

Development of an algorithm for risk-based management of wastewater reuse alternatives

Hossein Shakeri and Sara Nazif

ABSTRACT

Due to water resources limitations, special attention has been paid to wastewater reuse in recent years. The risks associated with wastewater reuse alternatives should be considered in decision-making. Even when selecting the alternative with the least risk, risk management issues are of high importance. This study aims to develop an algorithm for risk-based management of wastewater reuse alternatives. This algorithm uses a three-step risk assessment and management approach. Risks are identified, then risks of alternatives are assessed, and, finally, risk management measures are proposed for risk reduction in the selected alternative. In risk identification, economic, social, health, and environmental aspects are taken into account. In risk assessment, its three components of likelihood, severity, and vulnerability are considered through a fuzzy inference system. Alternatives are prioritized based on calculated risks using a fuzzy VIKOR method. A case study is presented in which the proposed algorithm is used to select the best alternative for reuse of treated wastewater from Ekbatan Town, located in the western part Tehran in Iran. The results showed that the proposed approach provides the users with an easier understanding of risks and increases the relative confidence of decision-makers about the selection of the best alternatives for wastewater reuse and their risk control methods.

Key words | fuzzy inference system, fuzzy VIKOR, risk assessment, risk management, wastewater reuse

Hossein Shakeri

Sara Nazif (corresponding author)

School of Civil Engineering, College of Engineering,
University of Tehran,
Tehran,
Iran
E-mail: snazif@ut.ac.ir

INTRODUCTION

The increased demand for water due to population growth, the decline in quality and quantity of available water resources, as well as mismanagement of water resources have all contributed to a water crisis around the world, especially in arid and semi-arid regions. Regarding the developments in wastewater treatment technology, the reuse of treated wastewater has been considered as an alternative for water supply. Wastewater reuse involves all processes of sewage collection and treatment, and finally its discharge into water bodies or its usage for different purposes. Consumptive use of treated

wastewater should be investigated from different aspects of economic, social, health, and environmental effects.

During the past decades, extensive research has been conducted on wastewater reuse. However, there are few studies on risk analysis and management of wastewater reuse alternatives considering environmental, social, health, and economic aspects. A comprehensive risk analysis of wastewater reuse alternatives requires identification of technical, economic, environmental, and social aspects of the system and related uncertainties (Ganoulis 2005). The available studies commonly focus on identification and assessment of wastewater reuse hazards. Bayramov (2007) evaluated risks associated with reuse of treated urban wastewater only from a health perspective. He defined risk as a function of concentration of toxic substances in the reused water.

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In evaluation of wastewater reuse alternatives, beside the economic benefits of wastewater reuse, costs of utilization, operation and maintenance of wastewater reuse systems should be taken into account (Jiménez 2013). The wastewater reuse process may be energy-intensive and costly (Jiménez & Asano 2008). Furthermore, social side effects are important issues in wastewater reuse alternatives evaluation. Drechsel *et al.* (2015) argue that the importance of social hazards is to such an extent that if all technical, health, and environmental considerations are predicted, the system may still face failure when designers do not present a good evaluation of social acceptance of wastewater reuse.

Ghaneian *et al.* (2010) have studied the importance of health risk assessment of wastewater reuse in agriculture. They define risk of wastewater reuse as a product of the likelihood of health risks and the damage severity on the environment components. Alavi (2011), by creating a probabilistic Bayesian network, calculates the risk of wastewater reuse in agriculture on humans and plants. The results of this study show that cadmium pollution results in the highest risk level on humans. Detergents and nitrates result in second level of risk. Salehi & Talebi (2014) have qualitatively analyzed socio-cultural hazards of wastewater reuse. The study is based on interviews and field studies, in which women employees, workers, and students are selected as target groups. The results of this study indicate that although respondents have recognized the water crisis, they are reluctant to use treated wastewater, because of reasons such as hatred, perception of risk, and sense of mistrust. Mirabi *et al.* (2014) evaluated the risks of different methods of wastewater collection and treatment in Niasar-Iran, to select the best alternative with the least risk. For risk assessment, they used a multi-criteria decision-making method based on Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) while taking into account environmental, health, and economic aspects. In this study, risk is defined as undesirable consequences of system application from economic, health, and environmental aspects and the risk of wastewater reuse alternatives is not qualified. Furthermore, uncertainties in risk evaluation are not included in this study.

Ganoulis (2012) presented a framework for risk assessment and management of wastewater reuse. This research is one of the few studies which takes into account various

economic, health, and environmental aspects of wastewater reuse. In this study, risk components are not taken into account and risk is defined as exceedance of input loads from the allowed thresholds. For risk assessment, multi-criteria decision-making methods of goal programming and compromise programming are used. This research is only focused on wastewater reuse in agriculture and does not consider social risk assessment.

Different definitions are provided for risk in the literature. In the most important and valid definition, risk is defined as a combination of three components of likelihood (L), severity (S), and vulnerability (V) of the system ($R = L \times S \times V$) (Torres *et al.* 2009). Tchórzewska-Cieślak (2011) presented a model based on fuzzy rules for risk analysis of 'water supply systems' by considering three components including likelihood, severity, and vulnerability. However, in wastewater reuse risk assessment, less attention is paid to these components. Various methods such as statistical analysis, probability models and the theory of fuzzy sets can be used for quantifying the risks associated with wastewater reuse (Ganoulis 2009). Statistical methods are appropriate for analyzing economic risks of wastewater reuse (Chu *et al.* 2004). However, based on Chowdhury (2012), when there are insufficient environmental data, statistical analysis and probability models cannot be used for risk assessment. Fuzzy approach can consider natural and unnatural uncertainties of wastewater reuse (especially in the case of insufficient information), whereby its risk and components can be evaluated using the theory of fuzzy sets and applying fuzzy functions and numbers (Ganoulis 2009).

Although the details of risk management processes for different systems may differ a little depending on the system characteristics, in general, risk management has three important parts of identification, analysis, and control and mitigation (Baas *et al.* 2008). Metcalf *et al.* (2003) define risk management as a process of mitigating unacceptable risks. Based on PMI (Project Management Institute) (2000) definition, the risk management is a six-step process including risk management planning, risk identification, qualitative risk analysis, quantitative risk analysis, risk response planning, and risk monitoring and control. Based on this definition, Ganoulis (2012) considers the following steps for risk management of wastewater reuse in agriculture: identification of reuse alternatives, assessment of

costs in various risk levels, evaluation of technical feasibility of alternatives, selection of acceptable options and implementation of the optimal choice. In his view, multi-criterion decision-making is a useful tool for risk management of wastewater reuse. Various methods are used for multi-criterion decision-making in wastewater reuse including fuzzy Analytical Hierarchy Process (AHP) method (Chowdhury & Al-Zahrani 2014), compromise programming, and Elimination et Choice in Translating to Reality (ELECTRE) (Ganoulis 2012). Other methods such as VIKOR are also available for decision-making in risk management processes but they have not been used in risk management of wastewater reuse. Liu *et al.* (2012) employed an extended VIKOR method for risk evaluation in various failure modes of general anesthesia process in hospitals, and for selection of the most critical mode. Kim & Chung (2013) employed fuzzy VIKOR for assessing the vulnerability of the water supply system to climate change in South Korean provinces, and determined the most vulnerable province.

The current study aims to propose an approach for risk-based management of wastewater reuse alternatives by taking into account different aspects of environmental, social, health, and economic effects. To develop a comprehensive framework for risk analysis, three components of risk including likelihood, severity, and vulnerability are considered. Utilization of a fuzzy approach and a model based on analytic hierarchy in risk assessment of wastewater reuse alternatives makes it possible to take into account the associated uncertainties. Using the above framework, it is also possible to analyze the effectiveness of the suggested risk control and mitigation approaches in each of the wastewater reuse alternatives. This helps to increase the confidence of the decision-makers about their selected wastewater reuse alternative and risk control solutions.

MATERIALS AND METHODS

Treated wastewater can be used for industrial, agricultural, recreational, and domestic purposes as well as groundwater recharge. The proposed scheme in this study for risk analysis and management of wastewater reuse alternatives includes three main steps. First, hazards and sub-hazards of wastewater reuse alternatives are identified. Second, the risk of

identified hazards is assessed. Finally, based on the risk assessment results, risk management of the selected wastewater reuse alternatives is conducted. Figure 1 illustrates the algorithm suggested in this research for risk-based management of wastewater reuse alternatives.

First step – identification of hazards and sub-hazards

Hazards of urban wastewater treatment systems can be classified into the three classes of environmental, economic, and social-health hazards. The identification of hazards for a system requires an awareness of all side effects and interactions with the surrounding environment. For this purpose, review of articles, reports, technical literature, and collection of experiences, results obtained about the considered system and other wastewater reuse systems worldwide as well as interviews with experts could be helpful.

Second step – risk assessment

In this step, the risks associated with the hazards identified in the previous step, are quantified. There are different sources of uncertainties in risk analysis of wastewater reuse alternatives; therefore, fuzzy approach is selected to deal with these uncertainties. Two approaches can be used for fuzzy risk analysis including application of fuzzy operators and application of fuzzy rules. In fuzzy risk analysis of wastewater reuse alternatives, no specific mathematical or statistical relationship exists between hazards and sub-hazards, and evaluation of some hazards is done based on experts' judgment. Furthermore, it is impossible to use known functions and fuzzy operators and define new functions to calculate risk due to diversity of sub-hazards. Therefore, the fuzzy rules approach based on fuzzy inference systems is used for risk analysis. In the developed structure in this study for risk assessment, each sub-hazard affects the condition of the main hazards; for example, economic hazard is an outcome of a set of economic sub-hazards. Furthermore, the calculated risk of each sub-hazard is a combination of independent likelihood, severity, and vulnerability components. Therefore, different parts of the risk assessment model are linked together. As a result, a model based on analytic hierarchy and fuzzy inference

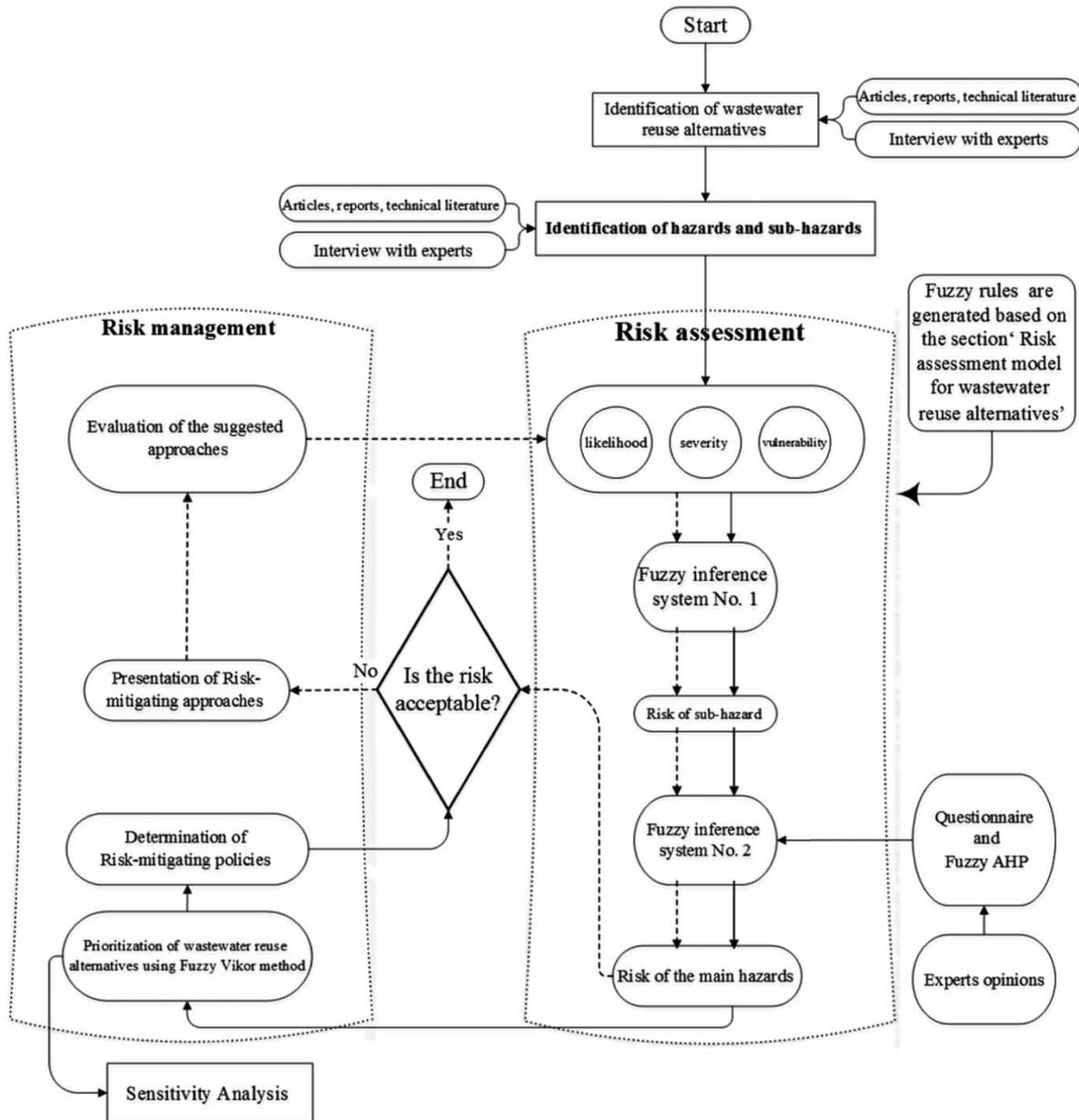


Figure 1 | The suggested algorithm for risk-based management of wastewater reuse alternatives.

system is presented for the risk assessment of wastewater reuse alternatives.

Risk assessment model for wastewater reuse alternatives

In the proposed risk assessment model, two fuzzy inference systems are included. In the first system, the risk of each

sub-hazard is calculated based on risk components (likelihood, severity, and vulnerability); then, in the second system, using the risks of sub-hazards, risks of triple hazard classes are calculated. In this model, the first and second fuzzy inference systems are named system No. 1 and No. 2, respectively.

In risk assessment of wastewater reuse alternatives, there is not commonly a clear mathematical relationship

between model inputs (risk components) and outputs (risk) and all risks are not measurable. For these reasons, fuzzy rules are elicited based on experts' experience and judgment. Fuzzy membership functions of inputs are determined using a five-scale function of linguistic values including 'very low, low, medium, high, very high', as shown in Table 1 and Figure 2. The results of fuzzy rules are also determined using the same functions. Both No. 1 and No. 2 systems are of 'Mamdani' fuzzy inference system type.

In developing Mamdani fuzzy inference systems No. 1 and No. 2, a method is required to determine the fuzzy rules' outputs based on different combinations of inputs. The method should be able to deal with lack of exact information and consider all possible combinations of risk components and different sub-hazards. For this purpose, a modified version of the method first introduced by Fares & Zayed (2010) for analyzing the risk of pipe failure, is used. In this method, the fuzzy rule includes n input with known linguistic values and an output with unknown linguistic value. Therefore, one fuzzy rule for each possible combination of fuzzy inputs is generated. Despite the relatively high computational volume, this is an efficient method for considering all possible combinations of inputs and the

model outputs will have the minimum uncertainty (Roobzahani *et al.* 2013). In this study, the consequent (output) part of each fuzzy rule is determined as a weighted combination of fuzzy rule inputs (Nozaki *et al.* 1997) as follows:

$$\text{Consequent part of each fuzzy rule} = \frac{\sum_{i=1}^n w_i \otimes A_{im}}{\sum_{i=1}^n w_i} \quad (1)$$

where i is the counter of fuzzy rule inputs, n is the number of inputs of fuzzy rule, w_i is the fuzzy weight of the i th input, and A_{im} stands for m th fuzzy membership function showing the linguistic value for the i th input. In this study, for each input, five linguistic functions exist, as shown in Table 1 and Figure 2. For fuzzy computations, addition, multiplication, subtraction, and division operations of Chen (1996) and maximum and minimum operations of Liu *et al.* (2012) are used.

In Equation (1), the weight factor (w_i) is determined based on expert judgment using fuzzy AHP in a two-stage process. First, the pairwise comparison matrix \tilde{X} is filled out by the expert using the numerical values of preferences as shown in Table 2. Each given value by the expert corresponds to a trapezoidal fuzzy number given in Table 2.

Before calculating the fuzzy weight of inputs, inconsistency of pairwise comparison matrix \tilde{X} is examined. Therefore, trapezoidal fuzzy numbers of matrix \tilde{X} are defuzzified as follows (Zheng *et al.* 2012):

$$Z = \frac{\int_z \mu_A(z)zdz}{\int_z \mu_A(z)dz} \quad (2)$$

where Z is the defuzzified value of number \tilde{A} and $\mu_A(z)$ is fuzzy membership degree of z . Therefore, matrix \tilde{X} is changed into the defuzzified matrix X . If X is a consistent pairwise comparison matrix, then \tilde{X} will be a consistent

Table 1 | Fuzzy functions of the linguistic values used for evaluation of likelihood, severity, vulnerability, and risk

Function	Linguistic values	Trapezoidal fuzzy number
\tilde{A}_{i_1}	Very low	(0,0,0.15,0.25)
\tilde{A}_{i_2}	Low	(0.15,0.25,0.35,0.45)
\tilde{A}_{i_3}	Medium	(0.35,0.45,0.55,0.65)
\tilde{A}_{i_4}	High	(0.55,0.65,0.75,0.85)
\tilde{A}_{i_5}	Very high	(0.75,0.85,1,1)

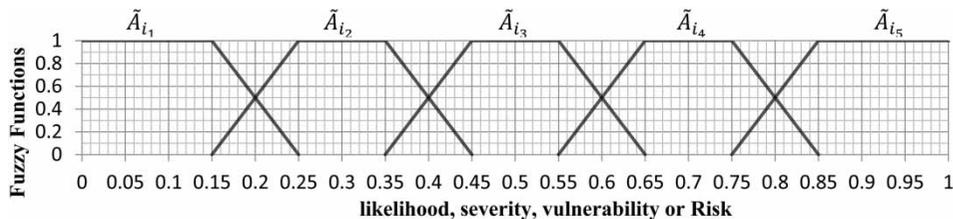


Figure 2 | Fuzzy functions of the linguistic values used for evaluation of likelihood, severity, vulnerability, and risk.

Table 2 | Numerical values of preferences in pairwise comparison (Zheng *et al.* 2012)

Linguistic	Scale of relative importance	Trapezoidal fuzzy number	Linguistic	Scale of relative importance	Trapezoidal fuzzy number
Absolute preference	9	(8,8.5,9.5,10)	Preference between 3 and 5	4	(3,3.5,4.5,5)
Preference between 7 and 9	8	(7,7.5,8.5,9)	Low preference	3	(2,2.5,3.5,4)
Very high preference	7	(6,6.5,7.5,8)	Preference between 1 and 3	2	(1,1.5,2.5,3)
Preference between 5 and 7	6	(5,5.5,6.5,7)	Equal preference	1	(1,1,1,1)
High preference	5	(4,4.5,5.5,6)			

fuzzy pairwise comparison matrix. In this process, if the inconsistency rate is less than 0.1, the pairwise comparison is acceptable; otherwise, the experts should revise their responses (Zheng *et al.* 2012). Expert Choice 11 software (Expert Choice Inc 2004) is used in order to examine the inconsistency rate of defuzzified matrix (X).

In the second stage, fuzzy weight values (\tilde{w}_i) of the i th input are determined as follows (Buckley 1985):

$$\tilde{w}_i = \left(\frac{\left(\prod_{j=1}^n a_{ij} \right)^{1/n}}{\sum_{i=1}^n \left(\prod_{j=1}^n d_{ij} \right)^{1/n}}, \frac{\left(\prod_{j=1}^n b_{ij} \right)^{1/n}}{\sum_{i=1}^n \left(\prod_{j=1}^n c_{ij} \right)^{1/n}}, \frac{\left(\prod_{j=1}^n c_{ij} \right)^{1/n}}{\sum_{i=1}^n \left(\prod_{j=1}^n b_{ij} \right)^{1/n}}, \frac{\left(\prod_{j=1}^n d_{ij} \right)^{1/n}}{\sum_{i=1}^n \left(\prod_{j=1}^n a_{ij} \right)^{1/n}} \right), \quad (3)$$

Equation (1) yields a trapezoidal fuzzy number called \tilde{G} that is located among the multiple fuzzy membership functions of Figure 2. Therefore, in order to determine the result of the fuzzy rule, the similarity of fuzzy trapezoidal number of \tilde{G} to trapezoidal linguistic functions of Figure 2 is determined. The most similar trapezoidal linguistic function to fuzzy number \tilde{G} is used as result of fuzzy rule. If A and B are two fuzzy trapezoidal numbers as $\tilde{A} = (a_1, b_1, c_1, d_1)$ and $\tilde{B} = (a_2, b_2, c_2, d_2)$, the similarity degree between these two trapezoidal fuzzy numbers of \tilde{A} and \tilde{B} in $[0, 1]$ is obtained as follows (Chen 1996):

$$F(\tilde{A}, \tilde{B}) = 1 - \frac{|a_1 - a_2| + |b_1 - b_2| + |c_1 - c_2| + |d_1 - d_2|}{4} \quad (4)$$

If more than one function has the greatest similarity to \tilde{G} , then the greatest linguistic function is selected as the

result of fuzzy rule to be more conservative. Therefore, the main differences of the proposed scheme in this study with Fares & Zayed (2010) method are as follows:

- (1) Fuzzy trapezoidal membership functions are used in this study while Fares & Zayed (2010) employed fuzzy triangular membership functions. Using trapezoidal functions increases the flexibility and is more useful for expressing linguistic values (Miao *et al.* 2014). Furthermore, trapezoidal functions outperform triangular functions in taking into account the uncertainties.
- (2) In this research, all components of Equation (1) including w_i , A_{i_m} and the fuzzy rule output are trapezoidal fuzzy numbers and fuzzy mathematical operations are used; whereas in Fares & Zayed (2010)'s method, all components of Equation (1) are defuzzified before mathematical operations.
- (3) In Fares & Zayed (2010) method, for determining the fuzzy rule result, results of Equation (1) are compared with an approximate measure obtained based on centroid of overlap areas of linguistic functions and then the linguistic value of fuzzy rule consequent part is determined. This approach increases uncertainties in calculation and decreases the accuracy of output results. However, in this study, Equation (4) proposed by Chen (1996) is used.

Fuzzy inference system No. 1

In this system, three risk components including likelihood of risk occurrence (L), severity (S), and vulnerability of wastewater reuse system (V) of each sub-hazard are inputs and the corresponding risk (R) is the only output of the fuzzy system. The likelihood of risk occurrence is defined as frequency of risk occurrence over time (Vermont 2012). Risk severity

stands for risk characteristics and describes the difficulty level of hazard (Li 2007). Vulnerability is defined as the amount or degree of damage caused to a system or society by hazard (Li 2007). Therefore, vulnerability depends on system characteristics including structural, procedural, physical properties and resilience of components. In some sub-hazards, there is no valid or specific method for determination of risk components, thereby experts' judgment is taken into account. In this study, the values presented in Table 3 are used for quantification and classification of likelihood, severity, and vulnerability of wastewater reuse system in all sub-hazards. The corresponding fuzzy numbers to the linguistic values are determined based on Table 1.

In Table 3, membership degree of the numerical values in overlap areas is less than 1, as shown in Figure 2, and the numerical values presented in this table correspond to the lower and upper limits of fuzzy membership functions. Based on this table, the likelihood at level 1 (very low) shows approximately impossible events while likelihood at level 5 (very high) corresponds to almost certain events. Therefore, likelihood of 0 shows the impossibility of occurrence and likelihood of 1 stands for certain occurrence of the sub-hazard.

Fuzzy rules of system No. 1 are generated as described in Equation (1). According to the similar role of likelihood, severity and vulnerability in definition of risk ($R = L \times S \times V$), the weight of all three components in Equation (1) is considered to be the same. As an example of developed fuzzy rules of inference system No. 1: 'if the likelihood (L) of hazard occurrence is very low, its severity (S) is high and its vulnerability (V) is low, then the risk (R) of hazard will be low'.

$$\text{If } L \text{ is } A_{1_1} \text{ and } S \text{ is } A_{2_4} \text{ and } V \text{ is } A_{3_2} \text{ Then } R \text{ is } A_{i_2} \quad (5)$$

where A_{ij} is determined based on Table 1.

Table 3 | Values of likelihood, severity, and vulnerability of wastewater reuse system

Likelihood, severity, and vulnerability	Numerical values
Very low	0–0.25
Low	0.15–0.45
Medium	0.35–0.65
High	0.55–0.85
Very high	0.75–1

Fuzzy inference system No. 2

For calculation of wastewater reuse risk from the triple aspects of environmental, economic, and social-health hazards, separate fuzzy inference systems are developed. Fuzzy rules of system No. 2 are generated as described in the section 'Risk assessment model for wastewater reuse alternatives', whereby the weight of triple hazards and weight of each sub-hazard are calculated using fuzzy AHP method and based on expert judgment. Because more than one expert is involved in determining fuzzy weights of hazards and sub-hazards, before determining the weights, integrated pairwise comparison matrix is generated, the components of which are calculated using Equation (6) (Dong *et al.* 2010):

$$\tilde{a}_{ij}^{[C]} = \left(\prod_{k=1}^n \tilde{a}_{ij}^{[k]} \right)^{\frac{1}{n}} \quad (6)$$

where n is the number of decision-makers, k is the counter of decision-makers, and i and j are row and column of pairwise comparison matrix, respectively, $\tilde{a}_{ij}^{[k]}$ is the component of i th row and j th column of pairwise comparison matrix of the k th decision-maker, and $\tilde{a}_{ij}^{[C]}$ is the component of i th row and j th column of integrated pairwise comparison matrix. It should be mentioned that for defuzzification of model outputs, center of area method which is the most common defuzzification method (Zheng *et al.* 2012) is used based on Equation (2).

Third step: risk management of wastewater reuse alternatives

In second step (risk assessment), the risks of sub-hazards and hazards for wastewater reuse alternatives are calculated. Therefore, by prioritization of alternatives based on their corresponding risks, the top alternatives for wastewater reuse with the least risk are determined. To take into account the uncertainties, fuzzy multi-criteria decision-making tools are preferred for this purpose, and in this study fuzzy VIKOR method is used. The process of risk management is performed on the selected alternatives to control and mitigate their risks in a reasonable way.

Fuzzy VIKOR method

Fuzzy VIKOR method is consistent with the risk analysis of wastewater reuse alternatives, because it both considers difference between the best and worst risk, and applies compromise programming to solve the contradiction and imbalance between the criteria (risks). By increasing the number of alternatives and analytic complexities, application of fuzzy VIKOR approach provides more benefits. In this study, the fuzzy VIKOR algorithm presented by Opricovic (2011) is used, but trapezoidal fuzzy numbers are used instead of triangular fuzzy numbers. Therefore, some changes are applied to the Opricovic (2011) method. The main steps of this algorithm are as follows:

1. The matrix of calculated environmental, social-health, and economic risks and their weight vector are developed as follows (Opricovic 2011):

$$D = \begin{matrix} & C_1 & C_2 & C_3 \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_j \end{matrix} & \begin{bmatrix} \tilde{f}_{11} & \tilde{f}_{12} & \tilde{f}_{13} \\ \tilde{f}_{21} & \tilde{f}_{22} & \tilde{f}_{23} \\ \vdots & \vdots & \vdots \\ \tilde{f}_{j1} & \tilde{f}_{j2} & \tilde{f}_{j3} \end{bmatrix} & , & W = [\tilde{w}_1 \ \tilde{w}_2 \ \tilde{w}_3] \end{matrix} \quad (7)$$

where A_j stands for alternative j , $j = 1, \dots, J$; J is the number of alternatives, C_i is the i th risk, $i = 1, 2, 3$; \tilde{f}_{ij} is the fuzzy number of the i th risk related to A_j alternative, and \tilde{w}_i is fuzzy weight for the i th risk. The weights of input risks are calculated using fuzzy AHP method. In this research, to express \tilde{f}_{ij} and \tilde{w}_i , trapezoidal fuzzy numbers of $(l_{ij}, m_{ij}, r_{ij}, t_{ij})$ and (w_1, w_2, w_3, w_4) are used, respectively. Given that the triple risks (environmental, economic, and social-health risks) as outputs of system No. 2 are crisp values, they should be fuzzified. For example, crisp value of 0.55 is presented as a trapezoidal fuzzy number of (0.55, 0.55, 0.55, 0.55).

2. The best $\tilde{f}_i^* = (l_i^*, m_i^*, r_i^*, t_i^*)$ and the worst $\tilde{f}_i^\circ = (l_i^\circ, m_i^\circ, r_i^\circ, t_i^\circ)$ values of all criterion functions, ($j = 1, 2, \dots, J$; $i = 1, 2, 3$) are determined:

$$\tilde{f}_i^* = \min_j \tilde{f}_{ij} \ , \ \tilde{f}_i^\circ = \max_j \tilde{f}_{ij} \quad (8)$$

3. The normalized fuzzy difference \tilde{d}_{ij} ($j = 1, 2, \dots, J$; $i = 1, 2, 3$) is calculated as follows:

$$\tilde{d}_{ij} = \frac{\tilde{f}_{ij} \ominus \tilde{f}_i^*}{t_i^\circ - t_i^*} \quad (9)$$

4. The values of $\tilde{S}_j = (S_j^l, S_j^m, S_j^r, S_j^t)$ and $\tilde{R}_j = (R_j^l, R_j^m, R_j^r, R_j^t)$ are computed for all alternatives:

$$\tilde{S}_j = \sum_{i=1}^3 (\tilde{w}_i \otimes \tilde{d}_{ij}) \ , \ \tilde{R}_j = \max_i (\tilde{w}_i \otimes \tilde{d}_{ij}) \ , \ j = 1, 2, \dots, J \quad (10)$$

5. The fuzzy VIKOR index, $\tilde{Q}_j = (Q_j^l, Q_j^m, Q_j^r, Q_j^t)$, is determined for all alternatives as follows:

$$\tilde{Q}_j = v \frac{\tilde{S}_j \ominus \tilde{S}^*}{S^{*t} - S^{*l}} \oplus (1 - v) \frac{\tilde{R}_j \ominus \tilde{R}^*}{R^{*t} - R^{*l}} \ , \ j = 1, 2, \dots, J \quad (11)$$

where $\tilde{S}^* = \min_j \tilde{S}_j$, $S^{*t} = \max_j S_j^t$, $\tilde{R}^* = \min_j \tilde{R}_j$, $R^{*t} = \max_j R_j^t$ and v is introduced as a weight for the strategy of maximum group utility, whereas $1-v$ is the weight of the individual regret (Opricovic 2011). The value of v is set to 0.5 in this study.

6. Finally, wastewater reuse alternatives are ranked based on fuzzy VIKOR index in ascending order. The alternative with the lowest \tilde{Q}_j will have the lowest risk (Liu et al. 2012). In the current research, the alternatives will be compared in pairs for ranking trapezoidal fuzzy numbers Q_j using Kumar et al. (2010) method. If $\tilde{Q}_1 = (Q_1^l, Q_1^m, Q_1^r, Q_1^t)$ and $\tilde{Q}_2 = (Q_2^l, Q_2^m, Q_2^r, Q_2^t)$ are the values of fuzzy VIKOR index for two reuse alternatives, the values of $K_1 = (Q_1^l + Q_1^m + Q_1^r + Q_1^t)/4$ and $K_2 = (Q_2^l + Q_2^m + Q_2^r + Q_2^t)/4$ are calculated for their comparison. If $K_1 > K_2$, then $Q_1 > Q_2$, and if $K_1 < K_2$, then $Q_1 < Q_2$. If alternatives are large in number, then the number of comparative modes significantly increases; in this case, the top alternative can be selected by ranking defuzzified values of S_j , R_j , and Q_j , based on the method proposed by Opricovic (2011).

Risk control and mitigation of wastewater reuse alternatives

The final step of risk management is risk control and mitigation of the selected alternatives. After determination of

alternative conditions and their prioritization, it is necessary to take the required measures and policies to monitor and mitigate risks of the selected alternatives.

Determination of risk-mitigating policies

To decide about risk mitigation policies, the risks of wastewater reuse alternatives are classified into five scales of ‘very low, low, medium, high, very high’ based on the available literature and information and using the linguistic values presented in Table 1. The risk mitigation strategy for each class of risk is given in Figure 3. The scale used in Figure 3 is defined in the interval [0, 1] whereby 0 stands for risk-free condition and 1 for the highest possible risk. Comparing the calculated environmental, social-health, and economic risk for the selected wastewater reuse alternative with the given scale in Figure 3, the required measures and policies for mitigation of the risk associated with that alternative are identified.

Experts have different ideas about the acceptable level of environmental, economic, and social-health risks. Based on a general definition, a level of risk whereby system performance continues and during which risk management and monitoring is performed in order to mitigate risk is called acceptable; under this condition, system performance does not require any particular risk management measure (Bell *et al.* 2006). From the perspective of human societies, acceptable risks are involuntary, with no previous history, unavoidable (even by taking precautions), and with minimal negative effects; such risk level does not cause outbreak of incurable diseases or death. From a social perspective, determination of acceptable risk is very complex and is obtained through experience and judgment. If the amount of economic benefit due to risk mitigation to a new level is less than the cost of risk mitigation measures, the level of current risk will be economically acceptable (Hunter *et al.* 2001). Based on

the above-mentioned issues about acceptable risks, two first classes of risk, i.e., ‘very low’ and ‘low’, can be considered acceptable.

Presentation of risk-mitigating approaches

After determination of general policy associated with risk level, risk mitigation approaches are suggested if they are necessary. The suggested risk mitigation approaches include procedural, structural, educational-cultural, etc., measures. To evaluate the suggested approaches’ effectiveness, the risk of wastewater reuse alternative while applying the risk mitigation measures is calculated. If the proposed risk mitigation measure does not decrease the risk level to the expected level, the proposed measure is rejected, and the next measure is examined. The process is repeated until a suitable measure is determined for risk control and mitigation of wastewater reuse alternative.

SENSITIVITY ANALYSIS

To perform sensitivity analysis, ‘the shape of fuzzy membership functions of linguistic values’ and ‘the weight of triple hazards and sub-hazards’, which have the highest impact on the results obtained from the risk analysis model presented in this study, are taken into account. By changing the above-mentioned issues, the sensitivity of final prioritization of wastewater reuse alternatives to these changes is examined.

Shape of fuzzy membership functions

In the first case, the small base of trapezoidal functions, i.e., the interval that membership degree remains equal to 1 is kept fixed while the overlap area of fuzzy membership functions as legs of the trapezoidal functions have been changed. The other variables are constant. In the second case, the small

very low	low	medium	high	very high	
0	0.2	0.4	0.6	0.8	1
No corrective actions required	watch out and monitoring required	Mitigation actions in the long term	Mitigation actions in the short term	Immediate mitigation actions required	

Figure 3 | Risk scale and risk-mitigating policies.

base of trapezoidal functions changes whereas other variables are constant.

Weight of triple sub-hazards and hazards

For sensitivity analysis of the model to the weights of triple sub-hazards and hazards, Alinezhad & Esfandiari's (2012) method is used. In this method, the weights of all criteria (risks) are defuzzified. If weight of the k th criterion changes by Δ_k , then the new weight of all criteria (\acute{w}_i) for two modes of $i \neq k$ and $i = k$ will be obtained based on Equation (12):

$$\acute{w}_i = \begin{cases} w_i + \Delta_k & \text{if } i = k \\ \frac{w_i(w_k - 1) + \Delta_k w_i}{w_k - 1} & \text{if } i \neq k \end{cases} \quad (12)$$

Based on the above method, if the weight of hazard k changes by Δ_k amount, then the values of S_j and R_j and finally the value of fuzzy VIKOR index of the j th alternative (Q_j) change, thereby the alternatives are again prioritized. Moreover, as the weight of one sub-hazard changes through using the above method, the result of fuzzy rule in system No. 2 changes, thereby calculation of triple risks and alternative prioritization are again performed.

CASE STUDY

The proposed risk analysis algorithm in this research is examined in risk management of the wastewater reuse

system of Ekbatan Town, located in the western part of Tehran, Iran (Figure 4). This wastewater treatment plant is located in Ekbatan Town and it is possible to analyze social-health, economic, and environmental hazards in a small size. Average output flow rate of the Ekbatan wastewater treatment plant is $550 \text{ m}^3/\text{h}$ and maximum output flow rate is $700 \text{ m}^3/\text{h}$. The treatment process includes preliminary treatment, biological treatment (anaerobic, anoxic, aeration, secondary sedimentation), and disinfection (Tehran Water Supply and Water and Wastewater Treatment Company 2015). The characteristics of Ekbatan wastewater treatment plant effluent are given in Table 4. The annual costs of operation and maintenance of Ekbatan wastewater treatment plant is 10 billion Rials.

There are three active alternatives for reuse of treated wastewater including 'green space irrigation of wastewater treatment plant of Ekbatan' G1, 'green space irrigation of Ekbatan Town' G2, and 'discharge into Firozabad River' G3. Based on local survey and interview with experts in the town and wastewater treatment plant, two more potential alternatives for wastewater reuse including 'recreational applications such as fountain, artificial ponds and artificial lake in Ekbatan Town or in places such as Eram Park located 5 km away from Ekbatan Town' G4 and 'irrigation of Chitgar Forest Park located 12 km away from this wastewater reuse system' G5, are also identified. The required water quality for each wastewater reuse alternative is determined based on local standards developed by Vice Presidency for Strategic Planning and

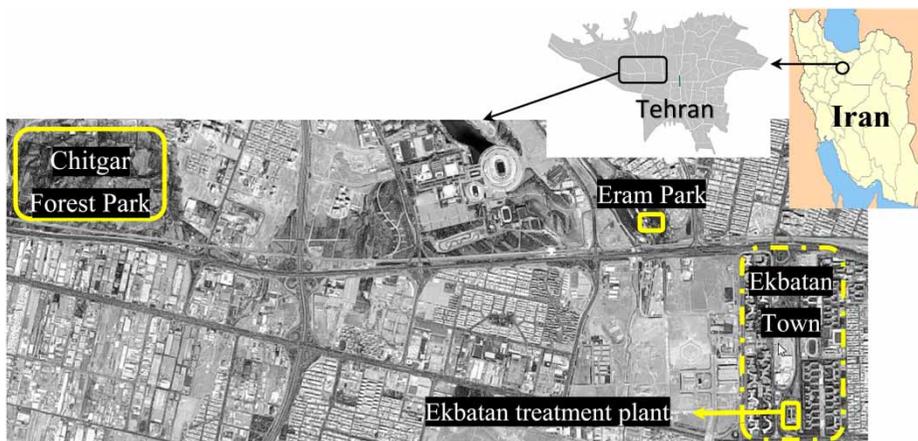


Figure 4 | Location of Ekbatan treatment plant in Tehran City in Iran.

Table 4 | The characteristics of Ekbatan treatment plant effluent (Tehran Water Supply and Water and Wastewater Treatment Company 2015)

Parameters	Values	Parameters	Values
Maximum effluent rate (m ³ /hr)	700	Minimum effluent rate (m ³ /hr)	450
Temperature (°C)	23–26	Average effluent rate (m ³ /hr)	550
Phosphate (mg/L)	2.71	pH	7–7.5
Sulfate (mg/L)	92.20	BOD ₅ (mg/L)	2–10
Nitrate (mg/L)	<40	COD (mg/L)	15–30
Nitrite (mg/L)	<1	TSS (mg/L)	8
Chloride (mg/L)	102.96	TDS (mg/L)	400–500
EC (µs/cm)	830	DO (mg/L)	4
Total coliform (number per 100 mL)	<1,000	<i>E. coli</i> (number per 100 mL)	<400
Heavy metals	0	Parasites (number per liter)	0

Supervision of Islamic Republic of Iran (2010) as given in Table 5. Based on this table, only total dissolved solids (TDS) (400–500 mg/L) and electrical conductivity (EC) (830 µs/cm) are a little more than required values for some reuse options.

Table 5 | The required quality for wastewater reuse for different purposes (Vice Presidency for Strategic Planning and Supervision of Islamic Republic of Iran 2010)

Parameters	Recreational and environmental	Agriculture and irrigation (non-food)	Artificial recharge	Discharge to surface water
pH	6–9	6–8.5	5–9	6.5–8.5
BOD ₅ (mg/L)	5	100	30	30
COD (mg/L)	–	200	60	60
TSS (mg/L)	–	100	–	40
TDS (mg/L)	750	450	–	–
DO (mg/L)	>5	>2	–	>2
Phosphate (mg/L)	–	50	6	6
Sulfate (mg/L)	–	500	400	40
Nitrate (mg/L)	45	–	10	50
Nitrite (mg/L)	–	–	10	10
Chloride (mg/L)	–	600	600	600
EC (µs/cm)	–	700	–	–
<i>E. coli</i> (number per 100 mL)	400	400	400	400
Total coliform (number per 100 mL)	2,000	1,000	1,000	1,000
Parasites (number per liter)	–	1	–	–

The daily average volume of Ekbatan treatment plant effluent is 13,200 m³. The green space areas around Ekbatan treatment plant (G1) and within Ekbatan Town (G2) are about 7 hectares and 40 hectares with irrigation water demands of 640 m³ and 2,000 m³ (Babaei 2012), respectively. Currently, 10,560 m³ of daily wastewater treatment plant effluent is discharged into Firozabad River (G3).

In order to obtain the weights and experts' judgment about hazards and sub-hazards of Ekbatan system, the pairwise comparison (or outranking) matrix was prepared in the form of a questionnaire and 11 experts in different fields of wastewater reuse from different academic or professional positions who have managerial, administrative, or research backgrounds completed them.

RESULTS AND DISCUSSION

After identification of active and potential wastewater reuse alternatives of Ekbatan Town, in the first stage, hazards and sub-hazards of wastewater reuse alternatives from different aspects, after an extensive review of articles, reports, technical literature, were determined as shown in Table 6.

In the second step, the risk assessment model is developed. For this purpose, the pairwise comparison matrix is developed for determining the relative weights of hazards based on the experts' answers to the questionnaires. The incompatibility rate was estimated and was less than 0.1 for all questionnaires. By generating the aggregated

Table 6 | Hazards and sub-hazards of wastewater reuse alternatives of Ekbatan system

(1) Environmental hazards	(2) Social and health hazards	(3) Economic hazards
(1-1) Contamination of soil resources	(2-1) Disease outbreaks caused by direct or indirect wastewater use	(3-1) Significant costs of system operation and maintenance and impossibility to provide them at the right time
(1-2) Contamination of surface water resources	(2-2) Social resistance in form of no use of wastewater or no use of products or places where wastewater is used	(3-2) No access to the required raw materials and technology
(1-3) Contamination of underground water resources	(2-3) Social protest against inappropriate function of wastewater reuse system	(3-3) No revenue streams from wastewater sale or other by-products of wastewater reuse system
(1-4) Contamination of food crops	(2-4) An undesirable prospect of urban, tourism, and recreational areas (due to bad odor and presence of insects)	(3-4) Physical and hydraulic system failure
(1-5) Harmful effects on reproduction and development of non-edible plants		
(1-6) Harmful effects on animals		
(1-7) Ecosystem imbalance (increase or decrease of a specific species)		

comparison matrix of the experts' opinions, fuzzy weights of triple hazards and sub-hazards were calculated. Results are shown in [Table 7](#).

Then the frequency of sub-hazards' occurrence during the system performance was determined in order to determine the likelihood of occurrence. Historical records of system effluent characteristics as well as expert judgment for sub-hazards that have not happened in the past are considered to determine the occurrence likelihood of the sub-hazards based on the classification presented in [Table 3](#). The results are given in [Table 8](#). The severity of the sub-hazards is determined based on 'the percentage of exceedence from the standards values' as shown in

[Table 9](#) and results are shown in [Table 8](#). It should be emphasized that in this study it is considered that hazards occur just when the related factors exceed the standard values.

In sub-hazards for which a specific numerical value cannot be determined as the maximum or minimum allowable amount (standard) (e.g., social and cultural sub-hazards), information and data that are available in the literature and experts' judgment are used for determining the sub-hazard severity. The given classification for hazards' severity in [Table 9](#) is determined based on an assessment of reports as well as experts' judgment in order to facilitate and organize the process of decision-making; undoubtedly,

Table 7 | Fuzzy weights of triple hazards and sub-hazards

Hazard	Sub-hazards	Fuzzy weight	Hazard	Sub-hazards	Fuzzy weight
Environmental hazards (0.12,0.15,0.23,0.3)	1-1	(0.09,0.12,0.20,0.26)	Social and health hazards (0.39,0.50,0.77,0.95)	2-1	(0.41,0.50,0.71,0.84)
	1-2	(0.15,0.19,0.30,0.39)		2-2	(0.08,0.10,0.15,0.20)
	1-3	(0.19,0.25,0.39,0.49)		2-3	(0.13,0.16,0.25,0.31)
	1-4	(0.06,0.08,0.13,0.17)		2-4	(0.05,0.07,0.10,0.12)
	1-5	(0.04,0.06,0.09,0.12)	Economic hazards (0.12,0.15,0.24,0.31)	3-1	(0.19,0.25,0.39,0.50)
	1-6	(0.04,0.05,0.08,0.10)		3-2	(0.13,0.16,0.25,0.33)
	1-7	(0.04,0.05,0.08,0.11)		3-3	(0.08,0.10,0.16,0.20)
			3-4	(0.23,0.29,0.45,0.56)	

Table 8 | Likelihood, severity, and vulnerability of sub-hazard of wastewater reuse alternatives of Ekbatan system

Wastewater reuse alternatives															
Sub-hazard	G ₁			G ₂			G ₃			G ₄			G ₅		
	Likelihood	Severity	Vulnerability												
1-1	0.19	0.04	0.03	0.21	0.04	0.04	0.20	0.04	0.01	0.17	0.04	0.04	0.19	0.04	0.04
1-2	0.21	0.03	0.01	0.24	0.03	0.04	0.26	0.03	0.12	0.20	0.03	0.05	0.23	0.03	0.08
1-3	0.05	0.05	0.05	0.08	0.05	0.08	0.10	0.05	0.05	0.20	0.05	0.05	0.08	0.05	0.10
1-4	0.10	0.03	0.15	0.14	0.03	0.25	0.38	0.03	0.20	0.05	0.03	0.25	0.12	0.03	0.30
1-5	0.36	0.03	0.05	0.44	0.03	0.20	0.34	0.03	0.10	0.08	0.03	0.05	0.44	0.03	0.23
1-6	0.13	0.01	0.01	0.17	0.01	0.05	0.35	0.05	0.12	0.30	0.05	0.08	0.20	0.01	0.10
1-7	0.37	0.02	0.05	0.38	0.02	0.05	0.45	0.02	0.08	0.40	0.02	0.15	0.40	0.02	0.10
2-1	0.10	0.01	0.02	0.14	0.01	0.04	0.16	0.01	0.14	0.08	0.01	0.03	0.14	0.01	0.08
2-2	0.02	0.01	0.01	0.30	0.05	0.03	0.20	0.05	0.05	0.25	0.02	0.02	0.30	0.03	0.04
2-3	0.03	0.15	0.04	0.35	0.17	0.10	0.36	0.20	0.15	0.30	0.10	0.10	0.25	0.17	0.15
2-4	0.05	0.03	0.10	0.17	0.12	0.15	0.20	0.05	0.10	0.26	0.06	0.17	0.18	0.10	0.16
3-1	0.28	0.02	0.05	0.37	0.05	0.10	0.25	0.03	0.10	0.45	0.10	0.10	0.70	0.20	0.30
3-2	0.18	0.02	0.04	0.20	0.04	0.10	0.15	0.02	0.10	0.20	0.08	0.15	0.20	0.10	0.25
3-3	0.15	0.1	0.05	0.30	0.20	0.20	0.80	0.90	0.03	0.25	0.20	0.20	0.35	0.25	0.30
3-4	0.18	0.03	0.05	0.28	0.10	0.16	0.15	0.20	0.20	0.25	0.16	0.10	0.60	0.25	0.35

Table 9 | Classification of hazard severity

Numerical values	Severity	The values exceed the standard of parameters determining hazards (%)
0–0.25	Very low	0–20
0.15–0.45	Low	20–40
0.35–0.65	Medium	40–60
0.55–0.85	High	60–80
0.75–1	Very high	More than 80%

more detailed studies are needed for their exact determination. Health and environmental standards required for assessment of hazards associated with using wastewater reuse along with standards of each wastewater reuse application are taken from local standards developed by Vice Presidency for Strategic Planning and Supervision of Islamic Republic of Iran (2010) (Table 5). Furthermore, in examining the economic sub-hazards, operation and maintenance costs and the revenue from the wastewater reuse were compared with conventional costs of similar wastewater reuse systems. Due to no access to exact information of costs and revenues, the severity of sub-hazards was determined based on expert judgments.

To determine the system vulnerability when faced with each wastewater reuse sub-hazard, it is necessary to determine the degree of damage that is caused by that sub-hazard in the system. In the current study, based on literature review on environmental, social-health, and economic damages that could occur in wastewater reuse systems (Peavy *et al.* 1985; Metcalf *et al.* 2003; EPA 2009; Ivarsson & Olander 2011), systems' vulnerability is classified into five classes, as shown in Table 10. In this table, the most important possible damage of the wastewater reuse system are summarized and classified into five groups. This table can be extended to include a wider range of possible damage of wastewater reuse. Based on ERM (Enterprise Risk Management) Application Guide (2011), a specific percentage of average costs of a wastewater reuse system is considered as the amount of economic damage for each five-scale mode. It should be emphasized that the given values in this table just include direct economic costs of reuse hazards. The indirect costs as a result of social-health and environmental damages are not included in these values because they are separately considered. In order to determine vulnerability of wastewater reuse alternatives of the Ekbatan system based on Table 10, the experts'

Table 10 | Classification of wastewater reuse system vulnerability

Vulnerability	Numerical value	Explanations		
		Environmental (Metcalf <i>et al.</i> (2003); EPA (2009); Ivarsson & Olander (2011))	Social-health (Peavy <i>et al.</i> (1985))	Economic
Very low	0–0.25	Minor changes in environment which can be fully solved by self-purification capacity of nature	Diseases without the need for special treatment and hospitalization such as very mild skin or lung complications	<1 billion Rial economic loss
Low	0.15–0.45	Relatively minor contamination of water and soil resources not leading to toxicity of widespread areas	Diseases with short-terms side effects such as mild gastrointestinal effects (nausea and vomiting), short-term skin and lung side effects	1–3 billion Rial economic loss
Medium	0.35–0.65	Contamination of non-edible plants as well as toxicity of a huge part of soil and water resources	Relatively severe gastrointestinal (cholera, typhoid, etc.), lung, and skin diseases	3–6 billion Rial economic loss
High	0.55–0.85	Destruction of a relatively large part of ecosystem and drastic changes of water and soil resources	Incurable diseases such as hepatitis, polio, and different types of cancer	6–10 billion Rial economic loss
Very high	0.75–1	Irreparable environmental pollution, complete change of soil structure and uselessness of water resources	Death and mortality	More than 10 billion Rial economic loss

Rial is the currency of Iran. 1 USD is approximately equal to 30,000 Rial (in 2015).

judgment was considered. Furthermore, the previous reports and researches associated with the considered reuse system were also reviewed.

Finally, using the values of likelihood of occurrence, severity, and vulnerability presented in Table 8, the risks of triple hazards and sub-hazards of wastewater reuse alternatives of the Ekbatan system were determined using fuzzy inference systems No. 1 and No. 2, as shown in Table 11. Prioritization of wastewater reuse alternatives of the Ekbatan system was performed using fuzzy VIKOR method and the results are shown in Table 12.

Based on the results given in Table 12, G₁ alternative has the lowest risk and is the best alternative. By comparing the calculated risk of environmental, social-health, and economic hazards with the given scale in Figure 3, it is understood that the risk level of the selected alternative of wastewater reuse for all three hazards is 'very low'. Therefore, in this case, the risks are acceptable. In addition to the first alternative, G₂ alternative lies within the 'very

low' class of risk in terms of all three main hazards. In this alternative, among 15 examined sub-hazards, 13 of them lie within 'very low' risk class and two of them are in 'low' risk level. Therefore, risks of this alternative are also acceptable, and system performance does not require any special risk management measures or corrective actions. In sub-hazard (1-5), particularly including green spaces of Ekbatan Town, as well as sub-hazard (3-3) associated with the revenue from wastewater reuse for irrigation of Ekbatan Town, according to Figure 3, control and monitoring is suggested in order to control and mitigate the current risk level in case of no increase in risk levels of other sub-hazards (especially economic risks).

G₃ alternative, however, is eliminated according to prioritization of alternatives and the calculated risk of its sub-hazards. In this alternative, the risks associated with social-health and economic sub-hazards (especially 3-3 sub-hazard, there is no revenue from wastewater reuse or its by-products in this alternative) have higher or sometimes significant values compared to the other two alternatives. Given that G₃ alternative discharges excess effluent of Ekbatan treatment plant into Firozabad River, other potential alternatives of the Ekbatan system can be used to replace this alternative and manage excess wastewater. Based on given data about water demand of G₁ and G₂ alternatives and daily effluent of the system, about 20% of the treated wastewater is daily used for G₁ and G₂ alternatives and there is no specific usage for the remaining effluent which is about 10,560 m³ per day. Based on prioritization of alternatives and the results of calculated risks of the remaining two alternatives (G₄ and G₅), G₄ alternative can be considered. Given that risks of this alternative of wastewater reuse in Ekbatan Town are also acceptable, application of risk mitigation strategies in this alternative is not justified.

For sensitivity analysis of the proposed risk assessment model, 'the shape of fuzzy membership functions of linguistic values' and 'the weight of triple hazards and sub-hazards' are taken into account. In the former case, the small base of trapezoidal functions, i.e., the length with membership degree value is equal to 1 remains constant; overlap area changes as legs of the trapezoidal functions change, whereas the other variables are constant. Through applying $\pm 10\%$ change to the overlap area, the risks of hazards and sub-hazards are changed but alternatives' prioritization does

Table 11 | The calculated risk of triple hazards and sub-hazards of wastewater reuse alternatives of Ekbatan system

Sub-hazard	Wastewater reuse alternatives				
	G ₁	G ₂	G ₃	G ₄	G ₅
1-1	0.1081	0.1081	0.1104	0.1037	0.1081
1-2	0.1081	0.1016	0.0995	0.1104	0.1037
1-3	0.0995	0.0995	0.0995	0.1104	0.0995
1-4	0.0995	0.0995	0.2102	0.0995	0.0995
1-5	0.1249	0.2745	0.0995	0.0995	0.2813
1-6	0.0995	0.1037	0.0995	0.0995	0.1104
1-7	0.1483	0.1701	0.3000	0.2102	0.2102
2-1	0.0995	0.0995	0.1016	0.0995	0.0995
2-2	0.0995	0.0995	0.1104	0.0995	0.0995
2-3	0.0995	0.1483	0.2102	0.0995	0.1483
2-4	0.0995	0.1037	0.1104	0.1483	0.1334
3-1	0.0995	0.1483	0.0995	0.3000	0.4000
3-2	0.1059	0.1104	0.0995	0.1104	0.2102
3-3	0.0995	0.2102	0.6000	0.2102	0.3000
3-4	0.1059	0.1249	0.2102	0.1249	0.4000
Environmental risk	0.0995	0.1037	0.1081	0.1081	0.1081
Social and health risk	0.0995	0.0995	0.1081	0.0995	0.0995
Economic risk	0.0995	0.1081	0.3000	0.3000	0.5000

Table 12 | Prioritization of wastewater reuse alternatives of Ekbatan system using Fuzzy VIKOR method

Alternatives	\tilde{S}_j	\tilde{R}_j	\tilde{Q}_j	\tilde{K}_j
G ₁	(0,0,0,0)	(0,0,0,0)	(0,0,0,0)	0
G ₂	(0.0625,0.0777,0.1200,0.1553)	(0.0598,0.0744,0.1150,0.1487)	(0.0535,0.0666,0.1029,0.1331)	0.0890
G ₃	(0.5772,0.7308,1.1198,1.4098)	(0.3938,0.5031,0.7683,0.9536)	(0.4112,0.5230,0.8000,1)	0.6836
G ₄	(0.1834,0.2277,0.3515,0.4560)	(0.1211,0.1507,0.2328,0.3011)	(0.1285,0.1598,0.2467,0.3196)	0.2137
G ₅	(0.2455,0.3045,0.4700,0.6107)	(0.1245,0.1538,0.2373,0.3093)	(0.1523,0.1886,0.2911,0.3778)	0.2527

not change. For example, with a 10% increase in the overlap area, sub-hazards' risk decreases by 1.71% and the triple risk by 1%, on average, however prioritization of alternatives does not change. However, when change is more than 10%, prioritization of alternatives changes. For example, with a 15% reduction in overlap area, prioritization of alternatives is changed as shown in Table 13.

In another case, small base of trapezoidal function, i.e., length with membership degree is equal to 1, is changed while other characteristics are constant. Through application of ±10% change, prioritization of alternatives does not change. For example, by an increase of 10%, sub-hazards' risk increases by 1.99% and triple risk by 1.29%,

on average, but prioritization of alternatives does not change. By application of changes greater than 10%, prioritization of alternatives will change. For example, by an increase of 15%, new prioritization of alternatives is obtained as given in Table 13.

For sensitivity analysis of the model results to the weight of triple hazards and sub-hazards, weight of each hazard and sub-hazard is changed according to coefficient of variation (standard deviation/mean) of the assigned weights by different experts. Coefficients of variation of environmental, social-health, and economic hazards are 0.1989, 0.1439, and 0.3972, respectively. Moreover, coefficients of variation for environmental sub-hazards from sub-hazard

Table 13 | Sensitivity of prioritization of alternatives to change in membership functions overlap area

Case 1

Alternatives	Initial prioritization	With 10% reduction in overlap area		With 15% reduction in overlap area	
		\tilde{Q}_j new	New prioritization	\tilde{Q}_j new	New prioritization
G ₁	1	(0,0,0,0)	1	(0,0,0,0)	1
G ₂	2	(0.0368,0.0459,0.0708,0.0916)	2	(0.0353,0.0440,0.0679,0.0878)	2
G ₃	5	(0.4112,0.5230,0.8000,1)	5	(0.2641,0.3352,0.5132,0.6433)	4
G ₄	3	(0.1286,0.1598,0.2468,0.3197)	3	(0.1222,0.1519,0.2345,0.3038)	3
G ₅	4	(0.1523,0.1886,0.2911,0.3786)	4	(0.4109,0.5219,0.7987)	5

Case 2

Alternatives	Initial prioritization	Small base of trapezoidal function increases by 10%		Small base of trapezoidal function increases by 15%	
		\tilde{Q}_j new	New prioritization	\tilde{Q}_j new	New prioritization
G ₁	1	(0,0,0,0)	1	(0,0,0,0)	1
G ₂	2	(0.1098,0.1394,0.2135,0.2678)	2	(0.0959,0.1215,0.1862,0.2357)	2
G ₃	5	(0.4112,0.5230,0.8000,1)	5	0.2432,0.3086,0.4756,0.5928)	4
G ₄	3	(0.1617,0.2022,0.3115,0.4000)	3	(0.1471,0.1837,0.2832,0.3642)	3
G ₅	4	(0.1856,0.2311,0.3559,0.4592)	4	(0.4109,0.5219,0.7987,1)	5

1-1 to 1-7 are 0.3989, 0.3814, 0.1977, 0.6891, 0.1950, 0.4798, and 0.3938, respectively. Coefficients of variation for social-health sub-hazards from sub-hazard 2-1 to 2-4 are 0.1645, 0.4719, 0.3990, and 0.3416, respectively, and these values for economic sub-hazards from sub-hazard 3-1 to 3-4 are 0.1920, 0.2708, 0.4940, and 0.1423, respectively. Therefore, each sub-hazard or hazard weight is changed separately as follows:

$$\Delta = \pm(\text{Coefficient of variation} \times \text{weight}) \tag{13}$$

where Δ is the amount of change in sub-hazard or hazard weight. Using this method, the differences in experts' judgments is taken into account in the process of sensitivity analysis. Hereby, in the first mode, by considering the weight of sub-hazards and other variables to be constant, the weight of one of the triple hazards is changed and weights of other hazards are modified based on Equation (12). This process affects the calculated values for the VIKOR index. For example, Table 14 shows the sensitivity of the model to the change in the weight of social-health hazard. Based on these results, with a 15% decrease in the weight of social-health hazards, prioritization of wastewater reuse alternatives of Ekbatan does not change. Similar changes are also considered for weights of economic and environmental hazards and results show that the prioritization of alternatives does not change even with a decrease or increase in environmental or economic hazard by 20% and

40%, respectively. However, through applying changes greater than coefficient of variation of experts' answers, prioritization of wastewater reuse alternatives of Ekbatan will also change, whereby the amount of applied changes (%) for each environmental, social-health, and economic weight is different. For example, with a 55% decrease in weight of social-health hazard, prioritization of wastewater reuse alternatives changes, the results of which are presented in Table 14.

In the second mode, by considering the weight of hazards and other variables to be constant, the weight of sub-hazards is changed which results in changes in fuzzy rules and their results in system No. 2. For example, by increasing and decreasing the weight of sub-hazard (1-1) by 40%, prioritization of wastewater reuse alternatives of the Ekbatan system does not change and remains constant. The investigation of the sensitivity of system results to other sub-hazards weights showed that prioritization of wastewater reuse alternatives of the Ekbatan system is not sensitive to the change of sub-hazards weights while this change is less than coefficient of variation of experts' judgments. However, by applying changes greater than coefficient of variation of experts' judgments, prioritization of wastewater reuse alternatives of the Ekbatan system changes, and the amount of the applied change (%) is different for the weight of each environmental, social-health, and economic sub-hazards. For example, through increasing the weight of sub-hazard (3-1) – significant cost of system

Table 14 | Sensitivity of prioritization of alternatives to change in weight of social-health hazard

Hazard (i th)	Initial weight	Weight changes of hazard (i th)	Δ_k	Weight of environmental hazard (new)	Weight of social-health hazard (new)	Weight of economic hazard (new)
Social-health	0.6572	-15%	-0.0986	0.2109	0.5586	0.2432
		-55%	-0.3615	0.3365	0.2957	0.3881
		With 15% reduction in weight of social-health hazard		With 55% reduction in weight of social-health hazard		
Alternatives	Initial prioritization	New prioritization		New prioritization		
G ₁	1	1		1		
G ₂	2	2		2		
G ₃	5	5		4		
G ₄	3	3		3		
G ₅	4	4		5		

operation and maintenance and failing to fulfill them at the right time – by 60%, prioritization of wastewater reuse alternatives changes.

CONCLUSION

This research addressed a methodology for risk-based assessment of wastewater reuse alternatives. Three components of risk (i.e., likelihood, severity, and vulnerability) are considered in risk analysis to provide a more comprehensive and reliable evaluation of alternative risks of wastewater reuse. Through applying fuzzy theory and developing multiple fuzzy rules, the uncertainties in experts' judgment about values of risks components are minimized thereby facilitating the possibility of simultaneous evaluation of various sub-hazards of a wastewater reuse system. However, it should be emphasized that reasonable and accurate determination of hazards and sub-hazards as well as the risk components for each of them is of high importance in correct decision-making about wastewater reuse alternatives even when using the proposed algorithm. Moreover, based on fundamental concepts of fuzzy inference systems and results of application of similar systems to other cases, the proposed risk assessment scheme yields greater values of risks (Roozbahani *et al.* 2013); therefore, the results are conservative and can be used with enough reliability in the risk management process. Regarding the important role of experts' judgment and experiences in risk assessment because of lack of statistical relationship between model inputs and outputs as well as impossibility of measuring the risk, application of fuzzy functions in risk assessment of wastewater reuse alternatives not only increases the validity of risk analysis, but provides users with a better understanding of the process and easier application. From this perspective, in all stages of model construction and risk assessment, methods based on linguistic functions and fuzzy approach were used. Risk leveling in the risk management step and determination of risk control and mitigation policies based on the desired level of risk, improve and simplify the risk management process of wastewater reuse alternatives; which both reduces the environmental, social-health, and economic costs of this process and accelerates future decision-making and programming.

In this research, the wastewater reuse system of Ekbatan Town was analyzed using three active alternatives; after risk assessment and prioritization of alternatives using fuzzy VIKOR method, 'green space irrigation of treatment plant' was selected as the best alternative. In addition, the 'green space irrigation of Ekbatan Town' alternative was selected and maintained based on fuzzy VIKOR index value and minimum calculated risks. However, 'discharge of excess of treated wastewater into Firozabad River' alternative can be eliminated due to the high level of risk; instead, other potential alternatives of reuse of Ekbatan system effluent such as 'recreational and irrigation usage in Eram park' and 'irrigation of Chitgar park' can be used. According to acceptable condition risks of the selected alternatives for reuse of Ekbatan system effluent as well as minimum risks of sub-hazards, more reduction in risk level does not seem logical. Application of risk-mitigating approaches in these cases does not provide considerable change in risks' values, but also increases economic risks. The proposed framework allows the analysis of effectiveness of proposed risk mitigation and control approaches in each wastewater reuse sub-hazard; in addition, by considering a conservative approach in the design of risk assessment and calculation model, this framework increases the relative confidence of decision-makers about collecting the top alternatives of wastewater reuse and their risk control measures. In conclusion, model sensitivity to effective factors including 'shape of fuzzy membership functions' and 'weight of hazards and sub-hazards' was analyzed, and the obtained results suggest suitable stability of the model against the applied changes.

Providing more frequent and precise measurements of wastewater treatment plant effluent quality and quantity and considering a wider range of quality indices as well as paying attention to new hazards in the study area, can improve the evaluations of wastewater reuse risk. In addition, this study can be further expanded through the following issues:

1. More accurate investigations on acceptable risk level.
2. Considering uncertainties in reused water usage.
3. More accurate calculation of the intervals associated with each of the fuzzy functions of the linguistic values that affect the calculation of risk.

4. Sensitivity analysis on assumptions made in this study such as shape of fuzzy membership functions and weight of triple sub-hazards and hazards.
5. Investigation on allowable values of economic and financial hazards and finding more extensive patterns of economic criteria for estimating economic risks.

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