pattern of irrigated lands, crop water requirements, surface and ground water withdrawal data, and irrigation efficiencies. Area and crop pattern information were obtained from the most recent agricultural census and from land-use maps based on satellite images. The model calculates water use in each irrigation unit by comparing the water requirements of the crop pattern with the water withdrawals of surface and ground water. The outputs from this model are actual water use from surface and ground water resources, water shortages, and the volumes of return flow.

2.1.3 AHP Fuzzy TOPSIS Approach to Prioritizing Strategies

SWOT analysis is suitable for evaluating agricultural water management. SWOT analysis must determine the relative weights of the factors used to evaluate management strategies, which may introduce subjective biases. For this reason, SWOT analysis has been combined with MCDM techniques (such as AHP) to prioritize the strategies.

The TOPSIS method is used widely for the ranking of problems in the field of water resources management (Simonovic and Verma 2008), in economics and environmental sciences (Xuebin 2009). The TOPSIS method ranks alternatives by determining their distance from the best and worst solutions. TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the best (positive ideal) solution and the longest geometric distance from the worst (negative ideal) solution.

The conventional TOPSIS method expresses the judgments of decision-makers with absolute quantities, i.e., as if they were known with certainty. In many instances, however, decision-makers must account for uncertainties in decision-making. Fuzzy logic incorporates uncertainty in decision making. Therefore, this study blends TOPSIS with fuzzy logic to achieve multi-criteria decision making under uncertainty. The AHP Fuzzy TOPSIS steps are as follows:

1st step: Specification of $\tilde{x}_{ij}, i = 1, 2, ..., n, j = 1, 2, ..., J$

in which $\tilde{x}_{ij}$ denotes the value of the i-th alternative or strategy for agricultural water management with regard to the j-th criterion; n = the number of management alternatives; and J = the number of decision criteria. The decision matrix X has elements $\tilde{x}_{ij}$.

2nd step: normalize the elements of the decision matrix as follows:

$$r_{ij} = \frac{\tilde{x}_{ij}}{\sqrt{\sum_{i=1}^{n} \tilde{x}_{ij}^2}} \quad i = 1, 2, \dots, n; j = 1, 2, \dots, J \tag{1}$$

which yields the normalized decision matrix $R = \left[r_{ij}\right]$ whose elements are in the range [0,1] when $\tilde{x}_{ij}$ >0, whereas the $\tilde{x}_{ij}$ s have values over diverse ranges.

3rd step: Calculate the weighted normalized decision-making matrix $\tilde{V}$ with elements $\tilde{v}_{ij}$:

$$\tilde{v}_{ij} = r_{ij} \cdot w_j \quad i = 1, 2, \dots, n; j = 1, 2, \dots, J \tag{2}$$

The weights w_j denotes the importance or weight of the j-th criterion, and they are normalized to add to 1: $w_1 + w_2 + \cdots + w_J = 1$. The weights are determined with the AHP method (Saaty 2008).

4th step: Define the fuzzy best alternative (A^*) and the fuzzy worst alternative (A^-). A^* and A^- are given by Eqs. (3) and (4), respectively:

$$A^* = \left\{\tilde{v}_1^*, \tilde{v}_2^*, ..., \tilde{v}_J^*\right\} \tag{3}$$

in which $\tilde{v}_j^*$ denotes the ideal (best) value with respect to the j-th criterion. The $\tilde{v}_j^*$ describe the aspired solution to the given problem that may or may not be achievable in practical terms.

$$A^- = \left\{\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_J^-\right\} \tag{4}$$

in which $\tilde{v}_j^-$ denotes the worst value with respect to the j-th criterion. The $\tilde{v}_j^-$ constitute the possible worst solution to a problem that may or may not occur in practical terms.

5th step: Calculate the (Euclidean) distance of each management strategy or alternative from the best and worst solutions using Eqs. (5) and (6), respectively:

$$D_i^* = \sqrt{\sum\nolimits_{j=1}^{n} [\tilde{v}_{ij} - \tilde{v}_1^*]^2} i = 1, 2, \ldots, n \tag{5}$$

$$D_i^- = \sqrt{\sum\nolimits_{j=1}^{n} [\tilde{v}_{ij} - \tilde{v}_j^-]^2} i = 1, 2, \ldots, n \tag{6}$$

in which D_i^* and D_i^- denote the separation of the i-th alternative from the best and worst solutions, respectively.

6[th] step: The relative closeness of the i-th alternative to the best solution, *CCi*, is calculated with Eq. (7):

$$CC_i = \frac{D_i^*}{D_i^* + D_i^-} i = 1, 2, \ldots, n \tag{7}$$

7[th] step: rank the alternatives based on the CC_i values.

The ranking of agricultural water management strategies applies a combination of analytical hierarchy criteria and the fuzzy TOPSIS method as follows:

- Collect the data and pre-process them.
- Determine appropriate criteria for the decision-making process.
- Use a multi-criteria decision-making analysis (Analytical Hierarchy Process, AHP, in this work) to determine the weights of each criterion.
- Evaluate the alternatives with the fuzzy TOPSIS method and ranking of the alternatives.

This paper's approach first defines the management strategies and the decision-making criteria. In this first stage the hierarchical structure is formed with the first, second, and third levels corresponding to the ultimate goal, decision making criteria, and alternatives, respectively. The weights of the criteria are calculated based on the geometric mean, and the pairwise comparison matrix is calculated based on Saaty's preferences (Saaty 2008). The fuzzy TOPSIS method is applied to rank the agricultural water management strategies. At this juncture the linguistic variables and associated triangular fuzzy numbers are applied to evaluate the management strategies.

Developing Sustainable Agricultural Water Management Criteria for Decision Making The evaluation of agricultural water management strategies is made in this study with technical and operational, environmental, socio-political, and economic criteria (Afsordegan 2015). The strategies must be acceptable to the pertinent agencies and relevant stakeholders. Another feature of the management strategies concerns their capacity to ensure environmental protection. Moreover, the technical and operational aspects of the strategies are essential to achieve effective implementation, operation, and maintenance of agricultural projects. After defining the evaluation criteria, they are weighted and the pairwise comparison matrix is calculated based on Saaty's preferences (Saaty 2008).

3 Study Area

The *Sefidroud* irrigation and drainage network constitutes this work's study area (Fig. 2). The *Sefidroud* irrigation network is one of the largest in Iran. This network covers parts of the three main basins of Iran including Talesh-Talab Anzali, Great *Sefidroud*, and *Sefidroud* -Haraz basins. There are regional conflicts over water that affects the *Sefidroud* irrigation network. The *Sefidroud* irrigation and drainage network is divided into three irrigation zones, namely, the Markazi, Fumanat, and Shargh irrigation zones.

Rice as a basic crop within the *Sefidroud* irrigation and drainage network where it is essential for food security. About 94% of the total cultivated agricultural land is dedicated to rice fields. Other crops are tea, citrus, and olives, which are of economic importance.

The *Sefidroud* river is the main source of water supply for the *Sefidroud* irrigation and drainage network through water releases from *Sefidroud* dam that are conveyed to the irrigation units through a network of diversion dams and channels. Besides the *Sefidroud* dam there are other sources of water for the *Sefidroud* irrigation and drainage network, such as local rivers, farm wastewater, small irrigation reservoirs, and groundwater. The main challenges in the study area are related to the development of agricultural lands in the upstream areas, drought recurrence, climate change, increasing water demand, and the incomplete development of the irrigation network. Furthermore, the need to maintain the role of rice in the study area as a strategic crop in food security of the growing population and increase the income of farmers poses additional challenges to water management in this large irrigation and drainage network.

The management of water distribution and delivery to the *Sefidroud* network has been impacted by droughts, such as that of 1998–1999. For instance, the intermittent irrigation

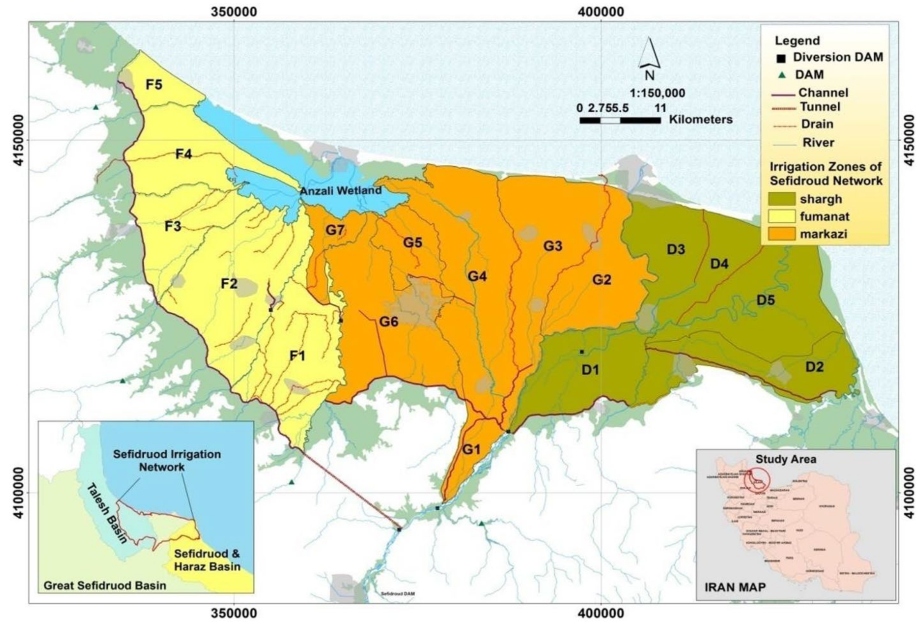


Fig. 2 The location of the study area

method used in some parts of the network has been replaced with permanent irrigation, and the amounts of water withdrawals from local rivers, drainages, and groundwater have increased without consideration of the associated environmental impacts.

4 Results and Discussion

This section describes the following topics:

- Analysis and evaluation of agricultural water consumption in the study area.
- SWOT analysis of agricultural water management in the study area.
- Strategy-ranking with multi-criteria analysis.

4.1 Agricultural Water Consumption Analysis

The area of paddy lands in the study area is variable depending of the available water resources, particularly on the amount of delivered water from *Sefidroud* dam. The total area of paddy fields is cultivated during periods of normal water availability, and a fraction of this area is fallowed in dry years. The data concerning water delivered to the *Sefidroud* irrigation and drainage network in recent years exhibits significant variations between normal and dry years. The largest volume of water delivered from *Sefidroud* dam to the *Sefidroud* irrigation network was about 2.2 billion cubic meters (BCMs) in 1994–1995 and the smallest volume water delivered was about 0.7 billion cubic meters in 1998–1999. The long-term average annual volume of water delivered to irrigation and drainage network is about 1.6 billion cubic meters. The average volume of water delivered to the *Sefidroud* irrigation and drainage network in recent years is about 1.3 billion cubic meters, which represents a reduction in the amount of water delivered to the network with respect to the long-term average. The difference between the amounts of water delivered to the *Sefidroud* irrigation and drainage network during normal and dry years is about 700 to 900 million cubic meters (Fig. 3).

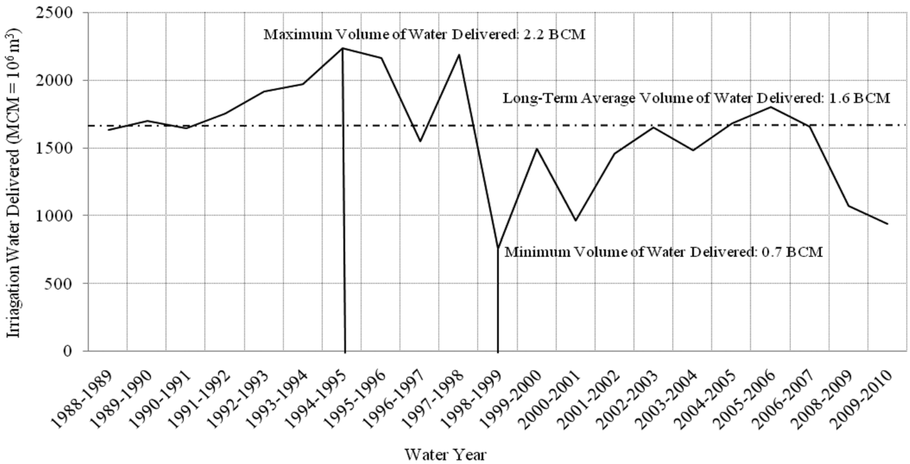


Fig. 3 The volume of water delivered to the *Sefidroud* irrigation and drainage network from 1988–1989 through 2009–2010 water years (MCM = 10^6 m^3; BCM = 10^9 m^3)

The cultivated areas with paddy fields in the *Sefidroud* irrigation and drainage network has been estimated from land use maps (Fig. 4) at about 157,000 hectares in dry years and about 179,000 hectares in normal (or average) precipitation years.

The area of irrigated land in the irrigation management zones of *Sefidroud* irrigation network are presented in Figs. 5a, b in normal and dry years.

As can be seen in these Figures, the most changes of irrigated land between normal and dry years in the study area is related to *Markazi* irrigation zone and the next ranks are related to *Fumanat* and *Shargh* irrigation zones.

This indicates the strong dependence of *Markazi* irrigation zone on water supply from *Sefidroud* dam. It should be noted that the changes in irrigated land are mainly related to paddy fields, which are visible due to the dependence of the irrigation management zones of *Sefidroud* irrigation and drainage network on water supply from *Sefidroud* dam. As can be seen under normal conditions, the highest area of irrigated land in the study area is equal to 79,529 hectares related to *Markazi* irrigation zone and the lowest area of irrigated land related to *Fumanat* irrigation zone is equal to 51,815 hectares. Similarly, in dry climatic conditions, the highest area of irrigated land is related to the *Markazi* irrigation zone equal to 70,412 hectares and the lowest area of irrigated land related to the *Fumanat* irrigation zone is equal to 46,069 hectares.

Accordingly, agricultural water use has been estimated in normal and dry years from long-term statistical analysis of water delivered to the *Sefidroud* irrigation and drainage network. The annual volumes of agricultural water use in the *Sefidroud* irrigation and drainage network during normal and dry conditions are listed in Table 1. It can be seen in Table 1 the cultivated area of paddy fields in *Sefidroud* irrigation and drainage network is about 179,181 hectares under normal conditions, and about 157,612 hectares under dry

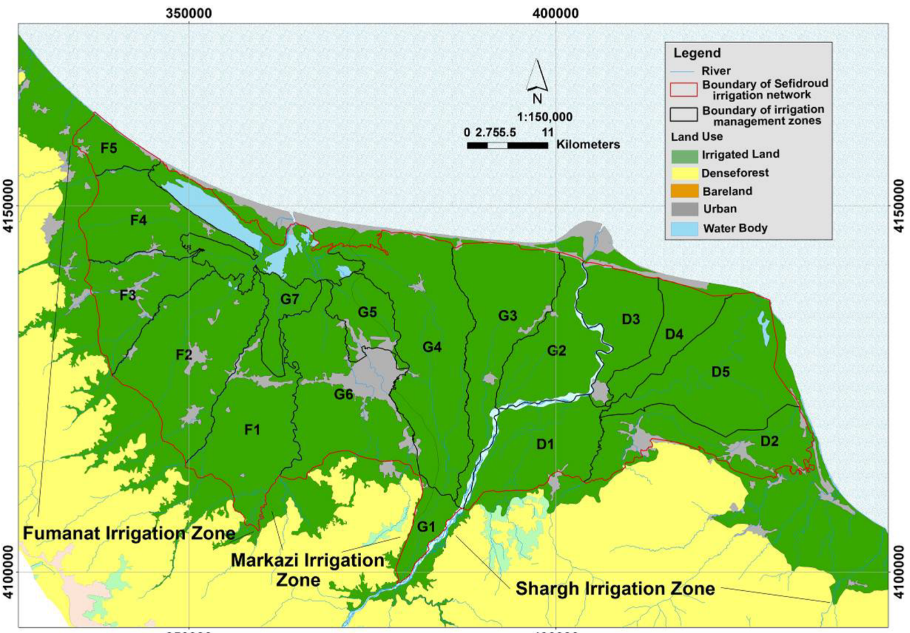
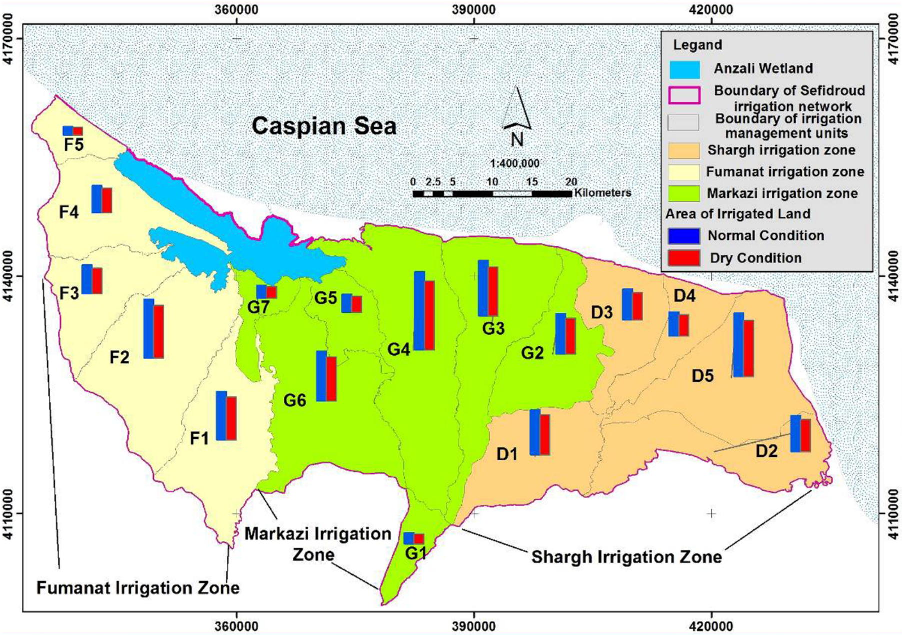
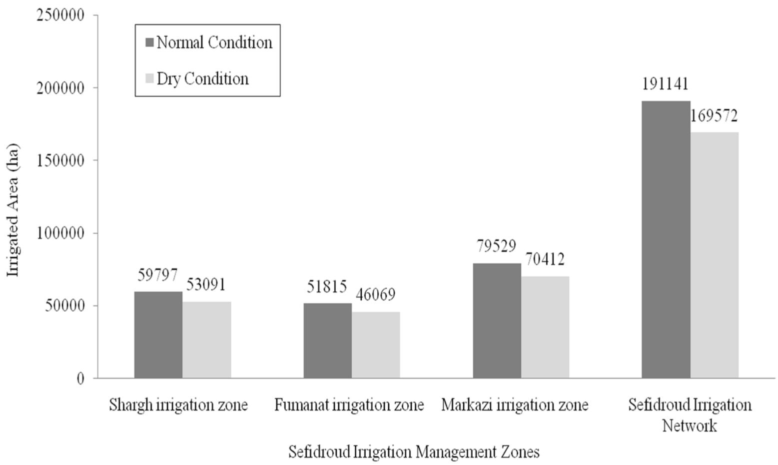


Fig. 4 The Landuse map of the study area



a. Spatial distribution of irrigated land in the study area.



b. The area of irrigated land in the irrigation management zones of *Sefidroud* irrigation network.

Fig. 5 **a**. Spatial distribution of irrigated land in the study area. **b**. The area of irrigated land in the irrigation management zones of *Sefidroud* irrigation network

Table 1 Summary of the current status of agricultural water use based on the water resources of the *Sefidroud* irrigation and drainage network

Normal Condition				Dry Condition			
Irrigated land area (ha)	Water Supply Resources	water consumption volume (10^6 m^3)	water use volume (m^3/ha)	Irrigated land area (ha)	Water Supply Resources	water use volume (10^6 m^3)	water use volume (m^3/ha)
191141	*Sefidroud* Irrigation network	1400	9404	169572	*Sefidroud* Irrigation network	939	8808
	local rivers	260			local rivers	390	
	tank irrigation	47			tank irrigation	58	
	Total surface water use	1707			Total surface water use	1386	
	Groundwater use	90			Groundwater use	107	
	Total water use	1797			Total water use	1494	

climatic conditions. The total annual water use of cultivated area in *Sefidroud* irrigation and drainage network is about 1.8 billion cubic meters under normal climatic conditions, of which about 1707 million cubic meters (95%) are surface water and 90 million cubic meters (5%) are groundwater. Of the total volume of surface water use about 1.4 billion cubic meters are from the *Sefidroud* dam and related canals, 260 million cubic meters from local rivers and farm wastewater, and about 47 million cubic meters from small irrigation reservoirs. The average volume of water use in the 191,141 hectares of irrigated lands of the *Sefidroud* irrigation and drainage network equals 9404 cubic meters per hectare under normal climatic conditions.

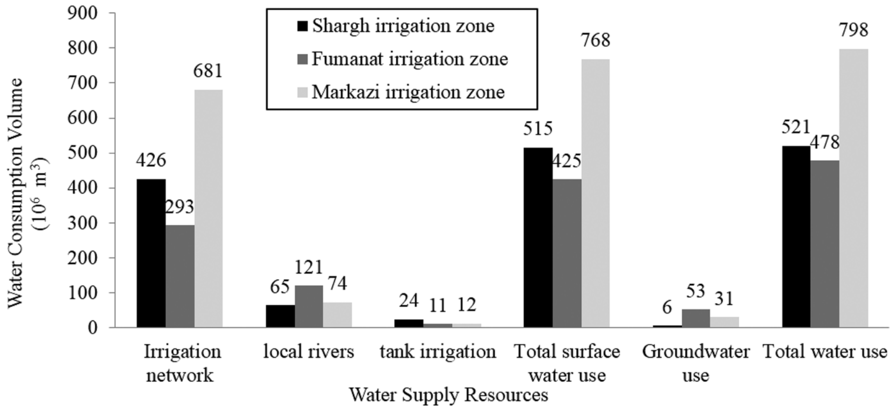
The total annual water use in the cultivated area in the *Sefidroud* irrigation and drainage network is estimated at 1.5 billion cubic meters under dry conditions, of which 1386 million cubic meters (93%) are surface water and 107 million cubic meters (7%) from groundwater. Of the total volume of surface water use 939, 390, and 58 million cubic meters are from *Sefidroud* dam and related channels, from local rivers and farm wastewater, and from small irrigation reservoirs, respectively. The average unit use of water in the *Sefidroud* irrigation and drainage network is about 8808 cubic meters per hectare under dry conditions in the 169,752 hectares of cultivated land (Figs. 6a, b).

A comparison of agricultural water use from surface water resources (i.e., from the *Sefidroud* dam and irrigation network, local rivers and farms waste water, small irrigation reservoirs) and groundwater use in the irrigation zones of the *Sefidroud* irrigation network including Shargh, Markazi and Fumanat under normal and dry climatic conditions is depicted in Tables 5 and 6, respectively. Figures 7a, b display the spatial distribution of water use in the *Sefidroud* irrigation and drainage network from surface and groundwater sources under normal and dry conditions, respectively. It can be seen that the water from groundwater, local rivers, and farm wastewater increases during the periods of water scarcity. Specifically, the water from local rivers and farm wastewater has been increased by 50% under deficit conditions compared to the normal condition. This increase is mainly from farm wastewater, which is a common supplementary source especially during drought periods in the irrigation network. Using more farm wastewater poses environmental risks due to the presence of pollutants such as nitrates and heavy metals, and by domestic and industrial effluents in the wastewater.

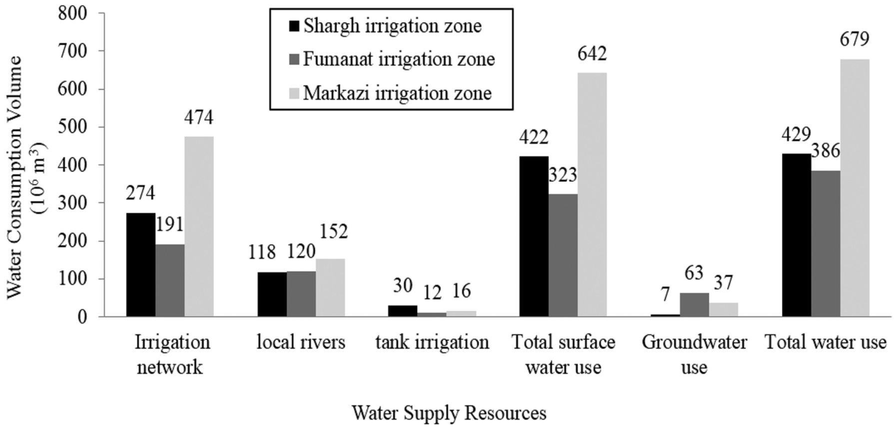
The volume of groundwater is equal to 90×10^6 m^3 annually under normal conditions, which increases to 107×10^6 m^3 annually under dry condition. This produces a 20% rise on the demands imposed on groundwater withdrawn from wells under dry conditions. A comparison between surface and groundwater use in the irrigation management zones of *Sefidroud* irrigation network are displayed through Figs. 8a–d.

4.2 SWOT Analysis of Agricultural Water Management

SWOT analysis has been applied successfully to complex water resources management (Tziritis et al. 2014). This paper applies SWOT analysis because of its capacity to incorporate present conditions (through strengths and weaknesses) and future conditions (through opportunities and threats) which are pertinent in the *Sefidroud* irrigation network, which is undergoing rapid changes in terms of land use change and upstream water resources development plans. SWOT analysis minimizes weakness and threats by converting weakness into strengths, and threats are converted into opportunities. Strengths and opportunities are exploited to optimize agricultural water resources management (Wickramasinghe and Takano 2009).



a. Description of agricultural water consumption in different irrigation zones of the *Sefidroud* irrigation network (Normal Condition)



b. Description of agricultural water consumption in different irrigation zones of the *Sefidroud* irrigation network (Dry Condition).

Fig. 6 **a.** Description of agricultural water consumption in different irrigation zones of the *Sefidroud* irrigation network (Normal Condition) **b**. Description of agricultural water consumption in different irrigation zones of the *Sefidroud* irrigation network (Dry Condition)

SWOT assumes that strengths and weaknesses are internally-related, while opportunities and threats are due to external influences. The separation between internal and external factors is made by the physical boundary of the *Sefidroud* irrigation and drainage network. Thus, the factors under the control and management of *Sefidroud* irrigation and drainage network are considered internal factors (IFs), and the others are considered external factors (EFs).

This study relies on knowledge and information gathered through interviews with relevant experts as the main input for the SWOT analysis. The viewpoints of the decision-making experts' committee members with expertise in the technical and operational aspects in the study area were gathered to improve the formulation of agricultural water management strategies. The strengths and opportunities factors are scored in the range of 3–4, and the weaknesses and threats factors are scored in the range of 1–2 based on work by David (2011). It is noteworthy that if the final score of the internal or external factors exceeds 2.5 then the strengths/opportunities overcome the weaknesses/threats, and vice versa.

The results of SWOT analysis for the agricultural water management in the *Sefidroud* irrigation network are presented in Tables 7 and 8. Table 7 lists the internal SWOT factors and weighted ratings of factors. Table 8 lists the external SWOT factors and weighted ratings of factors. The internal and external factors of agricultural water management include 10 strengths (S1-S10), 14 weaknesses (W1-W14), 6 opportunities (O1-O6), and 6 threats (T1-T6). The final scores of the internal and external factors were equal to 2.9 and 2.73, respectively. According to the literature (David 2011) this work's results indicate that the most attractive strategic type was SO (aggressive). The possible strategies are formed as a combination of two related strategies. For example, if the main strategy type is "SO" the relevant strategies are a combination of the "ST" and "WO" strategic types (David 2011). Based on this rule 17 strategies within 3 strategic groups were formulated by matching the IFs against the EFs based on SWOT analysis, and they are listed in Table 9. The next step is to rank the set of water management strategies with the AHP Fuzzy TOPSIS approach.

4.3 Strategy-ranking with the Fuzzy AHP TOPSIS Approach

The weights of the sustainable criteria related to agricultural water management were calculated based on the opinions of experts in the field of agricultural water management and applying the AHP. The calculated weights are listed in Table 2. The inconsistency ratio (*IR*) for the pairwise comparison matrix is determined that shows the consistency of results. The inconsistency index for a pairwise comparison matrix was introduced by Saaty (1996).

- Consistency index *C.I.* (Saaty 1996):

$$C.I. = \frac{\lambda_{max} - n}{n - 1} \tag{8}$$

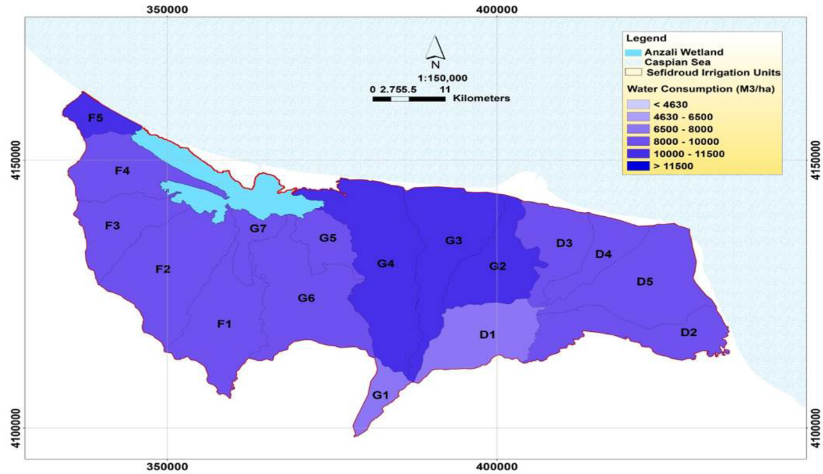
In Eq. (8), λ_{max} is the maximum eigenvalue of the pairwise matrix. According to Saaty, a pairwise comparison matrix with *C.I.* equal to or lower than 0.10 is sufficiently consistent. However, *C.I.* varies with *n*, which is why Saaty (2008) introduced a more suitable measure of consistency, i.e., the consistency ratio *C.R.:*

- Consistency ratio *C.R.*:

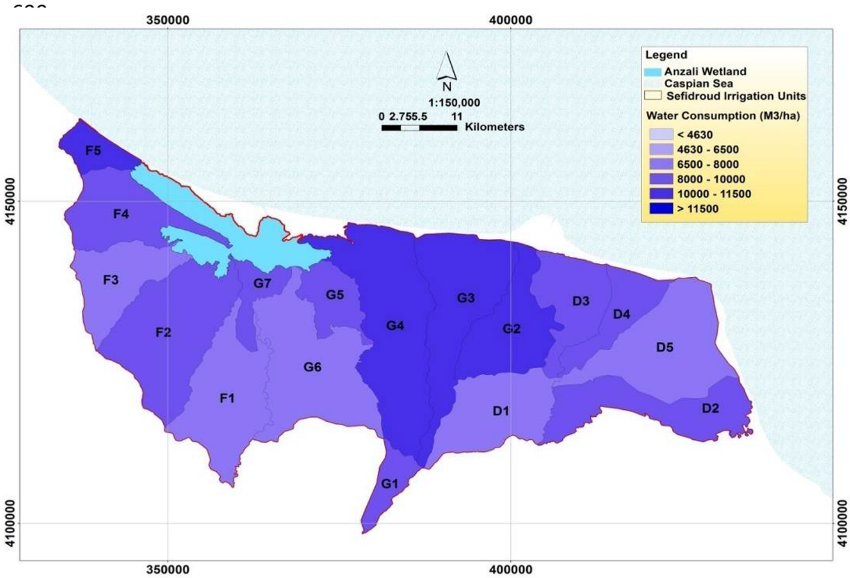
$$C.R. = \frac{C.I.}{R.I.} \tag{9}$$

The *R.I.* in Eq. (9) is the random inconsistency which is an average *C.I.* of random matrices (generated by the Monte Carlo method) of order *n*.

A pairwise comparison matrix with *C.R.* equal to or lower than 0.10 is sufficiently consistent. Notably, *R.I.* was found to converge to the value 1.58 with increasing *n* (Saaty 2008). This fact drew some criticism of the *C.R.* (and *C.I.*) because the random

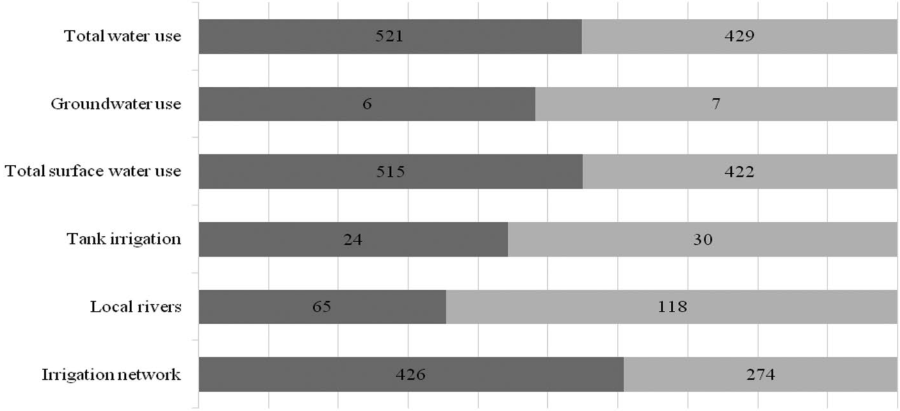


a. Spatial distribution of water use from surface and groundwater sources in the *Sefidroud* irrigation network (normal precipitation condition). (m^3/ha = m^3/hectare).



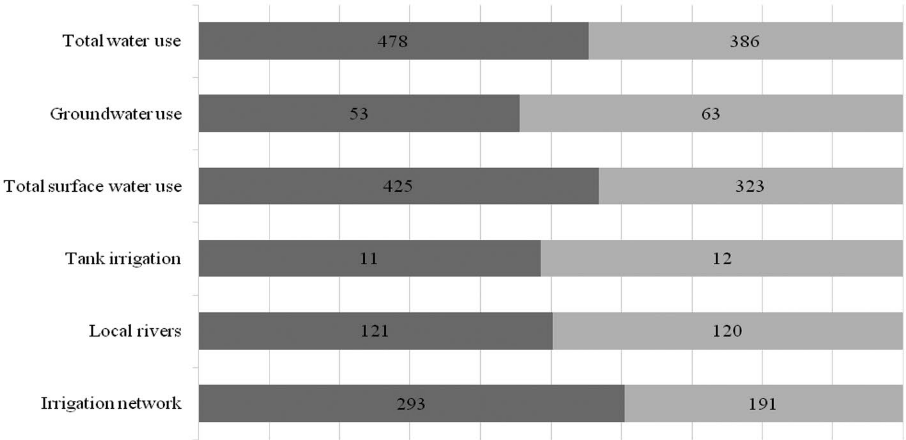
b. Spatial distribution of water use from surface and groundwater sources in the *Sefidroud* irrigation network (dry condition). (m^3/ha = m^3/hectare).

Fig. 7 **a.** Spatial distribution of water use from surface and groundwater sources in the *Sefidroud* irrigation network (normal precipitation condition). (m^3/ha = m^3/hectare). **b.** Spatial distribution of water use from surface and groundwater sources in the *Sefidroud* irrigation network (dry condition). (m^3/ha = m^3/hectare)



	Irrigation network	Local rivers	Tank irrigation	Total surface water use	Groundwater use	Total water use
■Normal Condition	426	65	24	515	6	521
■Dry Condition	274	118	30	422	7	429

a. Comparison between surface and groundwater use in *Shargh* irrigation zone (10^6 m^3).



	Irrigation network	Local rivers	Tank irrigation	Total surface water use	Groundwater use	Total water use
■Normal Condition	293	121	11	425	53	478
■Dry Condition	191	120	12	323	63	386

b. Comparison between surface and groundwater use in *Fumanat* irrigation zone (10^6 m^3).

Fig. 8 **a.** Comparison between surface and groundwater use in *Shargh* irrigation zone (10^6 m.^{3}). **b.** Comparison between surface and groundwater use in *Fumanat* irrigation zone (10^6 m.^{3}). **c.** Comparison between surface and groundwater use in *Markazi* irrigation zone (10^6 m^3). **d.** Comparison between surface and groundwater use in *Sefidroud* irrigation network (10^6 m^3)

Table 2 The results of the analytical hierarchical process (AHP)

Criteria	Weight	$_{max}$, CI, RIλ	CR
C1	0.356	$_{max}$ = 7.87 λ	
C2	0.287	CI = 0.14	
C3	0.231	RI = 1.3	0.1
C4	0.126		

C1: Technical and operational criteria, C2: environmental criteria, C3: socio-political criteria, C4: economic criteria, λmax: maximum eigenvalue, CI: Consistency index, RI: Random index

inconsistency should increase with increasing *n* (the larger a random matrix is, the more “mess” it contains) (Saaty 1996).

The main strategies were defined: St-1: development and rehabilitation of the physical structure of water resources system of *Sefidroud* irrigation network; St-2: improvement of operation management and maintenance of the *Sefidroud* irrigation network; St-3: wastewater management; and St-4: inter-basin water transfer within the *Sefidroud* irrigation network from the internal water resources of the system. These strategies were ranked with the AHP fuzzy TOPSIS approach.

The weighted fuzzy decision-making matrix was calculated using the weights of criteria obtained with the AHP method. The weighted fuzzy decision-making matrix is listed in Table 3, where St-1 to St-4 denote the strategies or alternatives (agricultural water management strategies) and C1 to C4 denote the decision-making criteria. Table 3 shows that the elements $\tilde{v}_{ij}$ for all values i and j, are normalized in the interval [0,1]. The fuzzy best and worst solutions are listed in Table 3, also.

The strategies were ranked based on their distances from the best and worst solutions based on the CC_i indices computed with Eq. (7). Calculations results related to the CC_i index are presented in Table 4. These results show that the combination of structural and non-structural strategies (the SO, ST, and WO strategies) with CC_i index equal to 0.248 was top ranked in terms of sustainable agricultural water management. The ranking of strategies based on the CC_i index is listed in Table 4.

Table 3 The weighted fuzzy decision making matrix for strategies

	C1	C2	C3	C4
St-1	(0.211,0.281.0.351)	(0,0,0.048)	(0.125,0.156,0.156)	(0.04,0.061,0.081)
St-2	(0.14,0.211,0.281)	(0.048,0.095,0.143)	(0.062,0.094,0.125)	(0.061,0.081,0.101)
St-3	(0.281,0.351,0.351)	(0.143,0.19,0.238)	(0,0.031,0.062)	(0.081,0.101,0.101)
St-4	(0.07,0.14,0.211)	(0.19,0.238,0.238)	(0,0,0.031)	(0.04,0.061,0.081)
Ideal (+)	$\tilde{v}_1^* = (1,1,1)$	$\tilde{v}_2^* = (1,1,1)$	$\tilde{v}_3^* = (1,1,1)$	$\tilde{v}_4^* = (1,1,1)$
Ideal (-)	$\tilde{v}_1^- = (0,0,0)$	$\tilde{v}_2^- = (0,0,0)$	$\tilde{v}_3^- = (0,0,0)$	$\tilde{v}_4^- = (0,0,0)$

St-1: development/rehabilitation/renewing of the *Sefidroud* irrigation network; St-2: improve the management of operation and maintenance of the *Sefidroud* irrigation network; St-3: wastewater management; and St-4: inter-basin water transfer within the *Sefidroud* irrigation network; C1: Technical and operational criteria, C2: environmental criteria, C3: socio-political criteria, C4: economic criteria

Table 4 The ranking of strategies based on the CC_i index

Strategies	D_i^*	D_i^-	CC_i	Final ranking of strategies
St-1	5.480	1.533	0.221	3
St-2	5.460	1.586	0.223	2
St-3	5.280	1.739	0.248	1
St-4	5.524	1.505	0.214	4

St-1: development/rehabilitation/renewing of the *Sefidroud* irrigation network; St-2: improve the management of operation and maintenance of the *Sefidroud* irrigation network; St-3: wastewater management; and St-4: inter-basin water transfer within the *Sefidroud* irrigation network

5 Concluding Remarks

This work presented spatial fuzzy strategic planning (SFSP) in combination with a MCDM approach to rank agricultural water management strategies. A spatial combination analysis of internal and external factors related to agricultural water management including strengths, weaknesses, opportunities and threats (SWOT) analysis matrix was applied in this work. The strategies were ranked with AHP and Fuzzy TOPSIS. The AHP method was used to determine the criteria weights, and the fuzzy TOPSIS model ranked the agricultural water management strategies in the study area.

This study applied linguistic variables that are converted to triangular fuzzy numbers to account for the uncertainty in the decision-making process. A model of decision making with respect to identified agricultural water management strategies was developed based on a defined set of criteria. This paper's model combines the concepts of fuzzy logic, the analytical hierarchy process (AHP), and the fuzzy TOPSIS method to resolve multi-criteria decision making under uncertainty. The analytical hierarchy process was applied for determining the weights in the decision-making process, and the TOPSIS method in a fuzzy environment was applied to obtain the ranking of strategies. The results indicate that a combination of structural and non-structural strategies (SO, ST, and WO strategies) are the top ranked strategy. The strategies offer the best path to improve agricultural sustainably and reduce social tensions.

The next step for implementing the sustainable agricultural water management strategies in the *Sefidroud* irrigation network is to apply structural and non-structural measures in selected modern and traditional irrigation zones having the highest priority for assistance. Agricultural water management strategies are likely to vary across irrigation zones. The applicability of this paper's methodology transcends the specifics of its study area. In fact, the proposed spatial fuzzy strategic planning (SFSP) in combination with MCDM and a conceptual agricultural water consumption model presented in this study could be adapted and applied in other large-scale irrigation and drainage networks.

Appendix

Table 5 Agricultural water use in the irrigation management zones of the *Sefidroud* irrigation network (normal condition)

No.	*Sefidroud* Irrigation Zones	Irrigated Area (ha)	Water Supply Resources	water volume (10^6 m^3)
1	Shargh irrigation zone	59,797	*Sefidroud* Irrigation network	426
			local rivers	65
			small reservoirs	24
			Total surface water use	515
			Groundwater use	6
			Total water use	521
2	Fumanat irrigation zone	51,815	*Sefidroud* Irrigation network	293
			local rivers	121
			small reservoirs	11
			Total surface water use	425
			Groundwater use	53
			Total water use	478
3	Markazi irrigation zone	79,529	*Sefidroud* Irrigation network	681
			local rivers	74
			small reservoirs	12
			Total surface water use	768
			Groundwater use	31
			Total water use	798
Sefidroud Irrigation Network		191,141	*Sefidroud* Irrigation network	1400
			local rivers	260
			small reservoirs	47
			Total surface water use	1707
			Groundwater use	90
			Total water use	1797

Table 6 Agricultural water use in the irrigation management zones of the *Sefidroud* irrigation network (dry condition)

No.	*Sefidroud* Irrigation Zones	Irrigated Area (ha)	Water Supply Resources	water volume (10^6 m^3)
1	Shargh irrigation zone	53,091	*Sefidroud* Irrigation network	274
			local rivers	118
			small reservoirs	30
			Total surface water use	422
			Groundwater use	7
			Total water use	429
2	Fumanat irrigation zone	46,069	*Sefidroud* Irrigation network	191
			local rivers	120
			small reservoirs	12
			Total surface water use	323
			Groundwater use	63
			Total water use	386
3	Markazi irrigation zone	70,412	*Sefidroud* Irrigation network	474
			local rivers	152
			small reservoirs	16
			Total surface water use	642
			Groundwater use	37
			Total water use	679
Sefidroud Irrigation Network		169,572	*Sefidroud* Irrigation network	939
			local rivers	390
			small reservoirs	58
			Total surface water use	1386
			Groundwater use	107
			Total water use	1494

Table 7 Internal SWOT factors and weighted ratings of factors (S = Strength; W = Weakness)

Internal Factors	**Weighted Rating**
S1: The largest irrigation and drainage network in Iran and the second largest rice producer for food security	0.202
S2: There is an experienced water company that operates and maintains the irrigation and drainage network	0.190
S3: Ability to strengthen the irrigation management institutions due to the long history of operation & maintenance of the *Sefidroud* irrigation network	0.232
S4: Existence of a management procedure by the *Sefidroud* Operation and Maintenance Company in accordance with of the regulations of the *Sefidroud* Irrigation and Drainage Network	0.160
S5: Establishment of the National Rice Research center in Gilan province and the high capacity of this institute for conducting applied research to increase water productivity in the paddy fields	0.320
S6: Construction of more than new 700 pumping stations in recent years on local rivers and drains to supply water of agricultural lands	0.251
S7: Use of intermittent irrigation method in paddy fields in recent years, especially during peak water use and water shortage periods	0.212
S8: Possibility of supplying required water for agricultural lands in the form of conjunctive use of several water sources (*Sefidroud* dam, local rivers, tanks, wells, springs, and natural drainages.) relying on existent infrastructure	0.273
S9: Possibility of reconstruction and improvement of tanks considering their multi-purpose use (agriculture, aquaculture, and environment)	0.312
S10: Humid and semi-humid climatic conditions and high rainfall in the study area	0.288
W1: Inadequate implementation of the development plan in 7 irrigation units of the *Sefidroud* irrigation and drainage network	0.027
W2: Improper operation and maintenance of *Sefidroud* irrigation and drainage network facilities	0.026
W3: Problems during implementation and operation due to incompatibility of the development plan of irrigation network with the existing traditional irrigation network	0.025
W4: Lack of necessary infrastructure for water delivery in the *Sefidroud* irrigation and drainage network	0.027
W5: Lack of proper coordination (1) in the development of on-farm irrigation network, (2) equipping and renovating lands during the development and rehabilitation of the *Sefidroud* main irrigation network	0.026
W6: Direct delivery of water to more than 300,000 water users within the *Sefidroud* irrigation network by *Sefidroud* operation and Maintenance Company without the participation of the water user association (WUA)	0.026
W7: Failure to establish local cooperative water management institutions to participate in water management, water delivery, and distribution within the irrigation network	0.030
W8: Lack of sufficient motivation by farmers to establish water user association under the current situation, especially after the failure of pilot projects	0.028
W9: Lack of monitoring system for agricultural water use	0.029
W10: The same price of agricultural water right for all irrigated areas within the *Sefidroud* irrigation network including irrigated areas fully covered by the irrigation network, local rivers, wells, natural drains, which creates dissatisfaction among farmers	0.034
W11: Design of *Sefidroud* irrigation and drainage network based on permanent irrigation method	0.033
W12: Planting in the canals encroaches on the irrigation network and the increase in water requirements	0.032
W13: Insufficient attention to dredge and poor maintenance of canals and small dams	0.034
W14: Lack of empowerment of water users for sustainable use of agricultural water	0.086
The final score of internal factors	**2.9**

Table 8 External SWOT factors and weighted ratings of factors (O = Opportunity; T = Threat)

External Factors	**Weighted Rating**
O1: Suitable soil resource potential, climatic conditions and topography for paddy fields (as a strategic crop) and orchards	0.25
O2: Suitable potential of internal water resources for the *Sefidroud* irrigation network including local rivers, dams and groundwater resources to supply water especially in drought condition	0.22
O3: Funding opportunities from national and international investors	0.22
O4: promotion of agro-tourism and industries related to the agricultural sector	0.30
O5: Possibility of developing the use of agricultural return flow in supplying part of the required water for agricultural lands, especially during peak consumption and water shortage periods taking into account environmental considerations and construction of technical facilities (rubber dams and diversion dams) in the downstream reaches of the rivers and natural drains	0.32
O6: Existence of rules, procedures, standards and technical guidelines for agricultural water resources management	0.27
T1: Expected decline of the amount of water entering to the *Sefidroud* reservoir due to upstream development projects	0.09
T2: Increased water demand due to land use change and conversion of paddy fields into aquaculture ponds	0.16
T3: Increasing competition between agricultural and non-agricultural sectors such as aquaculture and industry	0.13
T4: Improper extraction of sand from local riverbeds and increasing the depth of riverbeds and severe damage to water intake facilities especially during floods	0.11
T5: Instability of irrigation management institutions and uncooperative development of the agricultural sector	0.13
T6: Deteriorating quality of water resources due to discharge of effluents (urban and industrial) into rivers and drains, especially in the central irrigation zone of *Sefidroud* network	0.13
The final score of external factors:	**2.73**

Table 9 Agricultural water management strategies by SWOT analysis

Type of Strategy	Description of Strategy	No. of Strategy
Aggressive (SO)	Development and rehabilitation of small dams in the *Sefidroud* irrigation network	SO-1
	Inter-basin water transfer within the *Sefidroud* irrigation network with the construction of diversion and rubber dams in the downstream of rivers and drains with excess water	SO-2
	Possibly implementing agricultural water market in the *Sefidroud* irrigation zones	SO-3
	Development of agro-tourism in *Sefidroud* irrigation network	SO-4
	Implementing of irrigation development projects funded by national and international agencies	SO-5
	Development and implementation of the main irrigation and drainage network in the 7 remaining irrigation units of the *Sefidroud* irrigation network	SO-6
	Rehabilitation/Renovation of the *Sefidroud* irrigation network in under-operation irrigation zones (10 irrigation units)	SO-7
	Development of on-farm irrigation and drainage network in the remaining areas of the *Sefidroud* irrigation network	SO-8
Competitive (ST)	Planning land use especially in paddy fields	ST-1
	Strengthening the irrigation management institutions of the *Sefidroud* irrigation network with public participation	ST-2
	Supervision of *Sefidroud* irrigation network operation by consultant engineering companies and providing reports and documents for the irrigation management institutions	ST-3
	Development of sustainable water resources management plans regarding the upstream development plans of the *Sefidroud* basin	ST-4
	Assessment of the current situation of the *Sefidroud* irrigation network concerning agricultural water use and challenges facing the agricultural water sector	ST-5
Conservative (WO)	Establishment of agricultural water consumption monitoring system in the *Sefidroud* irrigation network	WO-1
	Establishment of water user association to promote stakeholders participation in the form of training, holding workshops and upgrading the capacities of irrigation management institutions within the *Sefidroud* irrigation network	WO-2
	Reduce water losses in *Sefidroud* irrigation network to promote irrigation efficiency by structural and non-structural measures	WO-3
	Empowerment and involvement of local communities and increasing the competitive ability of the *Sefidroud* irrigation units	WO-4

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Availability of Data and Materials The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability The codes that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics Approval All authors accept all ethical approvals.

Consent to Participate All authors consent to participate.

Consent for Publish All authors consent to publish.

Competing Interests There is no conflict of interest.

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