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Assessment of Urban Water Supply Options by Using Fuzzy Possibilistic Theory

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Abstract

A comprehensible framework for assessing water supply risk based on existing and under-construction projects is provided. In the proposed framework, the risk factors of current and future water supply options were first investigated using the Fuzzy Delphi method. Then, according to a survey of experts, the probability of the risk for each water supply option was assessed. Markowitz's theory was used, in the form of an opportunity from the optimistic to the most pessimistic possible case of the risk pool. The results showed that the framework based on the Fuzzy Delphi and possibility theory is befitting to information gathered from experts. Such a framework can provide a simple method to apply the proposed methodology to other water management projects, where, despite the high level of investment, there is no clear idea of the risks and their consequences.

Keywords Mashhad plain · Risk · Uncertainties · Water supply · Fuzzy Markowitz theory

1 Introduction

Nowadays, as the result of the rapid growth of inharmonious demand of water in many parts of the world, in addition to water resources diminution and weak management, water resources sustainability has become a major challenge (World Economic Forum 2015). Planning for the future is not a new perspective on water resources management. The traditional stationary perspective in infrastructural planning and future decision-making, assuming a historical continuity and data integrity, cannot be efficient nowadays to respond to rapid changes. The current and future changes are usually uncertain because of incomplete awareness and lack of information. The former, due to the lack of information and understanding in a system, and the latter, due to the inherent uncertainties in human societies in every natural and artificial system

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(Khatri 2013). Decision making in water resources systems is complicated due to behavioral uncertainties of individuals, lack of information, and errors in data acquisition, among others (Maqsood et al. 2005; Luyet et al. 2012; Mollaei et al. 2017; Pourmohamad et al. 2017, 2019; McIntyre et al. 2018; Eslami et al. 2020).

There are various types of uncertainty due to unplanned incidents, and managers should be able to predict and prevent them from happening. To predict these incidents, managers should understand and identify potential hazards. When hazards with a high level of risk are identified, it is necessary to design and implement risk management programs to reduce any likely damages (prevention, preparedness, response and recovery measures) (Ghandehari et al. 2015). Risk is uncertainty, which, if occurred, would affect the project objectives. The effect of risks would result in unanticipated positive or negative deviations in the targets of the project. The relationship between origin, risk, and impact are presented in Fig. 1 (Nazari et al. 2008).

Previous studies divided risk analysis and assessment methods into two different categories: a) retrospective and prospective methods; b) black and white box analysis techniques. Retrospective methods uncover the origin of anomalous and contradictory events in the past. The main objective of these methods is to find the main cause of the incident (guilty or responsible) and try to prevent a repetition of such events (Focazio et al. 2000). Root Cause Analysis (RCA) model is a retrospective method which is recommended for complex environments. The basic approach in this model is to identify the hierarchy of events that caused the incident. Focusing on deterministic events and neglecting other probable scenarios is the main problem of this model (St. Germain et al. 2008). Prospective methods are more successful in risk evaluation and analysis than retrospective methods. Hazard Analysis and Critical Control Points (HACCP) (Davidson et al. 2005; Griffith et al. 2005; Yokoi et al. 2006; Jayaratne 2008; Dominguez-Chicas and Scrimshaw 2010), Failure Mode and Effects Analysis (FMEA) (Dominguez-Chicas and Scrimshaw 2010), and Fault Tree Analysis (FTA) (Hong et al. 2009) are examples of prospective methods. In these methods, the general focus is on the abstract and subjective factors of the experts. Although prospective methods require limited data, collecting them (i.e., extracting them from expert minds) is often tricky and time-consuming. The advantage of these methods is to raise the expert team's awareness about the variety of plausible scenarios and to comprehensively assess the main and side effects of each scenario before making any decision. Since the correct estimation of costs and benefits of a consequence is very complicated, the main concern about using prospective methods is the methodology used for the quantification of risks and their effects.

The other risk analysis approach is a black or white box method (Simon 2014). In the black-box analysis, the risk is analyzed by the expert. Therefore, risk estimation would be based on the experience of an expert and has no exact calculation method (Tanaka et al. 2000). In the white box approach: users can easily understand the defined rules, the relationship between parameters, and the decision-making process in the system. Thus, fuzzy-logic risk analyses (Cazemier et al. 2001; Mohamed and McCowan 2002), and optimization methods are considered as white-box methods (Du and Wang 2003; Li et al. 2006, 2009; Cetinkaya et al. 2007; Xu et al. 2009; Guo et al. 2010; Lv et al. 2010; Simonović 2012).

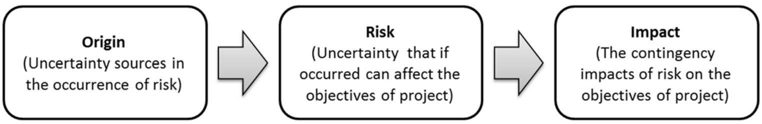

Fig. 1 The relationship between origin, risk, and impact

The complexity and dynamics of water resources systems are due to many factors, with many interactions and interdependencies. This interweaving causes different uncertainties in water resources planning and management processes. In this regard, analyzing the effects of this interweaving would be very difficult and, in some cases, impossible. To create a homogeneous model (or a heterogeneous model with the descriptions of all the information) is usually required to expand all the information using probabilistic or fuzzy logic techniques. However, there is still no specific instruction on how to select an uncertainty analysis technique, according to the source and type of uncertainty (Khatri 2013). Analysis of multivariate data based on probability theory is a convenient tool for analyzing uncertainties of a random phenomenon in the real world. The analysis of data based on possibility distribution is a suitable replacement for these calculations (Tanaka and Guo 1999).

Fuzzy logic is a perfect tool among white-box methods for risk analysis due to the capabilities in dealing with limited data, subjective and temporal variables, and modeling expert opinions, among others. When there is no clear understanding of future achievements (given the lack of experience), participating in fuzzy logic can provide better results (Bernhardt and Palmer 2011). In this paper, two types of models were considered for the selection among water supply options in Mashhad city: one was based on the expansion of Markowitz model to the fuzzy probability theory; the other was based on the possibility theory. The first one includes the ranking of projects, and the second one determines the reliability of the Mashhad water supply program. Due to the nature of the water supply problems (non-simultaneous completion of water supply projects), especially in this study, the problem was solved by considering the time of completion of each project.

2 Materials and Methods

2.1 Case Study

Mashhad city, which is located in Mashhad plain, has been experiencing fundamental problems in terms of water supply from groundwater and surface water resources. Land Subsidence, decrease in the volume of Mashhad plain's reservoir, population growth, and increase in the number of national and international visitors made the issue of Mashhad water supplement complicated (Bagheri and Hosseini 2008; Madani 2014; Rahnema and Mirassi 2014). A 1.5 million marginalized population, which does not have the minimum water supply infrastructure, causes severe challenges for the city (Davary et al. 2013).

The water demand in Mashhad plain, with 3.3 million people, is higher than its supply, and water scarcity has occurred. Despite transferring 800×10^6 m^3/year of water from Doosti-Dam to Mashhad Plain, there is a 100×10^6 m^3/year overexploitation from groundwater reservoirs, which caused the groundwater level going down. Especially in the western parts of the aquifer, the groundwater level drops by more than 2 m each year. In other words, water managers should be looking for water supply managerial solutions besides demand management to meet the challenges of water scarcity. Long-term demand management makes it possible to reduce and manage the crisis. Considering the current extremely critical situation in Mashhad plain, where there is a rapid growth in demand and development, finding new water resources should be part of the solution (Mozafari et al. 2012).

Currently, transferring water from Hezar-Masjed, Tajikistan, Oman Sea, and wastewater are four possible water supply options, with each having a different cost for Mashhad city. What raises concern among the authorities of the Iranian Ministry of Power is the challenges and uncertainties related to the provision and transmission objectives of each project. In this study, the risk of each water supply option for Mashhad City is analyzed. It has been tried to identify the different sources of uncertainty and risks and to provide a suitable framework for ranking projects with the help of fuzzy-possibility theory. The framework consists of the following steps: 1) defining challenges and opportunities in brainstorming sessions; 2) answering questionnaires by experts (Delphi method), which are prepared according to the brainstorming sessions; and 3) analyzing the results using Fuzzy-Possibility Theory. This procedure will lead to prioritizing the possible options which enable the authorities to make better and easier decisions on the future water supply of Mashhad.

2.2 The Subject Matter

There are six options for the Mashhad water supply program. At the moment, two options are exploited: 1) "harvesting water from the aquifer"; and 2) "transferring water from the Doosti Dam". Besides, four other options under consideration are briefly described in Table 1.

2.3 Steps to Follow

The research phases of this work can be summarized as follows:

A. With a total of 144 man-hours of brainstorming, challenges and opportunities of each transfer option were determined by at least ten experienced senior experts and managers of Khorasan-Razavi Regional Water Company (KRRWC). For this purpose, the table of perceived risk origins (Table 2) was created based on the type of risks which including political, environmental, social, transfer, international relations, climate change, development of upstream areas, and financial (PEST-ICDF) model (Ziout and Azab 2015). Since the "water supply of Mashhad" is the goal of all the above options, whole challenges and opportunities were investigated in terms of possible negative and positive effects on the considered goal, and it is considered as a risk when approved (Table 2; also refer to Appendix Table 11).

B. Risks and hazards for each option concluded in brainstorming sessions, are provided in Table 2. According to the meeting results, the probability and impact of every risk were determined using a questionnaire prepared based on the Delphi method and with the help of linguistic variables. Linguistic variables are building blocks of Fuzzy Logic whose values are expressed in the form of words or sentences. For example, the size of risk could be defined in the form of a numeric range [0, 100%]; or expressed with linguistic variables such as too high, high, medium, etc. Each of these terms can be interpreted as a fuzzy subset (e.g., X = [0, 1]), where X is the numerical value of the risk size. Since the parameters of the problem were numerous, and in order to reduce the calculations, parameters were grouped into time-dependent and time-independent. Trapezoidal and triangular fuzzy functions were used for time-dependent and time-independent parameters, respectively. Seven linguistic variables were defined, using fuzzy triangular numbers (Table 3).

C. Choosing the shape of the fuzzy number: expanding membership functions in the form of fuzzy numbers for various parameters is a topic of interest in fuzzy modeling. A great effort has been devoted to providing a variety of methods for the formation of fuzzy numbers. These methods are either based on direct intuition and perception of the studied parameters or on

Table 1 Brief description of the possible options for the water supply of Mashhad

Options	Description/ status	Annual supply volume (10^6 m^3)	Scheduled utilization time
Harvesting groundwater	• Aquifers in Mashhad study area are critically banned • Reduced harvest to restore the aquifer is required	300	Under exploitation
Doosti Dam	• There is a political conflict with Afghanistan	150	Under exploitation
Wastewater treatment	• A large percentage of wastewater in Mashhad is not still collected/ nor refined • Part of the treated wastewater is released into the river now	Currently 34% of urban consumption (depending on urban development, can increase up to 70%)	Under exploitation (gradually increases until 2040)
Water transfer from Hezar-Masjed Mountains	• Use of available surface waters and or Karst resources • Possibility of increasing conflicts with Turkmenistan and locals	40–30	2030
Water transfer from Oman Sea	• Long-distance transmission • Many challenges due to the magnitude of the project	157–220	2050
Water transfer from Tajikistan (Different routes)	• Reduces the political power of Iran in the region in terms of dependence on out-of-boundary waters including the transfer of water from Afghanistan, Tajikistan or Turkmenistan	300–400	2030–2050

Table 2 Uncertainty sources based on PEST- ICDF

	Type of risk	Description
1	Political	Political competition between the various decision-making bodies (metropolitan, provincial and national) can lead to lack of coordination among them, and thus, slow or stop the enforcement of options (governors, provincial managers, and parliamentarians, etc.)
2	Environmental	Environmental constraints and challenges in the origin or transmission path can run options into serious/unsolvable difficulties, and therefore, impair Mashhad water supply.
3	Social	Ethnic and regional conflicts concerning the transfer of water from an outside source can be a source of risks and negative impacts on the Mashhad water supply.
4	Transfer	The long path itself is a source of water hazards such as construction difficulty, high cost, operation, and maintenance complexity, etc. Transmission disruption is also possible due to technical, natural (e.g., earthquakes, etc.) and human causes.
5	International relations	The type of relationship with the state(s) located in the water conveyance line will affect the volume (even on having or not having) of flow to Iran. So, only border and cross-border options are exposed to this risk.
6	Climate change	Climate change can be a source of risk for Mashhad water supply in most options (except for wastewater treatment and transfer from the Oman Sea).
7	Development of upstream	Future developments in the origin or transmission path can disrupt the Mashhad water supply in the future as the final destination of the transmission line.
8	Financial	Risks due to the lack of financial supply (temporal/quantitative) will disrupt the Mashhad water supply. Whether the source of financing is private or public sector, delay or reduction in the required resources will jeopardize the objectives of the project.

algorithms and logical operators. The first method is an experiential and intuitive approach based on human knowledge and understanding of the phenomenon that takes place. So, the formation of fuzzy numbers is based on human understanding in this method. The analytical approach is an alternative method of the experiential approach, which uses deductive reasoning to form the fuzzy numbers. Conclusions are made based on a set of facts and knowledge and comparing them, and ultimately the membership functions of fuzzy numbers are created based on the results. Clustering is the alternative method, in cases where the relative parameters are compared with each other. This method is highly dependent on the priorities of different parameters, especially when a survey is conducted between individuals, and specific parameters are compared with each other (Haleh et al. 2010). When there is a set of input data, different algorithms, such as neural networks and genetic algorithms, can be used to form fuzzy numbers. Fuzzifiers are commonly used to define fuzzy numbers by taking into account a specific definition and a series of data to create membership functions (Haleh et al. 2010). There are different fuzzifiers with different characteristics and capabilities, depending on their

Table 3 Triangular fuzzy numbers for each of the linguistic variables

Row	Linguistic variable	Symbol	Fuzzy numbers
1	Very Low	VL	(0.1, 0.1, 0.3)
2	Low	L	(0.1, 0.1, 0.3)
3	Medium to Low	ML	(0.2, 0.3, 0.4)
4	Medium	M	(0.3, 0.4, 0.5)
5	Medium to high	MH	(0.4, 0.5, 0.6)
6	High	H	(0.6, 0.7, 0.8)
7	Very high	VH	(0.7, 0.9, 1)

input and output data (Khazaee and Hosseini 2013). TOPSIS method is an example of fuzzifiers, which produces the most suitable fuzzy number using parameters such as slope, location, and area of fuzzy numbers, in combination with concepts such as geometric distance, perimeter and height of fuzzy numbers (Haleh et al. 2010).

The Possibility Theory suggests the possibility of uncertain parameters in a set using membership functions. The fuzzy membership functions often require a subjective discussion about the shape and value of non-zero parameters, which in turn is an additional source of subjective uncertainties to the analysis. Shape and number of uncertain parameters are selected based on expert knowledge in case of using fuzzy membership functions of risk. Skew and inadequacy of the chosen shape should be carefully considered when selecting the membership function (Khatri 2013).

Various algorithms have been proposed to convert probability distribution function into fuzzy membership functions. The Figures used in the literature can also help to select the membership functions. Although there are several ways to fuzzificate the information, recent developments in converting information from one form to another are available, especially for continuous distribution and multi-constraint methods (Florea et al. 2008; Mauris 2010; Serrurier and Prade 2011). Nevertheless, these methods are still in the early stages of development. While most techniques have been developed for discrete data, some have used them to analyze single-sided and multisided parameters, many of which have no relevance to the membership functions and probability distribution functions. Many of the techniques are very complex in practice (Khatri 2013).

The fuzzy triangular shape is suggested for several cases such as: (1) when a probable amount is likely to be estimated; (2) a parameter, a specific range with sufficient confidence for data is available; (3) a unique value for the parameter is not known. However, if all conditions are established, and instead of a value, a range of values is estimated for the parameter, then the trapezoidal shape is appropriate (Khatri 2013).

Triangular and trapezoidal forms are widely used in modeling (Khazaee and Hosseini 2013). The triangular shape is suggested when a probable amount for a parameter is estimated, A known distance with sufficient reliability is available, and a unique parameter value is not known. The trapezoidal shape is appropriate when all conditions are met, and a distance can be estimated for the probable values of the parameter instead of one value (Khatri 2013).

D. Risks (severity and probability of each risk) were analyzed based on expert opinions, and the conclusions were presented in the form of fuzzy numbers. There are different methods for creating membership functions such as Neural Networks and Genetic Algorithms. However, the fuzzy method was used based on the primary purpose of this research, which is the use of specialist knowledge. All possible hazards were considered (including the most optimistic to the most pessimistic scenarios) in risk analysis, and hazard uncertainties were presented in fuzzy triangular numbers.

E. The following Eqs. (1, 2 and 3) describe the general form of risk:

$$R = H \times E \times V \tag{1}$$

where R, H, E, and V stand for Risk, Hazard, Exposure, and Vulnerability, respectively. H is a function of probability and severity:

$$H = f(Probability, Severity) \tag{2}$$

Thus, Eq. (1) becomes:

$$R = f(Probability, Severity) \times E \times V \tag{3}$$

Hazard (i.e., H=P × I) is a risk from an outside project source, whose negative effects are exerted on the project. In this study, vulnerability and exposure values were assumed unity. Thus, the risk is function of Hazards only. Given that the probability and impact have been set as fuzzy variables. The fuzzy risk is also the product of probability and impact of a hazard. If is the fuzzy membership function of fuzzy member *x* in the set T, then the membership function can take any real values between 0 and 1. As a result, the membership function is presented in the continuous form:

$$U_T(X) = \begin{cases} \frac{x-l}{m-l} & l < x \le m \\ \frac{u-x}{u-m} & m < x \le u \\ 0 & otherwise \end{cases} \tag{4}$$

where *l* and *u* are the lower and upper limits of fuzzy triangular numbers in the set. Two fuzzy numbers display the probability and impact of each hazard: and . *L* and *S* are shown in the form of mathematical equations:

$$U_L(X) = \begin{cases} \frac{x-l_1}{m_1-l_1} & l_1 < x \le m_1 \\ \frac{u_1-x}{u_1-m_1} & m_1 < x \le u_1 \\ 0 & otherwise \end{cases} \tag{5}$$

$$U_S(X) = \begin{cases} \frac{x-l_2}{m_2-l_2} & l_2 < x \le m_2 \\ \frac{u_2-x}{u_2-m_2} & m_2 < x \le u_2 \\ 0 & otherwise \end{cases} \tag{6}$$

So, the fuzzy risk is calculated according to Fig. 2:

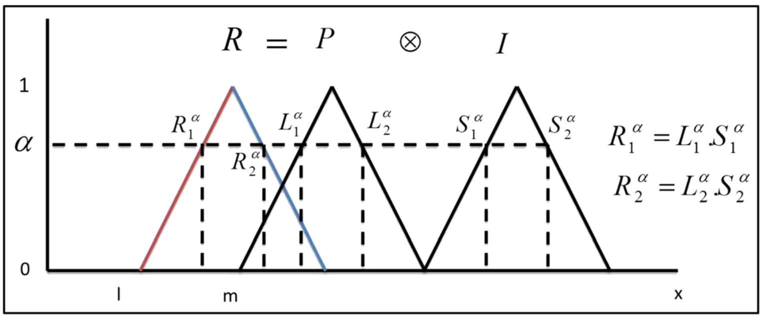

Fig. 2 The fuzzy risk calculation

F. In order to produce fuzzy triangular numbers based on the nature of data and the possibility of probable amounts of temporal parameters, a questionnaire that resulted from octet risks mentioned in Table 2 was prepared according to the operations, as discussed above. The fuzzy numbers considered the octet risks as time-independent parameters. The term time-independent means that Experts rated risks regardless of the time of project implementation. So, in another questionnaire, experts were asked to predict the completion time of projects for optimistic, pessimistic, and probable modes. The trapezoidal fuzzy numbers of water transfer options were produced based on the time-dependent questionnaire. We chose the trapezoidal shape since it was possible to estimate a time window as the best estimate of the time for completion of the projects. Finally, the options were ranked using their produced fuzzy numbers and the K_j index (Smith 1995), which is calculated by subtracting the trapezoid area from the possibility distribution area, as in Eq. (7) (Mohamed and McCowan 2002):

$$K_j = 0.5\left[1 - \frac{RA_j - LA_j}{R - L}\right] \quad (7)$$

where R and L are the maximum, and the minimum range of the decision function and LA_j and RA_j are the gray trapezoidal areas on the left and right sides of the possibility of distribution in Fig. 3. The higher the K_j value for an option, the higher the position it gets in the ranking.

G. The evaluation of water supply program in the form of portfolio projects (Tanaka et al. 2000): Markowitz model states that if there are n shares in the portfolio S_j ($j = 1,\ldots,n$), and the performance (r_j) and the total proportion of shares (x_j) are available, then:

$$\sum_{j=1}^{n} x_j = 1 \quad (8)$$

where r_i are random variables in discrete-time ($i = 1,\ldots,n$), and n is the vector efficiency type $r^0 = [r_{i1}\ r_{i2}\ldots r_{in}]$. Thus, for the efficiency period, the total data is displayed by Eq. (9):

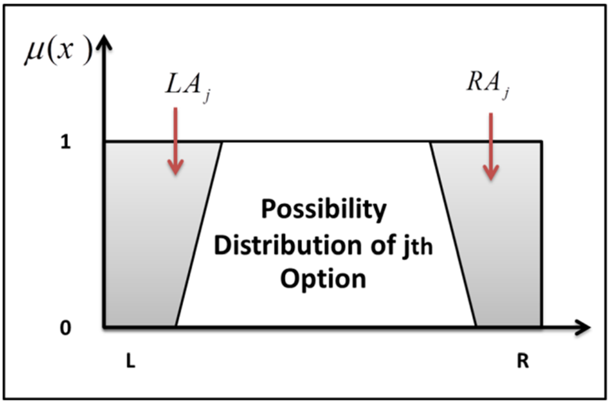

Fig. 3 The ranking index of project risks based on fuzzy numbers

$$\begin{pmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{pmatrix} \tag{9}$$

The mean vector of efficiencies in m periods is expressed as in Eq. (10):

$$r^0 = \begin{bmatrix} \sum_{i=1}^{m} r_{i1}/m \\ . \\ . \\ . \\ \sum_{i=1}^{m} r_{in}/m \end{bmatrix} \tag{10}$$

The covariance matrix can be rewritten as in Eq. (11):

$$\begin{aligned} & q_{ij}^2 = \sum_{k=1}^{m} \left(r_{ki}-r_i^0\right)\left(r_{kj}-r_i^0\right)/m \\ & i = 1, \dots, n \\ & j = 1, \dots, n \end{aligned} \tag{11}$$

Therefore, random variables were determined by (r^0, Q), where r^0 is the mean vector, and Q is a matrix of covariance. Now, the performance is related to efficiency with x as follows:

$$z = x^t r \tag{12}$$

The mean and variance of z are calculated by Eqs. (13) and (14):

$$E(z) = E(x^t r) = x^t Er = x^t r^0 \tag{13}$$

$$V(z) = V(x^t r) = x^t Qx \tag{14}$$

When variance is considered as investment risk, the best investment must have the least variance in the average efficiency r_s, if your plan becomes an issue.

As mentioned above, projects finishing points are different from each other. As time passes by, Mashhad water demand increases. Therefore, each water supply project is needed at its finishing point. In conclusion, the overall picture is given in Fig. 4, where cumulative supply and demand are shown simultaneously.

In Fig. 4, Q_t is a water volume rate at time t, d_i is water demand at the I period, and D is the total water requirement.

By rewriting this issue in fuzzy conditions, similarly, it will be concluded: experts recommend data set as (r_i, h_i) (i = 1,…, n), where h_i is a degree of feasibility to reflect the degree of similarity between the future and i state. The mean fuzzy vector $a = [a_1, \dots, a_n]^t$ is determined by Eq. (15):

$$a = \sum_{i=1}^{m} (h_i r_i) / \sum_{i=1}^{m} h_i \tag{15}$$

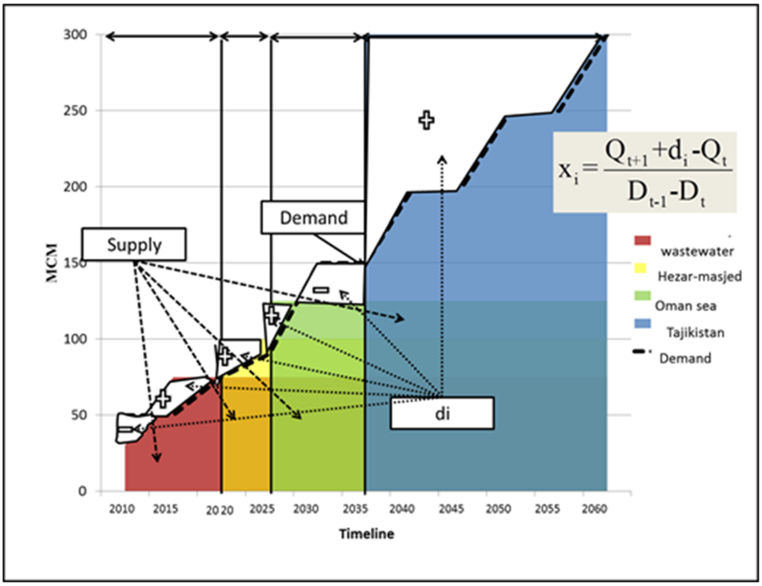

Fig. 4 Possible water availability from different supply projects in Mashhad

Similarly, the weighted fuzzy covariance matrix $\sum = [\sigma]$ is determined by Eq. (16):

$$\sigma_{ij} = \left\{ \sum_{k=1}^{m} (r_{ki} - \alpha_i)(r_{kj} - \alpha_j) h_k \right\} / \sum_{k=1}^{m} h_k, \qquad i = 1, \dots, n \quad j = 1, \dots, n \tag{16}$$

The weighted average vector and covariance matrix (z, $\sum$) average and covariance of efficiency (z) can be determined by Eqs. (17) and (18):

$$E(z) = x^t a \tag{17}$$

$$V(z) = x^t \sum x \tag{18}$$

Our problem is now a question of general optimization. However, as noted above, given the nature of the water supply problem, this problem becomes a question of assessment, especially in the current case study (Mashhad water supply program). Now, risk can be defined according to the conditions of the Mashhad water supply program as follows:

$$Risk = h_i \left(\frac{Q_f}{D} \right) + \frac{Q_a}{D} \tag{19}$$

where h_i is the degree of possibility, Q is the fuzzy flow rate of supplied water in a period (f and a indicate before and after completing the project, respectively), and D is total water demand (Fig. 5).

3 Results and Discussion

Challenges and opportunities for each option were extracted. The results of the risk analysis are provided in the following. Finally, the transmission options were prioritized based on other criteria such as cost and added capacity to the Mashhad water supply.

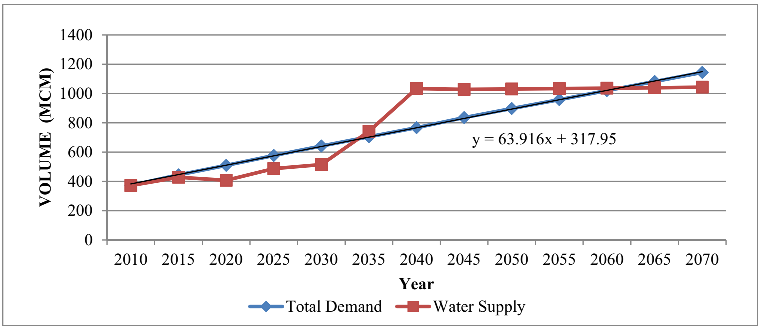

Fig. 5 Water supply and demand prediction for the 2070 horizon

Table 4 Risk categories

Row	Risk	Risk title	Descriptions
1	H_1	The possibility of insecurity in the origin	Many cases, such as the proximity to the borders, can cause the failure of the Mashhad water supply
2	H_2	The possibility of sabotage in the transmission path or at the facility (terrorism / Passive Defense)	Factors such as failure in maintenance and operation can face the Mashhad water supply system with troubles
3	H_3	The possibility of opposition from environmental NGOs	Environmentalists could hinder their projects
4	H_4	The possibility of inadequate funding by program	Lack of procurement of funds is usually a function of the magnitude of the project and the capital requirements
5	H_5	The possibility of reduced water supply for Mashhad due to upstream developments	Can development in the country of origin or the path of transfer
6	H_6	International relations	Economic boosters inside Afghanistan, the involvement of other countries, mutual balance
7	H_7	Climate change (hydrological regime change in Syr-Darya / Amu-Darya)	Climate change is likely to lead to reduced Mashhad water supply, in particular in 50 years; the Himalayan glaciers will be significantly reduced
8	H_8	Increased water allocation by setting fixed water rights	Increased water rights, regardless of the natural water regime, climatic fluctuations and development scenarios
9	H_9	Social problems in opposition to Mashhad water supply	Social problems caused by distrust to authorities or competition of cities with Mashhad
10	H_{10}	Environmental impacts or pollution of water resources	Trespassing over protected areas and legal restrictions
11	H_{11}	Rejection of Alternative treated wastewater due to cultural issues	This option is exclusive for the wastewater option
12	H_{12}	The complexity of working with karst resources	This option is exclusive for the Hezar-Masjed option
13	H_{13}	Political competition in transfer route resulted in a decline of the share Mashhad	
14	H_{14}	Possible technical problems in transfer route and installations	Pump failure, Earthquake, Power failure, Tsunami, etc.
15	H_{15}	Social costs related to the satisfaction of residents in the origin and path	Management and control of some damages are expensive.

Table 5 Identifying the risks of Mashhad water supply options by linguistic variables

Option	Level	Hazard categories														
		H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15
Wastewater treatment	optimistic	–	–	VL	VL	–	–	–	VL	VL	VL	VL	VL	–	VL	VL
	probable	–	–	L	L	–	–	–	L	L	L	VL	L	–	VL	L
	pessimistic	–	–	L	MH	–	–	–	H	VH	ML	L	MH	–	L	ML
Hezar-Masjed mountain	optimistic	VL	VL	VL	VL	VL	VL	VL	–	VL	VL	–	VL	VL	VL	VL
	probable	L	VL	L	L	VL	L	VL	–	VL	VL	–	VL	L	VL	VL
	pessimistic	ML	VH	H	MH	VL	MH	L	–	VL	VL	–	VH	H	VH	VL
Oman Sea	optimistic	VL	VL	VL	M	L	–	–	–	L	VL	–	–	VL	VL	VL
	probable	L	L	VL	ML	MH	–	–	–	H	VL	–	–	L	ML	H
	pessimistic	M	VH	L	VH	VH	–	–	–	VH	VL	–	–	VH	VH	VH
Tajikistan	optimistic	VL	VL	VL	VL	VL	VL	VL	–	VL	VL	–	–	VL	VL	VH
	probable	L	L	VL	VL	ML	L	L	–	VL	VL	–	–	L	L	VH
	pessimistic	VH	VH	VL	VL	MH	VH	M	–	ML	VL	–	–	VH	VH	VH

Table 6 Experts' opinions on quantifying the risks of water supply options based on possible, optimistic and pessimistic scenarios

Options	Level	Hazard Categories													Distribution values		
		H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}	H_{13}	H_{14}	H_{15}	
Waste water treatment	optimistic (a)	0	0	6	12.1	0	0	0	5	6.5	9	9	1	0	1	10	3.9
	probable (b)	0	0	10	25	0	0	0	25	25	25	24	27	0	5	30	13.1
	pessimistic (c)	0	0	10	64	0	0	0	70	81	49	30	64	0	32	49	29.9
Hezar-Masjed mountain	optimistic (a)	8	6.7	9	11.2	3	3	3	0	5	10	0	3	1	2	25.4	6.0
	probable (b)	25	9	25	30	9	25	9	0	9	15	0	9	30	15	25.4	15.6
	pessimistic (c)	36	81	63	56	9	64	25	0	9	15	0	72	63	81	25.4	39.9
Oman Sea	optimistic (a)	1	12.6	1	29.2	25	0	0	0	17.5	1	0	0	12.7	21	33	10.2
	probable (b)	25	20	9	49	50	0	0	0	63	9	0	0	25	36	70	23.7
	pessimistic (c)	50	72	35	81	72	0	0	0	72	10	0	0	81	81	81	42.3
Tajikistan	optimistic (a)	16	9	2	4	23	16	6	0	18	1	0	0	16	25	49	12.3
	probable (b)	25	32	5	9	49	49.8	25	0	20	5	0	0	35	36	63	23.5
	pessimistic (c)	81	72	9	40	62	81	49	0	42	9	0	0	72	72	81	44.6

Table 7 Matrix of quantitative fuzzy decisions on the completion time, which was made by the experts for pessimistic, probable, and optimistic modes

Duration of the project (option)			
	Optimistic (a)	Probable (b-c)	Pessimistic (d)
Wastewater treatment	7 (0.46)	(9–10) (0.6–0.66)	15 (1)
Hezar-Masjed	10 (0.66)	(11–12) (0.73–0.8)	15 (1)
Oman Sea	17 (0.49)	(21–30) (0.6–0.85)	35 (1)
Tajikistan	25 (0.45)	(36–40) (0.65–0.72)	55 (1)

3.1 Challenges and Opportunities

The use of Mashhad water resources will be continued at the current or lower rate (to balance the aquifer). However, this decaying source of water cannot be an option for the future development of water resources in the region. Since this study sought to prioritize the new possible options for investment. The Doosti Dam, which has already been invested, was omitted from the list of options. The list of challenges and opportunities for water supply options for Mashhad plain is briefly presented in Table 4.

The expert opinions were taken based on Delphi group decision making and brainstorming techniques in 10 meetings of six groups of regional water experts (each session was held with the presence of 10 experts). Groups of experts have been selected from the members of "Board of Directors", "Corporate Vice principals", and "executive project managers" of Khorasan Regional Waters Company. All hazards have been identified and sorted into groups of 15 in a breakdown structure and were represented to the experts in the form of questionnaires (Table 4). To increase the awareness of attendees in the session, Table 4 was also presented with the questionnaires.

3.2 Questionnaire Results

The first stage of the study consisted of identifying the quality of the hazards (i.e., raw expert data) and creating a dataset of probability and impact of each hazard on Mashhad water supply options. At this stage, the exposure and vulnerability factors have not been directly used to mitigate the impacts, severity, and probability of each hazard. It is because

Table 8 Fuzzy numbers dedicated to each Mashhad water supply option

Row	Water transfer options	Trapezoidal fuzzy numbers	LA	RA	K_j index
1	Wastewater transfer	(0.49, 0.73, 0.79, 1.29)	0.61	1.04	0.235
2	Wastewater treatment	(0.72, 0.88, 0.96, 1.39)	0.8	1.17	0.224
3	Hezar-Masjed mountain	(0.59, 0.83, 1.08, 1.42)	0.71	1.42	0.175
4	Tajikistan	(0.57, 0.88, 0.95, 1.44)	0.725	1.195	−0.2

Table 9 Priorities of water supply options for Mashhad

Row	Options	Cost (10^6\$) (C)	Water supply capacity (10^6M^3) (Q)	Risk (K_j)	Coefficient (ω)	CI	Priorities
1	Oman Sea	94,567	200	0.175	1.7	0.0205	3
2	Wastewater transfer	461	45	0.235	0.8	0.3	1
3	Hezar-Masjed mountain	9700	35	0.224	1.7	0.027	2
4	Tajikistan	33,150	300	−0.2	1.7	−0.076	4

experts get a relative mental awareness about the exposure and vulnerability of each option to hazards based on their Social Learning in brainstorming sessions (Pipattanapiwong 2004). To analyze the risk of Mashhad-water-supply options, probability and severity factors are influenced by exposure and vulnerability factors (Table 5). Based on the Probability and Severity of each hazard on the option failure, the total degree of vulnerability is expressed by linguistic variables from very low to very high (between 1 and 7). In fact, vulnerability refers to the inability of a system or a unit against the effects of a hostile environment (Turner 2010). Fuzzy numbers, which had been given by experts, were averaged to determine the severity and probability of each hazard.

Expression $\tilde{P}\otimes\tilde{I}$ was calculated as fuzzy triangular numbers $(PI_{11}, PI_{12}, PI_{13})$, based on Eqs. (1) to (6). The results were then averaged and made integers.

Triangular fuzzy numbers for each time-independent hazard were determined for water-transfer options. In the first step, experts were asked to qualitatively express their opinion about 15 hazard categories defined in Table 4. The results have been provided in Table 6. In the next step, the same experts were asked to estimate the hazards by considering the completion time of four options optimistically, pessimistically and possibly. The normalized results have been provided in Table 7. Since the experts instinctively consider hazards when they were asked for estimating the completion time of the options, Table 7 is a function of Table 6.

Finally, the trapezoidal fuzzy numbers of projects were calculated by summation of fuzzy numbers from Table 7 and Table 8, according to the first column of Table 8. Then, K_j index of the trapezoidal fuzzy number was calculated based on Eq. (7). Mashhad water supply options were prioritized according to the Eq. (7) and fuzzy numbers in Table 8, which are provided in the last column of Table 8. According to Table 8, the K_j index of wastewater transfer option was higher than that of other options, so this project is less risky than the others.

3.3 Prioritizing the Options

The simulation of possible distribution of the options showed that transferring water from Tajikistan has a higher risk, and consequently, its implementation will have a high level of risk. Transferring water from Hezar-Masjed Mountains had the lowest average risk. However, transferring wastewater had less possibility of occurrence than other options. As a result, transferring wastewater to the west of Mashhad is the top priority of implementation compared to the alternatives.

Table 10 Degrees of possibility and risk for each water supply option

Row		Description	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070
1	Degree of possibility	Wastewater transfer	0	0	0	1	1	1	1	1	1	1	1	1	1
2		Hezar-Masjed	0	0	0	0	1	1	1	1	1	1	1	1	1
3		Oman sea	0	0	0	0	0	0.9	1	1	1	1	1	1	1
4		Tajikistan	0	0	0	0	0	0	0	0.45	0.9	1	1	1	1
5	Degree of risk	Wastewater transfer	0	0	0	0.76	0.73	0.7	0.63	0.57	0.54	0.5	0.48	0.45	0.43
6		Hezar-Masjed	0	0	0	0	0.65	0.63	0.56	0.51	0.48	0.45	0.43	0.4	0.39
7		Oman sea	0	0	0	0	0	0.73	0.76	0.7	0.65	0.61	0.57	0.54	0.52
8		Tajikistan	0	0	0	0	0	0	0	0.28	0.65	0.71	0.67	0.63	0.6
Total risk	0	0	0	0.76	0.69	0.71	0.65	0.6	0.6	0.57	0.54	0.51	0.48		

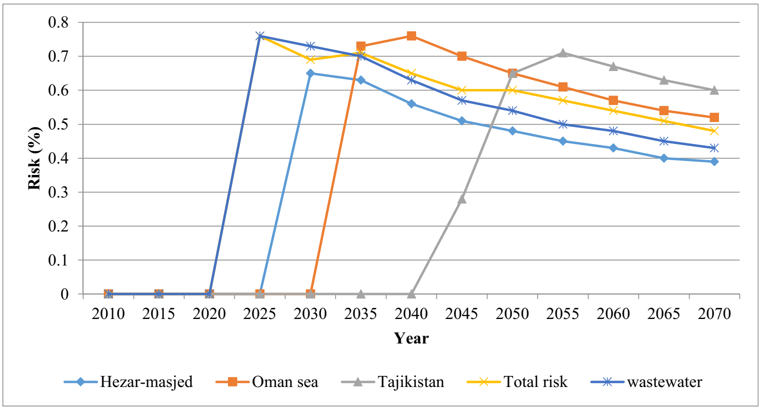

Fig. 6 Failure risk of different water supply options until the year 2070

There are other parameters that should be considered to prioritize the water supply options. For comparing the options, a Consumption Index (CI) was created and described as Eq. 20. One of these parameters is the project cost (C). The project, which costs less than other options, is more accessible and cost-effective. In contrast, expensive options would face many problems in running. The next parameter is based on the volume of water that the project will be transferring to Mashhad (Q): the higher the amount of water entering Mashhad, the more vital the project will be. Furthermore, by combining all these parameters, a composite index can be used to prioritize options (Table 9). In this regard, the omega coefficient (ω) is related to the rate of water reclamation in the basin. Since the extraction of water is from outside the basin, and urban consumption produces 70% of the returned water. The coefficient of 1.7 is selected for water imported into the basin. Also, wastewater replacement from the perspective of water resources management is considered to be advantageous in using groundwater with a 0.1 advantage. According to the index, the wastewater treatment and then the Hezar-Masjed option would be the most suitable criteria.

$$\boldsymbol{CI} = \left(\frac{\boldsymbol{Q} \times \boldsymbol{\omega}}{\boldsymbol{C} \times \boldsymbol{K}_j} \right) \tag{20}$$

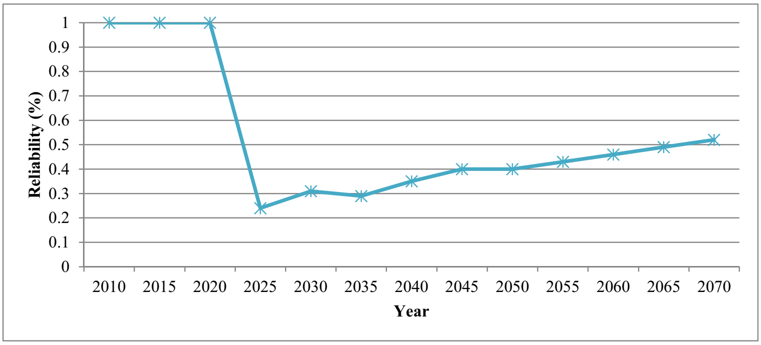

Fig. 7 The reliability level of the Mashhad Water supply projects in different periods based on the fuzzy Markowitz model

3.4 Risk Assessment of Options for Mashhad Water Supply Program

To assess the risk of the Mashhad water supply project options for the 2070 horizon, Eq. (19) was applied. The results were presented into two categories of "Degree of risk" and "Degree of possibility" in Table 10. The entire risk of the Mashhad water supply program is given in the last row Fig. 6.

Figure 7 shows the risk of projects caused by various factors in supplying water requirements of Mashhad city. Figure 7 depicts the reliability (one minus risk) of the Mashhad water supply project options. As can be seen in Fig. 7, reliability in the early year of the projects is very low and gradually approaches about 60% in the year 2070.

4 Conclusions

A simple logical framework for the quantification of expert opinions about water supply projects was presented based on the principles of possibility theory. Previous studies used possibility theory to analyze the risk with up to two options and suggested more than 70 different quantitative and qualitative methods for risk analysis. In this study, four appropriate water supply options were studied simultaneously using a consistent approach for determining the risks of water-supply options and introducing a new CI minimal-risk criterion for prioritizing projects.

A new method for risk assessment was introduced, which consists of qualitative and quantitative methods, in addition to a new simple concept that improves the expression of risk. This method assessed the risk of urban water supply options in the form of a framework. The proposed framework is a portfolio that includes various water supply options from inside and outside the catchment. Given the possibility of water failures on either of these options, the water supply situation in the city will be disrupted. Consequently, it is necessary to estimate the water supply risk in future time horizons, for which is not well-advised to use probability instead of possibility. Therefore, in this project, a combination of expert opinions was used to estimate water supply risk in future time horizons. Although researchers have applied the fuzzy hybrid approach to the feasibility of water supply options risk assessment, the main innovation of this study is to explore different water supply options simultaneously in the form of a portfolio. The first method of risk assessment was based on the fuzzy approach, where expert opinions were asked about the degree of probability and severity of uncertainties for each option using linguistic variables. Then, fuzzy numbers of time-dependent and time-independent factors were obtained for each option. In the end, the total risk was calculated based on fuzzy aggregation. Furthermore, the concept of the risk factor for water supply plans was introduced. In this regard, the entire risk of the Mashhad water supply project options was calculated in 2025 above 80% and will be decreased over time. In accordance with the fuzzy approach, cross-border water transmission (Tajikistan) had the highest risk level ($K_j = -0.2$). Wastewater transfer had the lowest risk ($K_j = 0.235$) based on expert opinion.

Compliance with Ethical Standards

Conflict of Interest The authors declare that there are no conflicts of interest.

Appendix

Table 11 Challenges and opportunities of water supply options for mashhad plain. Challenges / Opportunities

	Hezar-Masjed	Wastewater Treatment	Tajikistan	Oman
Water utilities in the region (the state of being at the boundaries)	*		*	
Uncertainty in future water consumptions and social problems in the region	*	*	*	*
Possibility of political interference from other countries			*	
Possibility of adverse consequences on groundwater quality due to the deep-percolation or direct infiltration of wastewater to the aquifer		*		
Multi-purpose use of the tunnel (dargz- ghoochan transportation road, water transfer etc.)	*			
Bigger project size means bigger security risk (high flow rate stimulates vandalism intensions)	*		*	*
Possibility of international investment and water use development in afghanistan			*	
Establishment of a relative water security in eastern parts of the country	*		*	*
Development of political and economic ties with the interacted countries			*	
Raise of mistrust to the regional water company due to the wastewater revenue		*		
Vulnerability of facilities in terms of passive defense	*		*	*
Recycling wastewater by initial treating properties of soil profile		*		
Enhancement of security at the borders by maintaining population centers	*		*	*
High transportation and maintenance costs in comparison with the amount of supplied water	*	*		*
Social problems	*	*	*	*
Water utilities in the region (political support)				*
Maximum allocation of groundwater exit from borders for optimum use of surface water resources	*			
Terrorism	*		*	*
Impact of climate change on river discharge	*		*	
Recharging the aquifer (the potential of water recirculating systems in Mashhad)	*		*	*
Threat of population concentration around water transfer line	*		*	*
Natural hazards (such as tsunamis) facing desalinization facilities near the sea				*
Civil war and insecurity in the basins of origin			*	
Pressures to change the path of transferring line	*			*
Competition between provinces and difficulty provincial managements				*
International environmental risk (desalinization of sea water)				*
Possible lack of funding from private investors or private sector		*		*
Certain circumstances for the use of wastewater in agriculture (special qualitative requirements of irrigation water for certain crops)		*		
Difficulties in the storage of projects			*	*
Water utilities in the area (political support)	*			
Underground maximum allocation of border output for optimum use of surface water resources	*			
The long distance of the transmission line, numerous stations and downtime risks (technical, earthquake etc.) + (delay in construction)			*	*

Table 11 (continued)

	Hezar-Masjed	Wastewater Treatment	Tajikistan	Oman
Inability to manage heterogeneous development and rising expectations with the arrival of new supply of water	*	*	*	*
Reject treated wastewater culturally		*		
Instability in foreign policy of the origin countries			*	
No need to desalinization (reduce operating costs and reduce the chances of coping with environmental groups)	*		*	
Domestic advantage and the absence of oppositions (no dependence on other countries in term of supplement)		*		*
Opportunity to bargain with other possible suppliers of water (Turkmenistan, Afghanistan, etc.)				*
Capability of supplying water for the cities located in the route of transmission line and gain their participation (justifications and approvals)				*
Reduce the social challenges in south east and east of the country due to the volume of investments				*
Reducing the power of country in the region			*	
Traditional agriculture and the lack of conditions for rapid development in the basins of origin			*	
Shortage in electrical power and natural gas in the basins of origin: water and energy exchange			*	
The border situation of rivers and the need to speed up plans to prevent water from leaving the country	*			
Difficult studies of identification phase and uncertainty in them	*			
The relative insecurity and lack of rapid development in these countries (slowing the development of countries of origin)			*	
The uncertainty about delivered water price	*	*	*	*
The need for 16 local wastewater treatment plants		*		
Lower transfer cost than that of transfer options from outside of the basin	*	*		
Proximity to Mashhad (short route)	*	*		
Various development programs funded by international organizations in Afghanistan (project Dakar, etc.)			*	
Existence of water-abundant and relatively water-abundant rivers			*	
Presence of international environmental groups to stop the project			*	
Ongoing social problems in the procedure of water transfer	*			*
Existence of protected areas on the track of transfer	*			*
Interference of mps and intensification of conflicts and/or political tensions	*			*

Table 12 Indices' list symbols

	Description	Symbols	Description
VL	Very Low	**Q**	matrix of covariance
L	Low	**rs**	minimum risk
ML	Medium to Low	**Q**	a water production rate at the time of t
M	Medium	**d**	water demand at the period of i
MH	Medium to High	**D**	the total time-dependent water requirement
H	High	**hi**	degree of feasibility to reflect the degree of similarity between the future state and i state
VH	Very High	**a**	mean fuzzy vector
R	Risk	**σij**	covariance matrix
H	Hazard	**Q**	the fuzzy flow rate of supplied water in a period
E	Exposure	**D**	total water demand

Table 12 (continued)

	Description	Symbols	Description
V	Vulnerability	**H1**	The possibility of insecurity in the origin
I	Impact	**H2**	The possibility of sabotage in the transmission path or at the facility (terrorism / Passive Defense)
μT(X)	the fuzzy membership function of fuzzy member x in the set T	**H3**	The possibility of opposition from environmental NGOs
T	the set T	**H4**	The possibility of inadequate funding by program
UT(X)	Function T	**H5**	possibility of reduced water supply for Mashhad due to upstream developments
X	Membership	**H6**	International relations
L	lower limits of triangular fuzzy numbers in the set	**H7**	Climate change (hydrological regime changes in Syr-Darya/Amu-Darya)
U	upper limits of triangular fuzzy numbers in the set	**H8**	Increased water allocation by setting fixed water rights
L	fuzzy number	**H9**	Social problems in opposition to Mashhad water supply
S	fuzzy number	**H10**	Environmental impacts or pollution of water resources
M	number	**H11**	Rejection of Alternative treated wastewater due to cultural issues
KJ	Rank index	**H12**	The complexity of working with karst resources
R	maximum range of the decision function	**H13**	Political competition in transfer route resulted in a decline of the share Mashhad
L	minimum range of the decision function	**H14**	Possible technical problems in transfer route and installations
LAJ	gray trapezoidal areas on the left side of the possibility of distribution in Fig. 3	**H15**	social costs related to the satisfaction of residents in the origin and path
RAJ	gray trapezoidal areas on the right side of the possibility of distribution in Fig. 3	**C**	project cost
XJ	shares	**ω**	the rate of water reclamation in the basin
RI	random variables in discrete time (i = 1,…,n)	**CI**	CI index
R0 = [RI1		mean vector	

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