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Developing an integrated risk management framework for agricultural water conveyance and distribution systems within fuzzy decision making approaches

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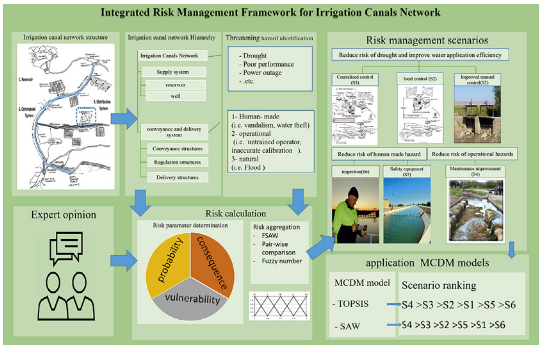
HIGHLIGHTS

- Inefficient agricultural water systems have been led to significant operational water losses.
- Canal network as the primary agricultural water distribution systems is exposed to a variety of hazard.
- Risk assessment of the hazards, evaluate the possibility of water distribution system failures.
- A risk management framework for selecting irrigation modernization strategies is developed.
- The framework is employed for risk management of the Qazvin irrigation canal network.

GRAPHICAL ABSTRACT



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ABSTRACT

Irrigation canal networks, as the primary agricultural water conveyance and delivery systems, are exposed to a variety of hazards affecting the water distribution processes. This study, for the first time, develops a comprehensive risk management framework for the canal network through a Fuzzy Hierarchical method. In this regard, the risk is analyzed by a combination of probability, consequence, and vulnerability against identified hazards based on the hierarchical framework. The developed model is based on fuzzy numbers to consider the uncertainties arise from experts' opinion. To aggregate the calculated risk in the hierarchical framework, the Fuzzy Simple Additive Weighting (FSAW) approach was employed. To enhance the reliability of the water distribution system and decrease the risk of failure, six risk management alternatives are proposed based on the risk assessment results and the most significant hazards. To prioritize managerial scenarios, two sets of criteria were selected including quantitative criteria (consisting of cost of operation and risk reduction) and a qualitative set (compromising social and operational criteria). The risk management scenarios were prioritized based on two rational multi-criteria decision-making (MCDM) methods of a Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Simple Additive Weighting (SAW). Regarding different degrees of importance of the criteria, a pair-wise comparison was conducted by a group of experts to determine the relative weight of the criteria. According to the risk assessment results, the riskiest hazards are poor maintenance, seepage, unexpected event, drought, and vandalism of the structure. Moreover, employing the MCDM model in risk-based

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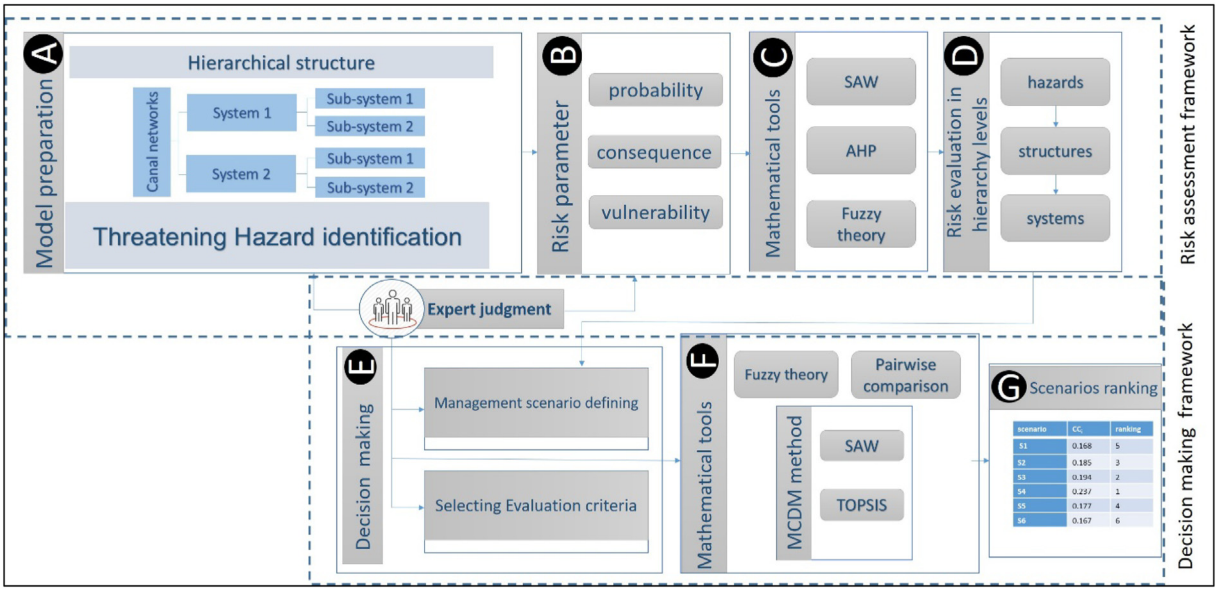
decision-making reveals that “maintenance improvement” is ranked as the first scenario, with score values of 0.851 and 0.237 employing the SAW, and TOPSIS approaches, respectively.

1. Introduction

Performance of the irrigation sectors, as the most significant water users in developing countries, needs immediate improvements due to increasing demands for crop production and competition for water allocation between agricultural and non-agricultural sectors (Kanooni and Monem, 2014). Practical measures to achieve this goal have been concentrated on two broad categories of on-farm and off-farm activities. The former has focused on activities which consist of cropping pattern optimization (Amini Fasakhodi et al., 2010; Montazar et al., 2010; Garg and Dadhich, 2014), and application of modern technologies at the farm scale to ensure proper water management within the farms (Ismail and Almarshadi, 2013; Hassan-Esfahani et al., 2015). However, in off-farm practices, application of automatic control systems to minimize operational water losses and increase flexibility of water distribution has been reported (Horváth et al., 2010; Van Overloop et al., 2010; Xu et al., 2011; Fele et al., 2014; Maestre and Negenborn, 2014; Horváth et al., 2015). Moreover, applying advanced operational strategies including in-line water storage (Hashemy Shahdany et al., 2012), and fair water distribution along the main canal (George et al., 2011a, 2011b; Shahdany et al., 2016), using automatic techniques, constitute operational performance improvements at this level. However, it should be noted that the first task required in providing efficient agricultural water management is a comprehensive assessment of the current weakness and strength of the conveyance and delivery systems.

This evaluation requires the specification of the real potential of the system in achieving any water management objectives, regardless of on-farm and off-farm activities. The performance appraisal methods used currently are based on qualitative and quantitative assessments (Montazar et al., 2013). These methods consist of a wide range of indicators considering different aspects including managerial, social, environmental, and economic indices. Using the approaches mentioned above, the performance of the system is compared to relevant indicators with the assigned targets. Despite the advantages of these methods, however, there are some limitations which have influenced the appraisal results. The first of these is the sectional accomplishment of the evaluation projects which do not lead to a comprehensive assessment of irrigation networks due to limitations in financial resources. The next limitation is ignoring the various threatening hazards which influence the performance of the system or even cause failure in water supply, conveyance or delivery procedures under present conditions. In another words, the conventional appraisal methods are not capable of recognizing the future challenges of the irrigation district. Moreover, due to the lack of a multi-faceted perspective in these methods, system failure prevention may not be achieved. In these conditions, disorganized maintenance activities are proposed based on the uncoordinated performance evaluation projects within the irrigation districts. Furthermore, funding and on-time maintenance implementation are serious obstacles, where mostly deferred maintenance is not effective and comprehensive rehabilitation is needed (Donaldson, 2013). Therefore maintaining the system in desirable performance conditions and providing continuous service at lower cost is preferable rather than an approach focused on repair and maintenance. To deal with the limitations mentioned above, the risk-oriented assessment project is proposed which has been extensively carried out within related infrastructure, such as urban water supply and wastewater systems.

Risk assessment by combining the probability and consequence of system failure and vulnerability of components against the threatening hazards, evaluates the possibility of failure in the system (Torres et al., 2009). Different studies note the advantages of risk assessment in water supply systems. Fares and Zayed (2010) used the fuzzy hierarchical system to evaluate the failure risk considering 16 failure factors. Roozbahani et al. (2013) presented an integrated risk assessment framework for an urban water system in Urmia city, Iran, to evaluate the risk associated with the water supply system, treatment plant, and water distribution system. The fuzzy numbers were used to consider uncertainty in the inputs. Macey et al. (2014) developed a risk-based framework for rehabilitation planning in Colorado Springs. The risk was based on probability and consequence and the risk was determined based on the risk matrix.



scenario	CC_i	ranking
S1	0.168	5
S2	0.185	3
S3	0.194	2
S4	0.237	1
S5	0.177	4
S6	0.167	6

Fig. 1. The proposed risk management framework.

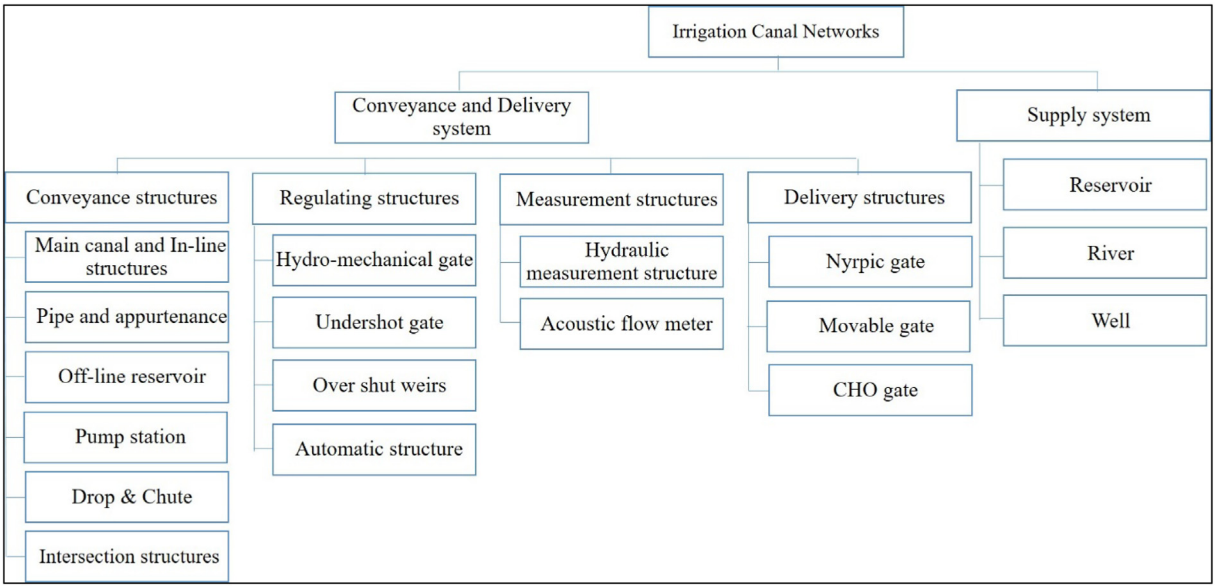


Fig. 2. The developed hierarchical structure of an irrigation network.

Risk assessment has similarly been extensively employed in wastewater management. In this regard, risk maps were developed using ArcGIS software. To achieve this end, the risk of failure was evaluated by three methods of fuzzy inference, risk matrix and multiplying risk elements (Salman and Salem, 2012). Elsawah et al. (2014) evaluated the urban water supply and sewer system considering interactive effects. Inanloo et al. (2016) identified vulnerable points in Miami city with consideration of municipal water, sewer, and transportation.

To handle the complexities of extensive systems assessment, such as large canal networks, application of the hierarchical framework is common. Taking this approach leads to a systematic framework in which risk can be evaluated in separate stages, considering hierarchical relations from the lowest level (i.e., hazards) to the highest level (i.e., total risk). The structure developed in this study is capable of being employed for any other irrigation districts including different types of conveyance and control structures.

Table 1
Identified threatening hazards for the irrigation network hierarchy.

Component	Hazards	Component	Hazards
Main canal and in-line structures	Poorly design of canal reaches	Overshot weir	Poor maintenance
	Seepage		Vandalism
	Poorly execution of canal reaches		
	Poor maintenance activities	Automatic structure	Failure of communication systems
	Water theft		Failure of power supply
	Filling the canal capacity by sandstorm and wind erosion		Poor inspection
Pipes and appurtenance	Equipment aging		
	Poorly designed and execution	Hydraulic structure	Untrained operators error
	Poor maintenance		Inaccurate calibration and poor maintenance
	External loads	Acoustic flow meter	Vandalism/theft of onsite equipment
Off-line reservoirs	Failure of automatic operation in automatic operation		Failure of communication systems
			Failure of power supply
	Untrained or inexperienced operators error in manual operation		Poor installation and maintenance
	Poor maintenance activities	Nyrpic module	Poor installation and maintenance
Pump station	Power outage		Vandalism
	Poor maintenance		
	Equipment aging	Moveable Gates	Inaccurate calibration
			Untrained operators error
			Poor maintenance
Drop and chute	Poor maintenance		Inaccurate calibration
	Poorly designed and executed structures	CHO	Inaccurate calibration
	Poor operation of the stilling basin		Untrained operators error
	Failure of protection structures		Vandalism
Intersection structure	Unexpected event		Poor installation and maintenance
	Waterlogging due to failure of trash rack	Reservoir	Flood
	Poor maintenance activities		Drought
	Poorly designed and executed structures		Poor performance
Hydro-mechanical structure	Vandalism/theft of onsite equipment	River	Drought
	Inaccurate calibration		Water inflow fluctuation
	Equipment aging		Sediment
	Poor maintenance activities		Flood
Undershot gates	Inaccurate calibration	Well	Drought
	Poor maintenance activities		Power outage and pump failure
	Untrained or inexperienced operators error		Poor maintenance
	Vandalism/theft of onsite equipment		

Table 2
Fuzzy rating scale (Lima Junior et al., 2014).

Linguistic variables	Very low	Low	Medium	high	Very high
Fuzzy numbers	(0, 0, 0.25)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.75, 1, 1)

Threatening hazards are identified with respect to presented hierarchical structure, based on independent librarian studies and a couple of field visits as well. Moreover, an expert-based system was used in different parts of the study area, so that expert opinion and judgments are taken into account. To deal with the uncertainty in the expert's perspectives, risk calculation was carried out based on fuzzy numbers. Accordingly, from the results of the risk assessment, critical hazards and components are identified allowing the introduction of appropriate actions for preventing any probable failures. The second part of the study focused on risk management scenarios considering the results obtained from the risk assessment. Moreover, expert's perspectives were collected via a questionnaire. Finally, the proposed scenarios were prioritized employing a multi-criteria decision-making method, considering the preference criteria.

As far as the authors are aware, this study for the first time presents a risk assessment of the conveyance and delivery system of the irrigation district through the fuzzy hierarchical method. The main objective of the study is to rectify the conventional performance appraisal methods by presenting an expert-based model. The results of the study provide a set of practical solutions for local authorities within a risk management framework.

2. Materials and methods

This study aims to present a comprehensive framework for risk management, consisting of “risk assessment” and a “risk-based decision-making framework,” within the canal networks. Fig. 1 presents the relationship between the components of the entire process and provides a general overview of the risk management process.

2.1. Risk assessment model

The steps required to be carried out to accomplish the risk assessment are described in the following sections.

2.1.1. Step 1: developing a hierarchal structure of a canal network

To accomplish a practical assessment for such an extensive system, a wide range of details should be considered for every subsystem. Conducting hierarchical structures is a standard way that makes it possible to have a thorough evaluation. This method breaks down the system into components and subcomponents, and then, the risk will be assessed through the hierarchical relationship from the lowest level to the highest one. Fig. 2 presents a comprehensive hierarchical framework for an irrigation canal network including a broad range of operational and management structures. Irrigation districts can be grouped into major components of the supply system and the conveyance and delivery systems. The former includes water resources (i.e., reservoir, river, and well) and the latter includes structures employed in the water conveyance and delivery process.

2.1.2. Step 2: hazard identification

The second step in the risk assessment model is the identification of the hazards affecting components and sub-components of the canal network. This part is a crucial step and requires enough knowledge and experience about the structures and their performances. There are two ways to identify threatening hazards. The first method is based on screening the hazards which have been reported by the canal authorities. Reliability and validity of the reported hazards are highly dependent on the existence of an authentic data set within the irrigation district. Natural hazards such as flood and drought events can be identified through this method. The second approach is employed when the data set is out of date, or no reliable information is found within the district. In such cases, hazards can be identified via a survey throughout the district and through interviews with the managers, experts, and skilled operators working in the district. This study employs the latter approach since a reliable dataset cannot be found in most of the irrigation districts. Table 1 shows the identified hazards according to the hierarchical framework. Steps 1 and 2 are included in panel A in Fig. 1.

2.1.3. Step 3: risk parameter calculation

Regarding the identified treating hazard (Table 1), risk values for every hazard relating to each component are calculated. The risk consists of probability, consequence, and vulnerability (Torres et al., 2009) and these parameters are separately calculated based on the opinion of experts. This step refers to panel B in Fig. 1.

2.1.4. Probability

Probability is the frequency of the hazard and is determined according to the existing recorded data or the expert's judgment. Due to a lack of recorded data in most of the irrigation districts, the probability should be defined in terms of the fuzzy linguistic variable by the experts. This study applies the fuzzy membership values, extracted from the proposed fuzzy linguistic variable proposed by Lima Junior et al. (2014) depicted in Table 2.

The opinion and perspectives of the experts, managers, and operators collected from questionnaires and debate sessions do not follow a particular probabilistic distribution. Accordingly, the fuzzy linear membership function, consisting of trapezoidal and triangular functions, is employed in this situation. Since the source of the uncertainties is related to just a single number declared by the experts, and not an interval, the triangular membership function is proposed for this case (Ross, 2009).

Table 3
Consequence evaluation criteria.

Criteria	Sign	Definition
Adequacy	C (1)	The amount of water shortage when the hazard occurs
Equity	C (2)	The spatial nonuniformity due to hazard occurrence
Efficiency	C (3)	The amount of excess water derived from a supply source
Economic losses	C (4)	the amount of investment to recover the system and also estimate losses due to a service level reduction
Functional importance	C (5)	In the case of occurring the hazard how much performance of the canal system is influenced.

Table 4
Vulnerability evaluation criteria.

Criteria		Definition
Structural vulnerability	V (1)	Vulnerability refers to duty and roles that each structure has in the canal system
The recovery capability	V (2)	Assess the anticipation of enough means and management instrument to recover the system in a short time
Access possibility	V (3)	Investigate the degree of being exposed to the dangers and easy access
Flexibility	V (4)	The system adaption capability against the hazards and changes
Monitoring instrument	V (5)	Assesses the tool of recognition and prevention of hazards

Table 5
Risk calculation order.

Calculation order	Hierarchy level	Input	$R\sim_{output}$
1	Component	Hazards risk ($R\sim_H$)	Components risk ($R\sim_c$)
2	Structures	Components risk ($R\sim_c$)	Structures risk ($R\sim_{st}$)
3	Systems	Structures risk ($R\sim_{st}$)	Main systems risk ($R\sim_s$)
4	Total risk	Main systems risk ($R\sim_s$)	Total risk ($R\sim_t$)

2.1.5. Consequence

The consequence is an estimation of adverse effects of each hazard which may occur in a system (Roozbahani et al., 2013). In this study, the negative consequence of hazards is determined by a combination of five criteria, evaluating the consequences from different aspects. One of the controversial issues in this regard is defining the weight of the selected criteria. Since the criteria have different importance, Elsawah et al. (2016) proposed using the advantages of the fuzzy pair-wise comparison of the weights. Accordingly, the criteria are then scored with respect to a five-point scale of linguistic values, presented in Table 2. Finally, the result of the five criteria is aggregated by a fuzzy simple additive weighting approach (FSAW) and the final value of the consequences is obtained. The consequence assessment criteria are explained in Table 3.

2.1.6. Vulnerability

The vulnerability is defined as a property associated with a component of the system to reduce the possibility of being influenced by hazards with given likelihood and consequence. Similar to consequence assessment, to determine the vulnerability, five criteria are used. These criteria are then scored by experts according to linguistic variables, and pair-wise comparison calculates the weight of the criteria. Finally, overall vulnerability is determined by applying the FSAW method. The vulnerability assessment criteria applied in this study are given in Table 4.

2.1.7. Step 4: risk calculation

This step consists of a set of separate calculations regarding the "risk of the hazard" and the "risk of the components" as described below (see panel D in Fig. 1).

2.1.8. Risk calculation in hazard level

To achieve this objective, risk parameters (p, c, and v) for every hazard, computed in the previous step of the risk assessment model, are multiplied by each other and the fuzzy risk of each hazard is obtained (Torres et al., 2009).

$$R\sim_H = P\sim_H \times C\sim_H \times V\sim_H \qquad {}_{;H=1,\ldots,H} \tag{1}$$

where $R\sim$ is the calculated risk in the fuzzy term, $P\sim$ is the fuzzy probability, $C\sim$ is the fuzzy consequence, $v\sim$ is the fuzzy vulnerability and H is a counter of hazards.

2.1.9. Risk calculation in the hierarchical framework

To calculate risk in a hierarchical framework, the hierarchical relationship is the primary guideline. According to the hierarchical framework, the risk of the upper stage is determined by a combination of calculated risk in each stage. For instance, the risk to the irrigation canal network, at the top most level, results from aggregation of the calculated risk in the supply system, conveyance, and the delivery system.

Table 6
Membership function with 10% increase in overlap area.

Linguistic variables	Very low	Low	Medium	High	Very high
Fuzzy numbers	(0, 0, 0.262)	(0, 0.25, 0.512)	(0.238, 0.5, 0.762)	(0.488, 0.75, 1)	(0.738, 1, 1)

Table 7
Membership function with 10% decrease in overlap area.

Linguistic variables	Very low	Low	Medium	High	Very high
Fuzzy numbers	(0, 0, 0.238)	(0.012, 0.25, 0.488)	(0.262, 0.5, 0.738)	(0.512, 0.75, 0.988)	(0.762, 1, 1)

The risk aggregations are carried out according to Eq. (2). This process starts from a hazard level at the lowest level in the hierarchical framework and continues to component, structure and system level. In Eq. (2), f (.) refers to a fuzzy simple additive weighting approach which is chosen as an aggregation method and R∼ is the calculated risk. The order of risk calculation is presented in Table 5.

$$\tilde{R}_{\text{output}} = \text{f (input)} \tag{2}$$

2.2. Risk-based decision making

To provide a practical vision from the risk assessment results, risk-based decision making is performed. To achieve this, with a focus on one or more hazards, a few management scenarios are defined by the experts. To determine the management scenario, the most critical hazards affecting the total risk should be identified. Risk management procedures consist of three steps of hazard effect determination, assigning the scenarios, and ranking of the scenarios.

2.2.1. Step 1: hazard effects determination

To have an effective risk management, hazards with the most effect on total risk should be addressed. Accordingly, to determine the most significant hazards, the relative change in total risk is calculated assuming that the risk of hazard will decrease to zero. The reduction of total risk is defined according to Eq. (3):

$$\text{risk reduction} = \frac{\text{total risk (by consideration of hazard(i))} - \text{total risk (by eliminating the risk of hazard(i))}}{\text{total risk (by consideration of hazard(i))}} \tag{3}$$

2.2.2. Step 2: scenarios assignment

In the second phase, management scenarios which are capable of reducing the total risk should be addressed. The scenarios are assigned concerning the results from Step 1 and the perspectives of the expert. Each of the scenarios is focused on reduction of the risk of one or two hazards as the target hazards, while other hazards are affected indirectly. This step is shown in panel E from Fig. 1.

2.2.3. Step 3: scenarios ranking

Due to current limitations, the difference in the preferences of decision makers and the variety of stakeholders and their expectation, decision making is challenging and multi-dimensional. In this stage, multi-criteria decision making (MCDM) is a proper solution in which the

Table 8
Scale of relative importance used in the pairwise comparison matrix.

Preferences	Numerical value	Triangular fuzzy preferences
Absolutely important	9	(8, 9, 9)
Very strongly important	7	(6, 7, 8)
Strongly important	5	(4, 5, 6)
Weekly important	3	(2, 3, 4)
Equally important	1	(1, 1, 2)
Intermediate value	$\theta = 2, 4, 6, 8$	$(\theta - 1, \theta, \theta + 1)$

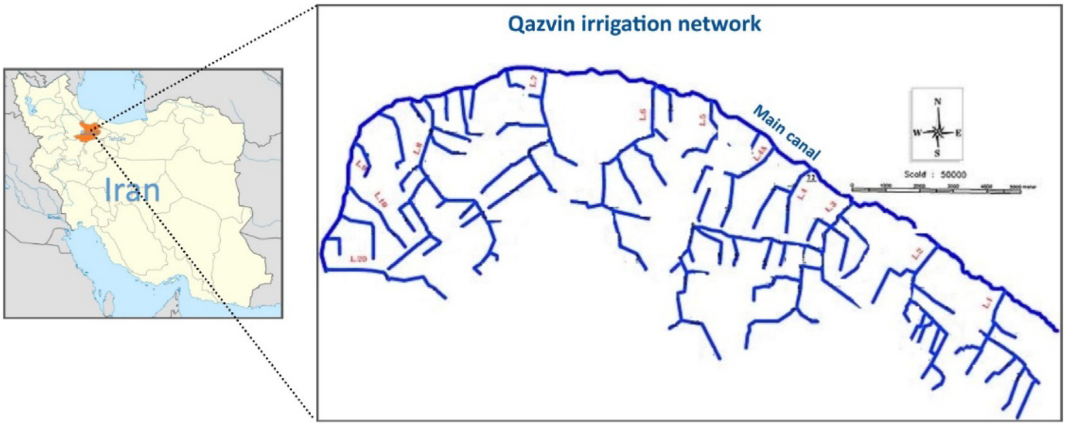


Fig. 3. Geographic location of Qazvin irrigation network in Iran.

best scenario is presented systematically. Every MCDM method includes four requirements: (1) selection of the alternatives, (2) selection of the criteria, (3) selection of the weighting methods to represent the importance of the criteria, and (4) decision making methods.

The description of alternatives is presented in Section 2.2.2 and to avoid redundancy further explanation is not repeated here. This step refers to panel G from Fig. 1.

2.2.4. Criteria selection

The criteria were identified based on a series of interviews with managers of irrigation districts; local authorities; canal operation professionals; researchers from agricultural research centers; and authors of other studies including (Motevallian et al., 2014; Shahdany and Roozbahani, 2016). The criteria should be measurable and encompass the significant aspects of decision-making issues such as management limitation (e.g., costs), manager's and stakeholder's expectations, and they should incorporate the alternatives. These criteria are categorized into the two classes of qualitative and quantitative. The value of the quantitative criteria is calculated according to risk assessment results after performing the scenario, and also, according to the implementation cost of the scenario. The qualitative criteria are determined based on a set of interviews with the experts, questionnaires from the stakeholders (i.e., WUA representatives and individual operators), and information collected through field surveys. It should be noted that to score the qualitative criteria, fuzzy numbers of linguistic variables (Table 2) are employed.

2.2.5. Economic criteria (A1)

The economic criteria evaluate management scenarios based on the implementation costs. Because of inflation, price differences in different parts of the irrigation network, and due to any probable imprecision in the calculation, the criterion is considered as a triangular fuzzy number with ±10% change over a calculated value as presented in Eq. (4).

$$\mathrm{Cost} = (0.9 * \theta, \theta, 1.1 * \theta) \tag{4}$$

where θ is the calculated cost.

2.2.6. Operation criteria (A2)

This criterion evaluates the ease of application for each scenario. Sufficient technical knowledge and experience regarding operational methods are essential for effective judgment of the criteria. This criterion is a quantitative one in which easy-operation scenarios obtain high scores in comparison to the difficult ones. Table 2 shows the scoring scale.

2.2.7. Social criteria (A3)

This criterion evaluates the acceptance level of the method by the beneficiaries and their satisfaction. This is a qualitative criterion. Therefore the expert's opinion is scored based on Table 2.

2.2.8. Effectiveness (A4)

This criterion evaluates the amount of risk reduction due to the application of the scenarios. The risk assessment model is performed under two managerial scenarios of the current situation, and reduction of total risk, to calculate the quantitative criterion. The hazards which will be influenced by the application of the scenarios should be determined in order to implement the model.

2.2.9. Operation time (A5)

A critical issue in conducting a management scenario is determining, based on the expert's judgments, the actual duration required to implement the scenario and to reduce the risk of the system.

2.2.10. Selection of the weighing methods

As with the risk assessment model, in this part, the advantages of FAHP are exploited.

2.2.11. MCDM method

MCDM methods include two main categories of scoring and compromising methods. The scoring method selects or evaluates an alternative according to its score. In these methods, comparisons between different attributes become possible through normalizing the scores to a fixed range (e.g. [0, 1]). A prevalent method in this category is the Simple Additive Weighting (SAW) method. This method calculates the overall score of an alternative as the weighted sum of the attribute scores (Xu and Yang, 2001; Majumder, 2015). On the other hand, the compromising

Table 9
Consequence weights and vulnerability assessment criteria.

Criteria	Weights ($W_{V_i}\sim$ and $W_{C_i}\sim$)				
Consequence	C (1) (0.118, 0.18, 0.358)	C (2) (0.102, 0.18, 0.311)	C (3) (0.044, 0.07, 0.135)	C (4) (0.102, 0.22, 0.311)	C (5) (0.205, 0.345, 0.623)
Vulnerability	V (1) (0.045, 0.07, 0.102)	V (2) (0.065, 0.10, 0.142)	V (3) (0.191, 0.3, 0.442)	V (4) (0.307, 0.535, 0.727)	V (5) (0.353, 0.54, 0.835)

Table 10
Weights of the components within the irrigation network hierarchy.

Component	Weight	Component	Weight
Main canal	(0.22, 0.304, 0.43)	Undershot gates	(0.109, 0.125, 0.145)
Drop and chute	(0.049, 0.062, 0.082)	Nyrpic module	(0.678, 0.833, 1.01)
Intersection structure	(0.452, 0.632, 0.861)	Movable gate	(0.138, 0.166, 0.207)
Hydro-mechanical structure	(0.756, 0.875, 1.009)	Reservoir	(0.678, 0.833, 1.01)
Conveyance structures	(0.55, 0.7, 0.879)	Well	(0.138, 0.166, 0.207)
Delivery structure	(0.048, 0.058, 0.073)	Regulation structures	(0.192, 0.239, 0.304)
Supply system	(0.414, 0.5, 0.828)	Conveyance system	(0.414, 0.5, 0.828)

method selects an alternative that is closest to the ideal solution. The TOPSIS method belongs to this category. This method first normalizes the decision matrix of an MCDM problem. Then based on the normalized decision matrix, it calculates the weighted distances of each alternative from an ideal solution (Hwang and Yoon, 1981). In order to have robust decision making and to represent certain scenarios, two well-known methods from the distinct category are selected to prioritize the scenarios. Additionally, the application of more than one MCDM method has been described in previous studies (Önüt and Soner, 2008; Lima Junior et al., 2014; Mulliner et al., 2016; Shahdany and Roozbahani, 2016). The calculation formula for the MCDM methods is presented in Section 2.4.

2.3. Risk management sensitivity analysis

A sensitivity analysis was conducted to investigate the impact of linguistic values (Table 2), implemented to score the variables used in the risk assessment and MCDM models. Similar to Shakeri and Nazif (2016) in this study, the interval of the triangular membership function is kept fixed and equal to one while the overlap area of every two fuzzy membership functions changes by ±10%. Next, the change in the calculated risk, and in the prioritization of risk management scenarios, was examined. The membership function with an increase in the overlap area is presented in Table 6. Table 7 presents the membership function with a decrease in the overlap area.

2.4. Mathematical methods

This section discusses the mathematical basis of the methods employed and refers to panel F in Fig. 1.

2.4.1. TOPSIS

The fuzzy TOPSIS method was developed by Chen (2000) to solve multi-criteria decision-making problems under uncertainty (Wang and Chang, 2007; Shukla et al., 2014).

Table 11
The result of risk parameter calculation.

Component	Hazards	Probability	Vulnerability	Consequence
Main canal and in-line structures	Poorly design of canal reaches	(0.25, 0.5, 0.75)	(0.153, 0.418, 1.133)	(0.213, 0.626, 1.517)
	Seepage	(0.75, 1, 1)	(0.518, 1.217, 1.811)	(0.154, 0.518, 1.339)
	Poorly execution of canal reaches	(0, 0.25, 0.5)	(0.153, 0.418, 1.133)	(0.213, 0.626, 1.517)
	Poor maintenance activities	(0.75, 1, 1)	(0.582, 1.302, 2.250)	(0.261, 0.719, 1.585)
	Water theft	(0.5, 0.75, 1)[*]	(0.672, 1.441, 2.174)[**]	(0.154, 0.518, 1.339)[***]
	Filling the canal capacity by sandstorm and wind erosion	(0, 0.25, 0.5)	(0.263, 0.627, 1.24)	(0.161, 0.537, 1.339)
Drop and chute	Poor maintenance	(0.25, 0.5, 0.75)	(0.193, 0.602, 1.468)	(0.051, 0.167, 1.339)
	Poorly designed and executed structures	(0, 0.25, 0.5)	(0.243, 0.679, 1.555)	(0.025, 0.111, 0.591)
	Poor operation of the stilling basin	(0.75, 1, 1)	(0.034, 0.361, 1.065)	(0.261, 0.719, 1.585)
	Failure of protection structures	(0, 0, 0.25)	(0.116, 0.351, 1.102)	(0, 0, 0.435)
Intersection structure	Unexpected event	(0.75, 1, 1)	(0.322, 0.926, 1.696)	(0.345, 0.854, 1.595)
	Waterlogging due to failure of Trash Rack	(0.25, 0.5, 0.75)	(0.491, 1.105, 1.918)	(0.312, 0.794, 1.741)
	Poor maintenance activities	(0.5, 0.75, 1)	(0.634, 1.401, 2.250)	(0.312, 0.794, 1.741)
	Poorly designed and executed structures	(0, 0.25, 0.5)	(0.176, 0.477, 1.220)	(0.051, 0.291, 0.847)
Hydro-mechanical structure	Vandalism. Theft of onsite equipment	(0.75, 1, 1)	(0.443, 0.899, 1.220)	(0.287, 0.75, 1.741)
	Inaccurate calibration	(0.5, 0.75, 1)	(0.022, 0.210, 0.883)	(0.287, 0.75, 1.741)
	Equipment aging	(0.5, 0.75, 1)	(0.039, 0.235, 0.919)	(0.025, 0.305, 0.948)
	Poor maintenance activities	(0.5, 0.75, 1)	(0.320, 0.795, 0.320)	(0.287, 0.75, 1.741)
Undershot Gates	Inaccurate calibration	(0.5, 0.75, 1)	(0.225, 0.553, 1.291)	(0.430, 1, 1.741)
	Equipment aging	(0.25, 0.5, 0.75)	(0, 0, 0.258)	(0, 0.25, 0.870)
	Poor maintenance activities	(0.75, 1, 1)	(0.302, 0.768, 1.660)	(0.430, 1, 1.741)
	Inaccurate calibration	(0, 0, 0.25)	(0.602, 1.334, 2.215)	(0.077, 0.222, 0.669)
Nyrpic module	Poor installation and maintenance	(0.25, 0.5, 0.75)	(0.212, 0.591, 1.406)	(0.287, 0.75, 1.741)
	Vandalism	(0.75, 1, 1)	(0.494, 1.185, 2.104,)	(0.430, 1, 1.741)
	Inaccurate calibration	(0.5, 0.75, 1)	1.144, 0.426, 0.153	(0, 0.25, 0.87)
Moveable Gates	Inaccurate calibration	(0.75, 1, 1)	(0.530, 1.163, 1.847)	(0.287, 0.75, 1.741)
	Untrained operators error	(0.75, 1, 1)	(0.530, 1.171, 1.833)	(0.430, 1, 1.741)
	Vandalism	(0.5, 0.75, 1)	(0.443, 0.924, 1.633)	(0.025, 0.305, 0.948)
	Poor installation and maintenance	(0, 0, 0.25)	(0.964, 1.535, 2.250)	(0, 0.055, 0.513)
Reservoir	Flood	(0.25, 0.5, 0.75)	(0.397, 0.929, 1.626)	(0.022, 0.287, 0.938)
	Drought	(0.5, 0.75, 1)	(0.496, 1.095, 1.770)	(0.397, 0.944, 1.673)
	Poor performance	(0, 0.25, 0.5)	(0.316, 0.819, 1.551)	(0.077, 0.376, 1.105)
Well	Drought	(0.5, 0.75, 1)	(0.551, 1.274, 2.128)	(0.183, 0.567, 1.427)
	Power outage and pump failure	(0.75, 1, 1)	(0.502, 1.105, 1.918)	(0.264, 0.712, 1.673)
	Poor maintenance	(0, 0, 0.25)	(0.143, 0.411, 1.110)	(0.264, 0.712, 1.673)

[*] $p = (5,0.75,1)$ obtained directly from the questionnaire.

[**] $V = \sum V_i \otimes W_{V_i} = (0.0.75,1,1) \otimes (0.191,0.296,0.442) + (0.0.75,1,1) \otimes (0.353,0.535,0.835) + (0,5.75,1) \otimes (0.065,0.1,0.142) + (0,0,0.25) \otimes (0.045,0.068,0.102) + (0.0.75,1,1) \otimes (0.307,0.535,0.727) = (0.672,1.441,2.174)$

[***] $C = \sum C_i \otimes W_{C_i} = (0.25,0.5,0.75) \otimes (0.118,0.178,0.358) + (0.25,0.5,0.75) \otimes (0.102,0.178,0.311) + (0.5,0.75,1) \otimes (0.044,0.074,0.135) + (0.25,0.5,0.75) \otimes (0.102,0.222,0.311) + (0.25,0.5,0.75) \otimes (0.205,0.345,0.623) \; = (0.1534,0.518,1.339$

Table 12
Calculated risk of threatening hazards in the supply system.

Subcomponent	Hazards	Fuzzy risk	De-fuzzified	Sub-component	Hazards	Fuzzy risk	De-fuzzified
Well	Drought	(0.051, 0.543, 3.0393)	1.211	Reservoir	Flood	(0.002, 0.133, 1.145)	0.427
	Power outage and pump failure	(0, 0, 0.464)	0.155		Drought	(0.099, 0.776,2.963)	1.297
	Poor maintenance	(0.461, 0.649, 0.891)	0.667		Poor performance	(0, 0.077, 0.858)	0.312
	Aggregated risk of hazards (well)	(0.127, 0.534, 2.311)	0.99		Aggregated risk (reservoir)	(0.052, 0.578, 3.191)	1.274

This method comprises the following steps:

(I.) Normalize the fuzzy decision matrix by the linear-scale transformation (Chen, 2000). The normalized fuzzy decision matrix (R) is obtained as expressed by Eqs. (5) to (9)

$$\tilde{R} = \left[\widetilde{r_{i,j}}\right] \text{ and } \widetilde{x_{i,j}} = \left(l_{i,j}, m_{i,j}, u_{i,j}\right) \tag{5}$$

$$r_{i,j}\sim = \left(\frac{l_{i,j}}{u_j^+}, \frac{m_{i,j}}{u_j^+}, \frac{u_{i,j}}{u_j^+}\right) \text{ and } u_j^+ = max_i u_{i,j}(\text{benefit criteria}) \tag{6}$$

$$r_{i,j}\sim = \left(\frac{l_j^-}{u_{i,j}}, \frac{l_j^-}{m_{i,j}}, \frac{l_j^-}{l_{i,j}}\right) \text{ and } l_j^- = min_i l_{i,j}(\text{cost criteria}) \tag{7}$$

(II.) Compute the weighted normalized decision matrix. The weighted normalized decision matrix is computed by multiplying the significant weight of the evaluation criteria in the normalized fuzzy decision matrix.

(III.) Determine the fuzzy positive ideal solution (FPIS, A^+) and fuzzy negative ideal solution (FNIS, A^-)

(IV.) Compute the distance of each alternative from FPIS (d_i^+) and FNIS (d_i^-) according to Eqs. (8) and (9)

$$d_i^+ = \sum_{j=1}^{n} d_v\left(v\sim_{ij}, v_j^+\right) \tag{8}$$

$$d_i^- = \sum_{j=1}^{n} d_v\left(v\sim_{ij}, v_j^-\right) \tag{9}$$

where $d(x\sim, z\sim)$ is the distance between fuzzy numbers.

(V.) Calculate the closeness coefficient for each alternative (CC_i) as expressed in Eq. (10):

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{10}$$

(VI.) Rank the alternatives according to their closeness coefficient.

2.4.2. Fuzzy simple additive weighting (FSAW)

Due to simplicity and practicality, simple additive weighting (SAW) is the most popular method of classical MADM (Modarres and Sadi-Nezhad, 2005). In this study SAW is used in determining the vulnerability, consequence, management scenario scores and also risk aggregating. The calculation formula is expressed as follows:

$$U\sim_i = \sum_{j=1}^{n} W_j\sim r_{ij}\sim\sim \tag{11}$$

where $W_j\sim$ is the fuzzy weight of each criteria in the consequence, vulnerability and scenario score determination, or the weights of the hazards/sub-component/component in the risk aggregation. $r_{ij}\sim$ is the score of the i^{th} alternative in the j^{th} criterion.

2.4.3. Weighting approach

In this study, all required weights are determined by pairwise comparison according to the method presented by Saaty (1990). The weighting process consists of three steps: at the first step, experts are asked to conduct a pair-wise comparison by using the numeric value of their preference as shown in Table 8, and a judgment matrix is constructed.

Table 13
Calculated risk of threatening hazards in the conveyance structure.

Conveyance structures	hazards	Fuzzy risk	De-fuzzified	Transmission structures	Hazards	Fuzzy risk	De-fuzzified
Main canal	Poorly design of canal reaches	(0, 0.036, 0.501)	0.179	Drop and chute	Poor maintenance	(0.002, 0.50, 0.737)	0.263
	Poorly execution of canal reaches	(0, 0.066, 0.806)	0.309		Poorly designed and executed structures	(0, 0.019, 0.460)	0.016
	Seepage	(0.082, 0.799, 3.031)	1.304		Poor operation of the stilling basin	(0.007, 0.260, 1.856)	0.707
	Poor maintenance activities	(0.166, 1.189, 3.919)	1.758		Failure of protection structures	(0, 0, 0.120)	0.04
	*Water theft	(0.052, 0.5604, 2.913)	1.175		Aggregated risk (drop)	(0.003, 1.72, 1.868)	0.681
	Filling the canal capacity by sand storm and wind erosion	(0, 0.0842, 0.845)	0.31	Intersection structure	Unexpected event	(0.084, 0.792, 2.707)	1.194
	Aggregated risk (main canal)	(0.060, 0.7588, 4.215)	1.678		Waterlogging due to failure of trash rack	(0.038, 0.439, 2.506)	0.994
	* $R = P \otimes C \otimes V =$ $(5,0.75,1) \otimes (0.1534,0.518,1.339) \otimes (0.672,1.441,2.174)$ $=(0.052,0.560,2.913)$				Poor maintenance activities	(0.099, 0.835, 3.919)	1.618
					Poorly designed and executed structures	(0, 0.035, 0.517)	0.184
					Aggregated risk (intersection)	(0.055, 0.531, 2.522)	1.036

Table 14
Calculated risk of threatening hazards in regulation structures.

Regulation structures	Hazards	Fuzzy risk	De-fuzzified	Regulation structures	Hazards	Fuzzy risk	De-fuzzified
Hydromechanical structure	Vandalism/theft of onsite equipment	(0.095, 0.675, 2.783)	1.184	Undershot gates	Inaccurate calibration	(0.049, 0.415, 2.249)	0.904
	Inaccurate calibration	(0.003, 0.118, 1.539)	0.554		Poor maintenance	(0, 0, 0.169)	0.056
	Equipment aging	(0.001, 0.054, 0.872)	0.309		Untrained or inexperienced operators error	(0.098, 0.769, 2.891)	1.253
	Poor maintenance activities	(0.046, 0.447, 2.707)	1.607		Vandalism/theft of onsite equipment	(0, 0, 0.371)	0.124
	Aggregated risk (hydro-mechanical)	(0.034, 0.467, 3.989)	1.497		Aggregated risk (undershot gates)	(0.041, 0.485, 3.291)	1.2272

Table 15
Calculated risk of threatening hazards in delivery structures.

Delivery structures	Hazards	Fuzzy risk	De-fuzzified	Delivery structures	Hazards	Fuzzy risk	De-fuzzified
Movable gate	Vandalism	(0.006, 0.212, 1.550)	0.589	Nyrpic module	Poor maintenance	(0.15, 0.222, 1.837)	0.691
	Inaccurate calibration	(0, 0.223, 1.608)	0.614		Inaccurate calibration	(0, 0.080, 0.996)	0.359
	Untrained or inexperienced operators error	(0.173, 1.172, 3.279)	1.541		Vandalism	(0.213, 1.186, 2.748)	1.382
	Poor maintenance	(0, 0.021, 0.578)	0.200				
	Aggregated risk	(0.072, 0.763, 3.518)	1.451		Aggregated risk	(3.143, 0.860, 0.115)	1.382

At the second step, the inconsistency of each matrix should be checked. If the inconsistency rate is less than 0.1, the matrix inconsistency is acceptable; otherwise, the experts should revise their response (Shakeri and Nazif, 2016).

In the last step, each value given by the experts is replaced by the corresponding fuzzy number presented in Table 5 and the fuzzy weight values are calculated as follows (Buckley, 1985):

$$\forall \widetilde{A_{ij}} = a_{ij}, b_{ij}, c_{ij} \Rightarrow \tilde{w}_i = \left[\frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n} c_{ij}^{t}}, \frac{\left(\prod_{j=1}^{n} b_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n} b_{ij}^{t}}, \frac{\left(\prod_{j=1}^{n} c_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n} a_{ij}^{t}} \right] \tag{12}$$

where n is the pare-wise matrix dimension, $A_{ij}\sim=(a_{ij}, b_{ij}, c_{ij})$ is the matrix element, and i and j are counters of the matrix rows and columns, respectively.

2.4.4. Defuzzification

The final value for the risk or alternatives scores in the SAW method is in fuzzy form, to simplify the analysis, this should converted to a crisp value.

The centroid of the area is applied in this study as the defuzzification method. This approach is explained as follows (Opricovic and Tzeng, 2003):

$$z = \frac{\int_z \mu_A(z) z dz}{\int_z \mu_A(z) dz} \tag{13}$$

Table 16
Calculated risk of structures in the conveyance system.

System	Structure	Fuzzy	De-fuzzified
Conveyance system	Conveyance structures	(0.036, 0.827, 3.979)	1.614
	Regulation structures	(0.030, 0.47, 4.505)	1.668
	Delivery structure	(0.088, 0.869, 3.927)	1.628

where z is the fuzzified value of fuzzy number A, and $\mu_A(z)$ is the fuzzy membership degree of z.

2.5. Case study

The Qazvin irrigation districts, shown in Fig. 3, are located in the central part of Iran, and have been selected to implement the proposed framework in this study of risk assessment for irrigation canal networks. Additionally, in order to suggest a set of practical management scenarios for the canal authorities, risk-based decision making is conducted on results obtained from the risk assessment. Qazvin irrigation district has one of the most extensive canal networks, encompassing an area of about 80,000 ha, which includes a broad range of structures with a long history of operation and maintenance activities. The district has a 94 km main canal which passes through Qazvin city, the suburb regions, rural areas and the industrial parks where a different set of controversial issues due to the social, environmental, managerial and operational concerns have been raised (Tehrani et al., 2012). Taleghan Dam is located at the upstream part of the district, and wells which are scattered over the district supply water for the canal networks. The current scheduling of irrigation water follows a rotational approach where the discharge delivered to each farm, the duration, and the irrigation frequency is fixed. The canal operational system follows upstream control, including manual control of the off-take structures, and employing the hydrodynamic gates for manipulating the water level regulating structures. Seepage and operational losses are two primary sources of the water losses through the conveyance and delivery systems. Unreliable and imprecise operational activities have led to inadequate performance of the canal system in surface water operation; spatial non-uniformity and unfair water distribution between the upstream and downstream users. Consequently, extra water is delivered at the upstream off-takes leading to drainage problems and imposing labor costs on the farmers. On the other hand, the farmers located at the middle and tail end of the canal, suffer from insufficient water delivery. Therefore, these farmers supply their water demands via extracting groundwater from numerous semi-deep and deep tube-wells resulting in the consumption of more energy and increased CO_2 emission.

Table 17
Impact of the most effective hazards on the irrigation network's total risk.

Risk	Impact (%)	Risk	Impact (%)
Drought (reservoir)	31.76	Unexpected event (intersection)	5.7
Poor maintenance (intersection)	9.4	Water theft (canal)	5.02
Vandalism (hydromechanical)	7.2	Waterlogging (intersection structure)	4.9
Seepage	6.3	Poor maintenance (hydromechanical)	4.02
Poor maintenance (canal)	6.2	Drought (well)	3.5

Table 18
Presented risk management scenarios.

Management scenario	Actions	Target hazard	Indirect hazard	Reference
Passive control (S1)	Increase water efficiency by Improving manual operation due to increase in number of operators and application of mobile control	Drought	–	(Shahdany and Roozbahani, 2016)
local control (S2)	Crease water efficiency by application of onsite regulator equipment and elimination of manual adjustment	Drought	Seepage, water theft, unexpected event	(Isapoor et al., 2011)
Centralized control (S3)	Develop a supervisory control method and making structure adjustment from a central location which leads to water use efficiency	Drought	Seepage, water theft, unexpected event	(Hashemy et al., 2013; Fele et al., 2014)
Maintenance improvement (S4)	Codify of short-term and seasonal maintenance priority, receive regular deficit report from operator and farmers, Periodic calibration of structures, create a database and collect maintenance, deficit reports for each of structure.	Poor maintenance	Seepage, inaccurate calibration (all structures)	This study
Establish a disaster management guideline and improve safety equipment (S5)	Improving crisis management guideline and specifying the tasks in in time of crisis, installing warning sign and legal notice, Installing rescue equipment like a floating rope and net and also animal escape stairs, Access limitation to regulating structures by installing fence	Unexpected event	Vandalism, water theft	This study
Vest inspection right (S6)	This scenario aims to incorporate farmers in management procedure by vesting inspection right to the delegate of farmers	Water theft	Vandalism	This study

Another obstacle faced by the canal authorities is a lack of maintenance guidelines and a reliable database containing records of the maintenance activities. These deficits are leading to deterioration of operational conditions and disorder in annual maintenance where the overall trend in operational efficiency has decreased from 1991 to 2016 despite a significant rise in maintenance cost (Vaez Tehrani et al., 2013).

3. Results and discussion

3.1. Weighting result

To calculate risk in the hierarchical structure, a pairwise comparison was accomplished, according to the formula presented in Section 2.4.3, using the following three steps: (1) weighting of the consequence and vulnerability assessment criteria, (2) weighting of the threatening hazards, (3) weighting of the components of the irrigation network hierarchy. The results of Steps 1 to 3 are presented in Table 9 and Table 10.

3.2. Risk assessment of the Qazvin canal networks

The obtained result from the risk assessment model is presented in four main parts including risk parameter calculation, risk assessment in the supply system, risk assessment in the conveyance and delivery system, and finally, total risk assessment.

3.2.1. Risk parameters

According to the presented framework in Step 3, Section 2.4.1, the initial step in the risk calculation process is the calculation of risk parameters for each hazard. To this end, the results of the risk parameters calculation are presented in Table 11.

3.2.2. Supply system

According to the results of the hierarchical risk assessment model, given in Table 12, among threatening hazards in the well and reservoir (the water supply resources), "drought" with de-fuzzified values of 1.21 and 1.297, respectively in both component, is the highest risk for the water resources in terms of hazard level. Moreover, in between the well and reservoir, the reservoir is assigned as the most critical subcomponent according to the aggregated risk value of 1.274 and the failure risk of the reservoir is 28% greater than the well.

3.2.3. Conveyance and delivery system

According to a hierarchical structure, Fig. 2, the conveyance and delivery structures, consists of three main groups of structures, where risk

Table 19
Pairwise comparison matrix of the evaluation criteria.

	A1	A2	A3	A4	A5
A1	(111)	(4.34 5.35 6.36)	(2.49 3.52 4.54)	(0.46 0.56 0.76)	(2.85 3.94 4.98)
A2	(0.16 0.19 0.23)	(111)	(0.33 0.42 0.55)	(0.17 0.2 0.25)	(0.87 1.15 1.43)
A3	(0.22 0.28 0.4)	(1.81 2.39 3.03)	(111)	(0.39 0.51 0.72)	(1.84 2.37 2.93)
A4	(1.32 1.78 2.17)	(4 5 6)	(1.4 1.97 2.56)	(111)	(4.1 5.16 6.21)
A5	(0.2 0.25 0.35)	(0.7 0.87 1.15)	(0.37 0.42 0.54)	(0.16 0.19 0.24)	(111)

Table 20
Weight of the assessment criteria.

Criteria	A1	A2	A3	A4	A5
Fuzzy weight	(0.22 0.33 0.49)	(0.05 0.07 0.1)	(0.1 0.15 0.23)	(0.1 0.15 0.23)	(0.05 0.07 0.11)

Table 22
Closeness coefficients.

Scenario	S1	S2	S3	S4	S5	S6
CC_i	0.168	0.185	0.194	0.237	0.177	0.167
Ranking	5	3	2	1	4	6

assessment results of each group are illustrated in the following sections.

3.2.4. Conveyance structure

The result of the risk assessment model for this section is presented in Table 13. According to the results, within the main canal as the primary structure, hazards of "poor maintenance activity" and "seepage from the canal" get the highest risk. Additionally, the risk assessment model reveals that for the other structures, "Poor Operation of the Stilling Basin" and "Poor maintenance activities" have the highest risks, respectively, for the drop and chute structures, and the intersection structures. Moreover, the aggregated risk value presents the main canal as the riskiest structure with a de-fuzzified value of 1.678, where the intersection structures and drops and chutes have been placed in the next ranks.

3.2.5. Regulating structure

The risk assessment results within the regulation structures, as shown in Table 14, demonstrates that in terms of hazard level, "Untrained or inexperienced operator's error", with the obtained value of 1.253, is the highest risk within the undershot gates. For the hydromechanical gates, the "vandalism" hazard with the value of 1.184 places it as the most significant risk. Aggregation of the potential for related hazards for each structure indicates that with the obtained value of 1.497, the hydromechanical gates are the riskiest structure among regulation structures of the Qazvin district. Furthermore, the undershot gates are the following risky structure with the de-fuzzified value of 1.220. The differences between the calculated risks of the regulation structures are obtained due to the weak nature of the hydromechanical structures against the human-made hazards, and the significant weight of this hazard in the hierarchical framework.

3.2.6. Delivery structures

According to the obtained results of the risk assessment within the delivery structures, which are given in Table 15, 'vandalism' and "untrained operator's mistakes" have the highest risk, respectively, for the Nyrpic module and movable gate. Comparison of the aggregated risk values indicates that the movable gate is a critical structure in this part and the risk of failure is 5% more than the Nyrpic structures. This result was obtained due to the high dependency on the operators experience and skills of the movable gates.

The final risks regarding this section (i.e., the entire conveyance, regulating and delivery structures) are aggregated in the main group with regards to the hierarchical relationship. Accordingly, as presented in Table 16, although the results are close to each other, regulating structures are recognized as more critical compared to the other structures, and their operational performance is more susceptible to failure than the other structures.

The final step in the hierarchical risk assessment model is determining separate risk values for the supply and conveyance systems and total risks of the irrigation canal network. According to the results, the risk of the conveyance system is 1.930 while the risk of the supply system is calculated as 1.449. Accordingly, performance failure of the canal networks is more probable in the conveyance system where more attention is needed. Additionally, the total risk of the Qazvin irrigation canal networks is obtained as 2.660. In the following sections, risk management action is investigated, and the results of the managerial scenarios will be compared to the total obtained risk value mentioned above. The capability of the scenarios is then assessed based on the reduction of the total risk value.

3.3. Risk-based decision making

As mentioned earlier, the risk-based decision-making process consists of three steps of determination of effective hazards, introducing the managerial scenarios, and ranking of the scenarios within MCDM approaches. The following sections present the results of each step.

3.3.1. Effective hazards determination

The hazards analysis is carried out, and the hazards with the largest impact on the total risk are determined. Concerning the obtained results 'drought' hazard in the reservoir, with 31.7% decrease in total risk is introduced as the most efficient hazard. Following drought, other hazards such as "poor maintenance" and 'vandalism' have the highest impacts. The hazards and their effects are given in Table 17. A comprehensive investigation of the hazards using the sensitivity analysis implies that the hazard, treating the performance of the Qazvin irrigation district, can be classified into three general groups. The first group refers to the hazards confronting the supply system, the second group influences the maintenance activities and the third group is the human-caused hazards.

3.3.2. Management scenarios

Concerning efficient hazard determination, six management scenarios, S1 to S6, (given in Table 18) are introduced based on discussion sessions and interviews with managers of the irrigation districts and local authorities. Each of the scenarios has at least one direct effect on a hazard, where the target hazards are determined based on the sensitivity analysis results. It should be mentioned that every scenario has indirectly influenced other hazards by affecting the probability of occurrence or consequence of the hazards. Therefore, it is noteworthy that the impact of each scenario on a particular hazard may be different.

Table 21
Fuzzy decision matrix for scenarios.

	A1($) $(\Theta - 10\%, \theta, \theta + 10\%)$	A2	A3	A4	A5
S1	(336,960,374,400,411,840)	(0.65,0.9,0.95)	(0.7,0.95,1)	(0.006,0.088,0.304)	(0.6,0.85,0.95)
S2	(343,440,381,600,419,760)	(0.3,0.55,0.8)	(0.35,0.6,0.8)	(0.011,0.165,1.229)	(0.25,0.55,0.8)
S3	(1,134,540,1,260,600,1,386,660)	(0.3,0.55,0.8)	(0.3,0.55,0.75)	(0.012,0.203,1.698)	(0.25,0.5,0.75)
S4	(33,696,37,440,41,184)	(0.35,0.55,0.7)	(0.1,0.35,0.6)	(0.006,0.114,1.492)	(0.3,0.55,0.75)
S5	(101,088,112,320,123,552)	(0.25,0.5,0.75)	(0.3,0.55,0.8)	(0.004,0.070,0.586)	(0.2,0.45,0.7)
S6	(168,480,187,200,205,920)	(0.15,0.3,0.55)	(0.2,0.4,0.65)	(0.003,0.058,0.745)	(0.2,0.45,0.7)

Table 23
Result of the FSAW approach.

Scenario	S1	S2	S3	S4	S5	S6
Fuzzy score	)0.167,0.318,0.572)	(0.089,0.235,0.791)	(0.071,0.213,0.895)	(0.234,0.454,0.1.204)	(0.121,0.266,0.670)	(0.079,0.186,0.608)
Defuzzified score	0.504	0.518	0.535	0.851	0.496	0.398
Ranking	4	3	2	1	5	6

Irrigation district managers have not been authorized to deal with water allocation from reservoirs supplying the agricultural water. Thus, the proposed scenarios focusing on drought threat have focused on increasing water efficiency. Accordingly, the first scenario (S1) aims to reduce operator errors, while S2 focuses on improving water distribution uniformity. The latter is achieved by replacing the conventional manual adjustments of the check gates with local automated structures. The third scenario (S3), upgrades the manual control with fully automatic structures manipulated by a centralized control system. The biggest advantage of this scenario is that the following are avoided: operational losses imposed by the operators; lack of a monitoring system to detect illegal withdraw throughout the canal; unreliable adjustments of the structures; and lack of continuous water level measuring within the canal reaches. Scenario S4 proposes a comprehensive maintenance guideline and prioritizes safety measures to eliminate, or at least decrease, the occurrence of unexpected events (such as humans, animals and vehicles falling into the canal) and minimizing the response time to the events via improving the recovery time. Finally, the last scenario, S6, incorporates farmer district management with the purpose of eliminating water theft and vandalism.

3.3.3. Weight of evaluation criteria

To determine the weight of the presented criteria, the pair-wise comparison is employed. Accordingly, a five number pair-wise comparison matrix is created to calculate the weight of the criteria in an aggregated matrix (w) as presented in Table 19. The calculated weights are shown in Table 20.

To complete the risk management, the MCDM approaches are employed to rank the scenarios. Two methods of fuzzy TOPSIS and SAW are used where the results are presented in following sections.

3.3.4. Scenario ranking using the MCDM method

The calculations are based on the matrix presented in Table 21. In this matrix, C1 and C4 are quantitative. However, the C2, C3, and C5 criteria are qualitative, and the presented values are the results of the aggregated opinion of five experts.

3.3.5. TOPSIS

According to the TOPSIS method, the scenario ranking is based on closeness factors. A large closeness coefficient indicates a short distance from the fuzzy positive ideal value and a considerable distance from the negative ideal value. Table 22 shows the six management scenarios by closeness coefficient. Their ascending rank is determined as follows:

$CC4 > CC3 > CC2 > CC5 > CC1 > CC6$

This means that S4 has the largest closeness coefficient value and it is the best scenario.

3.3.6. Fuzzy simple additive weighting approach (FSAW)

The second ranking method applied is the fuzzy simple additive weighting approach. The final fuzzy score, according to the decision matrix, is presented in Table 23. The de-fuzzified value of the score is the basis of the scenarios ranking, hence, the ranking order is determined as follows:

$S4 > S3 > S2 > S1 > S5 > S6$

Scenario number four, which focuses on improvement of maintenance activity, is ranked as the most important scenario regarding the different ranking methods, and also the next two scenarios (scenarios 3 and 2) have the same value in both approaches which illustrates the reliability of the decision making method.

3.4. Sensitivity analysis

According to the results, the overlap area has a direct effect on the calculated risk, with an increase in overlap area the calculated risk increases, and vice versa. The results of the sensitivity analysis for the risk assessment model are presented in Table 24. An increase in the overlap area led to an increase in the total risk of 2.1%, and a 1.02% decrease resulted from a decline in the overlap area. The potential for the supply and conveyance system increased 0.8% and 1.02%in the increased overlap case, respectively, and decreased 1.7% and 2.1% with a reduction in the overlap area. Changing overlaps in the range of 10% did not result in a significant change in the calculated risks.

The results of the MCDM models when changing the overlap area are presented in Table 25. According to the results, a change of overlap area

Table 24
The results of the risk assessment model concerning the change of overlap area.

Component	With increase of overlap area			With decrease of overlap area	
	Fuzzy risk	Defuzzified	Percentage of risk changes	Fuzzy risk	Defuzzified
Irrigation network	(0.036, 0.560, 7.248)	2.615	−2.130	(0.325, 0.560, 7.503)	2.699
Supply system	(0.055, 0.570, 3.646)	1.424	−1.772	(0.051, 0.570, 3.765)	1.462
Conveyance and delivery system	(0.032, 0.550, 5.103)	1.895	−2.182	(0.028, 0.550, 5.293)	1.957
Conveyance structure	(0.040, 0.549, 3.882)	1.490	−2.067	(0.035, 0.549, 4.028)	1.537
Regulating structures	(0.032, 0.47, 4.378)	1.627	−2.490	(0.029, 0.47, 4.556)	1.685
Delivery structure	(0.076, 0.896, 4.864)	1.945	−1.086	(0.068, 0.896, 4.968)	1.977
Nyrpic module	(0.092, 0.890, 3.947)	1.643	−1.073	(0.082, 0.890, 4.036)	1.669
Moveable gates	(0.096, 0.926, 4.091)	1.704	−0.717	(0.087, 0.926, 4.157)	1.723
Undershot gates	(0.043, 0.485, 3.219)	1.249	−1.837	(0.038, 0.485, 3.329)	1.284
Hydro-mechanical structure	(0.036, 0.467, 4.874)	1.459	−2.510	(0.032, 0.467, 4.034)	1.511
Intersection structure	(0.059,0.531,2.455)	1.015	−2.038	(0.051, 0.531, 2.550)	1.044
Drop and chute	(0.004,0.172,1.656)	0.611	−3.638	(0.003, 0.172, 1.786)	0.654
Main canal and in-line structures	(0.057,0.662,3.785)	1.501	−1.607	(0.050, 0.662, 3.908)	1.540
Well	(0.128,0.534,2.267)	0.976	−1.436	(0.126, 0.534, 2.327)	0.996
Reservoir	(0.055, 0.578, 3.121)	1.252	−1.724	(0.049, 0.578, 3.226)	1.284

Table 25
The results of the MCDM models concerning the change of overlap area.

Decision scenarios	Increase of overlap area				Decrease of overlap area			
	SAW		TOPSIS		SAW		TOPSIS	
	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking
S1	0.168	5	0.506	4	0.168	5	0.503	4
S2	0.185	3	0.514	3	0.185	3	0.510	3
S3	0.194	2	0.537	2	0.193	2	0.533	2
S4	0.237	1	0.853	1	0.237	1	0.850	1
S5	0.177	4	0.499	5	0.177	4	0.495	5
S6	0.167	6	0.397	6	0.166	6	0.394	6

has a little effect on the final score of scenarios in both MCDM models. The initial ranking for both methods was repeated and scenario 5 ranked as the best scenario.

4. Conclusion

This study aims to present an expert-oriented risk assessment model to evaluate the risk in an irrigation canal and its corresponding components. The developed model identified dangerous hazards which can lead to failure of the primary water conveyance and delivery systems. A wide range of structures and related hazards are taken into account in the model to present a general framework for employing in any irrigation district, including ones with different types of conveyance; water level regulating, and off-take structures. The risk of failure is considered as the combination of the probability of hazards; the consequence of failure; and the vulnerability of the system against the hazards. The risk was calculated according to a hierarchy relation of the subcomponents and structures. Using the uncertainties revealed by the comments and opinions of managers and experts, the risk assessment model was developed based on a fuzzy triangular membership function. Although the extensive application of such risk assessment models has been reported for the urban water systems and sewer collection systems previously, this study for the first time employed the model for risk assessment of irrigation districts.

Based on the findings of the risk assessment model in this study, “poor maintenance,” “seepage,” “unexpected event,” “drought,” and “vandalism” were found to be the riskiest hazards relating to the system's components and structures. Among the elements of the conveyance and distribution system, the regulatory structure was found to be the riskiest element.

The risk assessment model provides a decision support tool for accomplishing an integrated risk assessment which does not require complicated data gathering. The model enables canal authorities to deal with any knowledge and experience given by the local water boards and experts. The biggest advantage of employing the framework proposed in this study, rather than applying the conventional appraisal methods, is that it allows multiple perspectives to be included in the risk assessment method. This feature enables managers to maintain the system at a desirable performance level from different perspectives including technical, social, economic and environmental objectives. Moreover, the risk assessment model reduces unnecessary expenses by prioritization of problems and the solutions.

A further objective of this study refers to presenting a risk-based management policy to provide a range of practical solutions for authorities of the irrigation districts. The proposed managerial scenarios are not location-specific and are capable of being employed for any irrigation district. Scenario choice is carried out based on the output of the risk assessment model. According to the risk assessment results of this study, the hazards with the most influence on the total risk are determined and six management scenarios are defined.

Because of the multiple criteria inherent in the ranking of the scenarios, and also to increase decision-making reliability, two MCDM methods from a distinct category with different calculation bases were chosen to rank the scenarios. The management scenarios were evaluated based on five criteria including social, operational, effectiveness, operation time and economic perspectives. According to the obtained decision-making results, the first rank scenarios are those which target minimization of the operational water loss and improvement in maintenance by enhancing the canal operational systems. These scenarios propose that the canal authorities establish an integrated maintenance framework. Scenario S3 achieves the second rank in the prioritization process, proposing the application of a centralized control system for operation and maintenance. The S3 targets the drought hazard by eliminating the water losses occurring due to the operator's mistakes, and additionally, enables the monitoring of the canal path for the district managers. Moreover, employing the centralized operational systems leads to a reduction in the response time to any likely changes in future water demands. Despite the relatively high cost of implementation of these systems, which represents the main barrier to employing the method, this scenario ranked as the second most effective due to the potential for significant risk reduction. Similarly, decentralized control systems were placed at the third rank. This method proposes local control and monitoring of the system's element using classic controllers. According to the second and third ranked scenarios, it is highly recommended to take the canal automation techniques into considerations for any development plans, rehabilitation, renovations and modernization projects.

The relatively similar prioritization of the risk management scenarios obtained using the two MCDM methods, increases confidence in the decision making method. It should be noted that the presented risk management scenarios in this study are general and comprehensive enough to be proposed and applied to every irrigation district, regardless of the location and attitudes of the districts. Due to the similarity between irrigation districts in terms of physical characteristics such as conveyance, control, and water delivery structures; social issues; and economic and social preferences within the irrigation districts, the proposed managerial scenarios are not location-specific and are capable of being employed for any irrigation district.

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