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RESEARCH PAPER

Risk Assessment and Management of Wastewater Collection and Treatment Systems Using FMADM Methods

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Abstract To secure operation of wastewater collection systems and treatment plants, it is so necessary to detect any probable vulnerability and estimate undesirable events and severity of their effects. In this paper, a model has been developed to evaluate system operation management in order to deal with serious conditions. The risk assessment phase contains three parts including evaluation of probability of threats, severity of their effects–consequences and vulnerability of the system components. These parameters could be measured by fuzzy multi-attribute decision-making techniques by questionnaire and through defining some criteria for threat assessment. In the risk management phase, risk-controlling approaches are developed by professionals based on risk assessment results and prioritizing the threats. Risk assessment and management model has been conducted through two case studies in Tehran, respectively, as a sample of wastewater collecting and the biggest wastewater treatment system in Iran. The results show that "entry of chemical contaminant" and "change in wastewater quality" were taken the highest score for the west Tehran wastewater collection network and "earthquake" in processing units, sludge treatment and gas storages were taken the highest score in the south Tehran wastewater treatment, reduction strategies of which were presented for dealing of each risk.

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1 Introduction

Wastewater is consumed water whose chemical, physical and biological properties have been changed and has lost its ability to use and might be reused after purification at the best condition (Metcalf and Eddy Inc et al. 2003). Several researches have been conducted in order to evaluate water and sewage operation systems. Some of the concepts related to risk need to be defined prior to the literature review. In this research, threat is an event or incident having low incomputable probability and high negative consequences (federal emergency management agency: FEMA 2005). Risk is defined as a threat probability and severity of loss or damage. While there is a possibility of occurring desirable or undesirable phenomena, risk refers to undesirable one (Garvey 2009). Loss rate in each system depends on both accident severity and system vulnerability. Therefore, risk can be defined as $R = T \times C \times V$ where T is threat rating, C is consequence rating, and V refers to vulnerability rating (Torres et al. 2009).

Due to the complexities of water and wastewater systems and uncertainties affecting them and the threatening hazards, effective risk analysis is hard to accomplish by using most of the available risk assessment techniques. Some models can be found in the literature, which are still being used by water and wastewater utilities for risk assessment. Among them, fault tree analysis (Mays 2004), Markov models (Tidwell et al. 2005), Monte Carlo simulation (Rausand and Høyland 2004) and Bayesian networks (Babovic et al. 2002) have been used in different cases in recent years. Some of important researches carried out about the risks in water and wastewater systems are as follows.

Demotier et al. (2003) studied the risk rating of producing clean water in treatment plants according to water features, system specification and different related failure modes. This study was based on an environmental risk view point. Nazif and Karamouz (2009) defined a combinational indicator called system readiness index (SRI) in order to evaluate the function of water distribution system. This index was developed based on three concepts including reliability, flexibility and reversibility. Warren et al. (2009) examined role of emergency response plan (ERP) in water and sewage network. They distinguished necessity of facility requirement for ERP and obtained legal instructions related to emergency facility planning. Environmental risk of municipal wastewater treatment was studied by Escer et al. (2010). He calculated the risk rate of hazardous material presence from the conventional environmental risk equation as: $R =$ PEC/PNCE, where PEC is the predicted environmental concentration, PNEC is predicted no-effects concentration, and R stands for risk rate. Through a similar study, Meritxell et al. (2010) removed pharmaceutical agents from wastewater and evaluated the environmental risk using risk factors. Bagheri et al. (2010) conducted a study in the field of reconstructions and water management policy's impacts on water system failure after Bam's catastrophic earthquake in 2003. By a system dynamics model, they showed that more authoritarian water management policies should be taken in terms of minimizing water threat in the reconstruction period. Guikema and Aven (2010) assessed some evaluation ways of terrorist risks and intelligent attacks. They evaluated some main and usual methods (including game theory, semiquantitative risk calculation and locating resources in order to defending objectives and systems valuable assets) in terms of protecting technical systems such as transport networks, oil production centers and other governmental strategic infrastructures against deliberate attacks. Ultimately, they concluded that a combination of those aforementioned methods could be the best solution against risks and subversive attacks.

Van Leuven (2011) classified all crises facing the water system in three categories including natural destruction, man-made damage and infrastructural manpower. Then, he evaluated the vulnerability of water systems in order to determining critical components. He coupled each element with every specific threat and revealed the success rate of each disarranging deliberate action through this process.

Cieslak (2011) applied a fuzzy logic-based method for assessing drinking water system by defining some of fuzzy regulations. Roozbahani et al. (2013) developed an integrated fuzzy hierarchical risk assessment model (IFHRA-WSS) in order to analyze urban water systems risk including supply, treatment and distribution. This model used a hierarchical framework for breaking urban water supply system (UWSS) infrastructures in terms of reducing the total complexity of the system.

Delpla et al. (2014) developed a decision support system (DSS) to support decision making by small- and medium-plant operators and other water stakeholders, based on a sequential risk assessment approach that includes the consideration of catchment characteristics, climatic conditions and treatment operations. They provided a holistic evaluation of the water system, while also assessing human health risks caused by organic contaminants potentially present in the treated water.

Taheriyoun and Moradinejad (2015) applied a fault tree analysis (FTA) method for risk and reliability assessment of wastewater treatment plants when the effluent is reused or discharged to water resources. FTA is a top down, deductive failure analysis in which an undesired state of a system is analyzed. They also combined this method with Monte Carlo simulation to consider the uncertainties.

Baah et al. (2015) used a risk matrix and a weighted sum multi-criteria decision matrix to assess the consequence and risk of sewer pipe failure for a mid-sized city, using ArcGIS. They developed a map incorporating risk of sewer pipe failure and consequence to facilitate future planning, rehabilitation and maintenance programs.

Seto et al. (2016) evaluated the impacts of blending practices (i.e., a practice used to manage wet weather flows) on the effluent from the East Bay Municipal Utility District's wastewater treatment plant in Oakland, California, and water quality in the receiving water. They used a static-based quantitative microbial risk assessment (QMRA) to estimate the incremental risk to public health.

The vast majority of urban water infrastructure risk assessment studies have focused on water distribution networks, but wastewater collection and treatment systems have gained fewer attentions. Moreover, wastewater risk-analyzing researches mostly are conducted in the chemical and biological risk evaluation field. Technological risk management studies are much fewer. This study suggests an algorithm developed by federal emergency management agency model in the USA (FEMA 2005). FEMA's instruction is basically a general guideline for dealing with man-made and malevolent threats. The main significance of this guideline is its simplicity. In this study, FEMA's instruction is used and developed, exclusively for wastewater collection and purification infrastructure. Also different types of non-human threats (natural, technical and operational) and man-made threats are presented, and some indicators are designed in order to evaluate components vulnerabilities against non-human threats. Furthermore, fuzzy method will be used to obtain criterion weighting and expert's poll uncertainties. Objectives of this paper are summarized as follows:

1. Risk analysis which includes identification and quantitative estimation of threats, severity of consequences as well as system vulnerability.
2. Risk management of wastewater transmission and treatment including risks categorization, risk reduction and confrontation strategies.

2 Methodology

2.1 FMADM Methods

2.1.1 *Fuzzy Analytical Hierarchy Process (FAHP)*

The fuzzy AHP method was generalized from AHP classic method by Buckley (1985). In this method, decision maker is able to use fuzzy numbers for comparing paired options. This method is so flexible and applicable in consideration of uncertainties in decision makers' preferences for the elicitation of relative weights of criteria by using the trapezoidal fuzzy number. Trapezoidal fuzzy number (*a*, *b*, *c*, *d*) is defined in Fig. 1.

Decision maker compares the indicators with the language statements according to the first column of Table 1, which is in the fuzzy AHP defined as trapezoidal fuzzy number (*a*, *b*, *c*, *d*) as shown in Fig. 1. The compatibility of paired comparisons will be evaluated in terms of measuring response accuracy using some relations which are described in next sections. Maximized acceptable incompatibility rate is .1. If the rate is higher, it shows that matrix elements filled by decision maker are not compatible. In this case, respondent will ask to reconsider her/his comments. Then, weight vector (*W*) of each criterion will be obtained after normalization, using geometric mean and fuzzy AHP method.

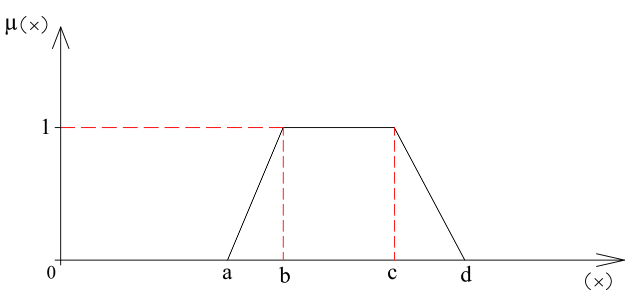

Fig. 1 Trapezoidal fuzzy number according to Buckley (1985)

2.1.2 *Fuzzy Simple Additive Weighing method (FSAW)*

SAW method is one of the oldest and simplest multiple attribute decision-making methods. This easy approach is applicable for prioritizing if options are possibly going to be compared at the same time. In SAW, utility function of *i*th option or rank of *i*th option or U_i is calculated by Eq. (1) (Bonissone 1982).

$$U_i = \frac{\sum_j (w_j r_{ij})}{\sum_j w_j} \quad (1)$$

Then, the most relevant A^* is obtained with assumption of W vector by Eq. (2).

$$A^* = \left\{ \max_i \left(U_i = \frac{\sum_j (w_j r_{ij})}{\sum_j w_j} \right) \right\} \quad (2)$$

where A_i stands for option *i*, W_j is weight of *j*th criterion, r_{ij} refers to related *i* rate option to *j* criterion. Finally, U_i is actual or implied utility for option *i*. Those fuzzy parameters in Eq. (1) are shown as Eq. (3) in the case of fuzzy SAW which is introduced by Bonissone (1982).

$$\tilde{U}_i = \frac{\sum_j \tilde{w}_j \tilde{r}_{ij}}{\sum_j \tilde{w}_j} \quad (3)$$

The value of membership function is obtained by Bonissone method. In this method, $\tilde{\boldsymbol{r}}_{ij}$ or *i* rate options of

Table 1 Numerical and fuzzy values of preferences in paired comparison criterion

Preference (criterion *i* to *j*) Complete and absolute importance	Value*	**Fuzzy preference—trapezoidal (*a*, *b*, *c*, *d*)
Very high importance	(8, 9, 10, 10)	$\tilde{9}$
High importance	(5, 7, 7, 9)	$\tilde{7}$
Slight importance	(3, 5, 5, 7)	$\tilde{5}$
Equal importance	(1, 3, 3, 5)	$\tilde{3}$
Intermediate preferences	(1, 1, 1, 1)	$\tilde{1}$
	–	$\tilde{2}$, $\tilde{4}$, $\tilde{6}$, $\tilde{8}$

* Values proposed by Saaty (1980)

** Fuzzy preference proposed by authors according to the display trapezoidal method of Buckley (since in Buckley, decision maker determines priority fuzzy values)

Table 2 Fuzzy numbers related to linguistic expressions in ranking based on Bonissone method

r_{ij} (positive criteria)	r_{ij} (negative criteria)	Trapezoidal fuzzy number (Bonissone method)
Very high	Very low	(0, 0, 0, .2)
High	Low	(0, .1, 0, .2)
Relatively high	Relatively low	(.2, .2, .2, .2)
Appropriate	Appropriate	(.5, .5, .2, .2)
Relatively low	Relatively high	(.8, .8, .2, .2)
Low	High	(.9, 1, .2, 0)
Very low	Very high	(1, 1, .2, 0)

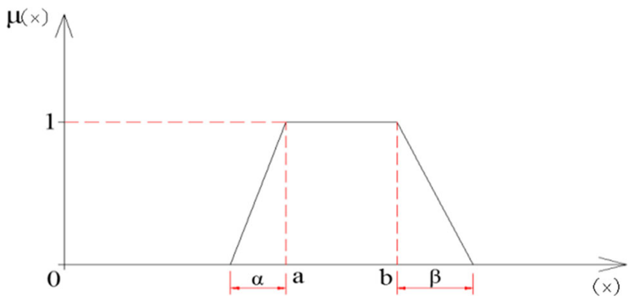

Fig. 2 Trapezoidal fuzzy number based on Bonissone (1982)??? method

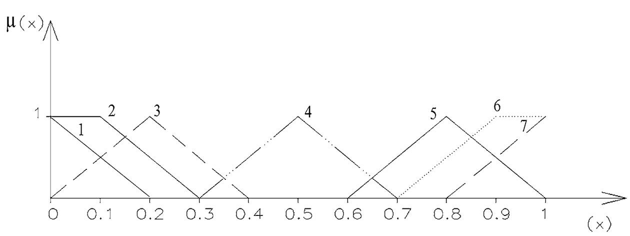

Fig. 3 Displaying trapezoidal fuzzy numbers related to seven linguistic expressions in Bonissone method

j are explained by linguistic expressions in Table 2 and then are shown in trapezoidal fuzzy number described as (a, b, α, β) as shown in Figs. 2 and 3.

To estimate the weights of criteria pairwise comparison, matrix (A) is used. For controlling the matrix compatibility, W vector related to paired comparison matrix was obtained by arithmetic mean (column-wise normalization). This value would be estimated as follows if eigenvalue of comparison matrix ($\lambda_{\max}$) is unknown (Saaty 1980):

$$A \times W = \lambda . W \tag{4}$$

$$\lambda_{\max} = \frac{\sum_{i=1}^{n} \lambda_i}{n}, \lambda_{\max} \geq n \tag{5}$$

where n is the dimension of matrix A and $\lambda_{\max}$ is the maximum eigenvalue of the comparison matrix A. Then, inconsistency index and inconsistency ratio were measured as follows:

Table 3 Random inconsistency ratio I.I.R (Satty, 1980)

N	1	2	3	4	5	6	7	8	9	10
I.I.R.	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$I.I = \frac{\lambda_{\max} - n}{n - 1} \tag{6}$$

$$I.R = \frac{I.I}{I.I.R} \tag{7}$$

where $I.I.R$ is random inconsistency ratio and can be driven from Table 3.

Then, fuzzy weight of each criterion was calculated by Buckley method (Buckley 1985). Primary assessment did not explore any differences among variety methods of final fuzzy weight calculation (Sadiq and Tesfamariam 2009). Fuzzy entries of paired comparison matrix were totally displayed as $A = [(a_{ij}, b_{ij}, c_{ij}, d_{ij})]$ in which $i, j = 1,\ldots,$N. (a_{ij}, b_{ij}, c_{ij}, d_{ij}) is the fuzzy feature of ijth entry of matrix A. Number of criteria is shown by N. Then, according to Buckley, w_i is obtained as follows:

$$w_i = \left(\frac{a_i}{d}, \frac{b_i}{c}, \frac{c_i}{b}, \frac{d_i}{a} \right) \tag{8}$$

where

$$a_i = \left[\prod_{j=1}^{N} a_{ij} \right]^{1/N}, \quad a = \sum_{i=1}^{N} a_i, \quad b_i = \left[\prod_{j=1}^{N} b_{ij} \right]^{1/N}, \quad b = \sum_{i=1}^{N} b_i$$

$$c_i = \left[\prod_{j=1}^{N} c_{ij} \right]^{1/N}, \quad c = \sum_{i=1}^{N} c_i, \quad d_i = \left[\prod_{j=1}^{N} b_{ij} \right]^{1/N}, \quad d = \sum_{i=1}^{N} b_i$$

After obtaining W, fuzzy vectors ($\tilde{w}$) which have been produced by FAHP method in this paper, $\tilde{\boldsymbol{r}}$ (options scores in each measure) and marginal utility function ($\tilde{U}_i$) for each function will be calculated by Eq. (3) using trapezoidal fuzzy number's arithmetic operators. For instance, the multiplying of two fuzzy numbers such as $D = (a, b, \alpha, \beta)$ and $N = (a, b, \alpha', \beta')$ is as follows (Bonissone 1982).

$$D.N = (aa', bb', a\alpha' + \alpha a' - \alpha\alpha', b\beta' + b'\beta + \beta\beta') \tag{9}$$

2.1.3 Defuzzification Methods

Yager (1980) suggested an index for defuzzification and ranking of fuzzy numbers. Yager ranking index obtains by Eq. (10) for ith option.

$$Y(\tilde{A}_i) = \frac{\int_0^1 x\mu_{\tilde{A}_i}(x)dx}{\int_0^1 \mu_{\tilde{A}_i}(x)dx} \tag{10}$$

where $\boldsymbol{Y}(\tilde{\boldsymbol{A}}_i)$ is longitudinal coordinates of the area center membership functions $\boldsymbol{\mu}_{\tilde{A}_i}(\boldsymbol{x})$. So, the option that has got the highest $\boldsymbol{Y}(\tilde{\boldsymbol{A}}_i)$ will have the first rank (Yager 1980).

2.2 Fundamentals of the Proposed Model

The procedure of the suggested algorithm of sewage system analysis and risk management is shown in Fig. 4. In the first step, different components are introduced as follows:

(a) Sewage collection and transmission network includes pipes, sewer lines and pumping stations.

(b) Wastewater treatment plant includes control systems, input pumping station, aerated pool, primary and secondary settling pool, processing units and sludge treatment, storage gas tank, return sludge pumping and so on.

Furthermore, a list of possible threats facing for each part of this huge infrastructure is presented through expert's poll. Listed threats were divided to four main groups: (1) natural hazards, (2) man-made threats, (3) functional-technical errors and (4) social-environmental threats. Experts were asked to determine relative weight of each group using paired comparison with FAHP technique because of having different ideas about the degree of importance for each group. Again another survey was conducted about probability of each threat. Finally, threat-ranking results and fuzzy ratings were aggregated by FASW method.

In the second step, some indicators were introduced such as financial and human consequences, functional value, possible replacement and service reduction in terms of assessing the intensity of effects (Fig. 4). The relative weights of these indicators were calculated by FAHP method and paired comparisons. At the end, severity of each threat was obtained by FSAW method. Similarly, the third risk determinant parameter (vulnerability) was measured by some elements including availability, ability to detect, weakness of component and rehabilitation.

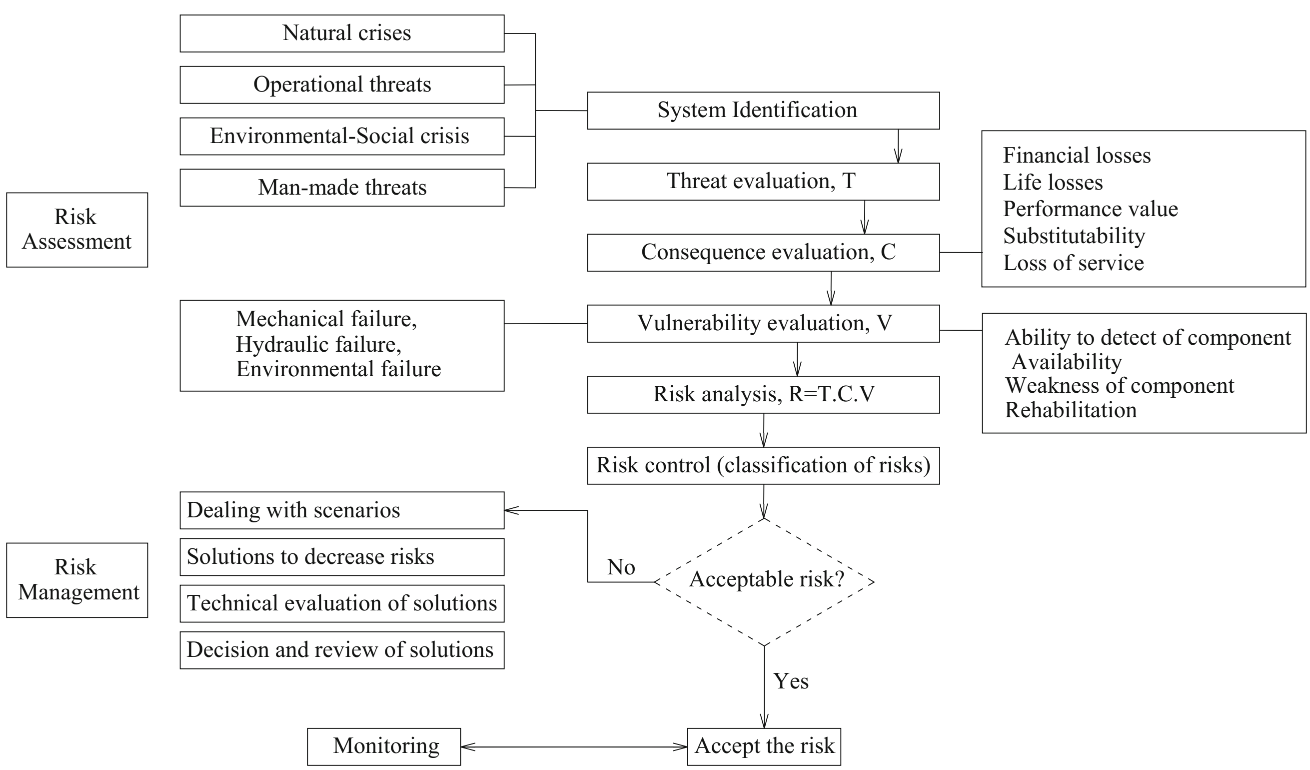

Fig. 4 Risk assessment and risk management stages

Likewise, criteria of vulnerability due to non-human risks including mechanical, hydraulic and environmental failures were defined. The detail of risk assessment phase which includes risk estimation, parameter metrics and types of threats (options) is displayed in Fig. 5. W_i and r_i represent the first and last level options in the risk assessment model, respectively.

2.3 Developing Expert Questionnaire

Set of questions were designed as questionnaires or interviews in order to attain research objectives. This study gathered information from 15 expert members of public and private water & wastewater sectors. In each case study, average values of information elicited from decision maker's comments and interviews were added in different phases of the study such as criterion weighing and threats scoring.

3 Case Study 1: Wastewater Network in West of Tehran

Wastewater network in the west part of Tehran was covered about 290 hectares by the length of 60 km at first stages of its operation, and it will be reached to 3800 hectares by 2032 (Tehran Province Wastewater Company 2015). Material of applied pipelines is emulsion-coating concrete along with epoxy by 1200–2000 mm diameter (Tehran Province Wastewater Company 2010).

3.1 Threat Assessment

The risk parameters (threats, consequences and vulnerabilities) were measured as shown in hierarchical procedure in Fig. 5. Firstly, threats were evaluated in three steps: (1) primary threats selection for each part of the system, (2) relative weight calculation for threat groups and (3) measuring the probability of each threat.

List of probable threats was prepared, and experts were asked to do paired comparison on all different groups. A sample of paired comparison matrix is shown in Table 4.

For example, in the first paired comparison matrix A1:

$$a_1 = \left[\prod_{j=1}^{4} a_{1j}\right]^{1/4} = (1 \times 3 \times 5 \times 5)^{1/4} = 2.94 \tag{11}$$

$$a_2 = \left[\prod_{j=1}^{4} a_{2j}\right]^{1/4} = \left(\frac{1}{7} \times 1 \times 3 \times 1\right)^{1/4} = 0.81 \tag{12}$$

$$a_3 = \left[\prod_{j=1}^{4} a_{3j}\right]^{1/4} = \left(\frac{1}{9} \times \frac{1}{7} \times 1 \times 1\right)^{1/4} = 0.35 \tag{13}$$

$$a_4 = \left[\prod_{j=1}^{4} a_{4j}\right]^{1/4} = \left(\frac{1}{9} \times \frac{1}{5} \times 1 \times 1\right)^{1/4} = 0.39 \tag{14}$$

$$a = \sum_{i=1}^{4} a_i = a_1 + a_2 + a_3 + a_4 = 4.493 \tag{15}$$

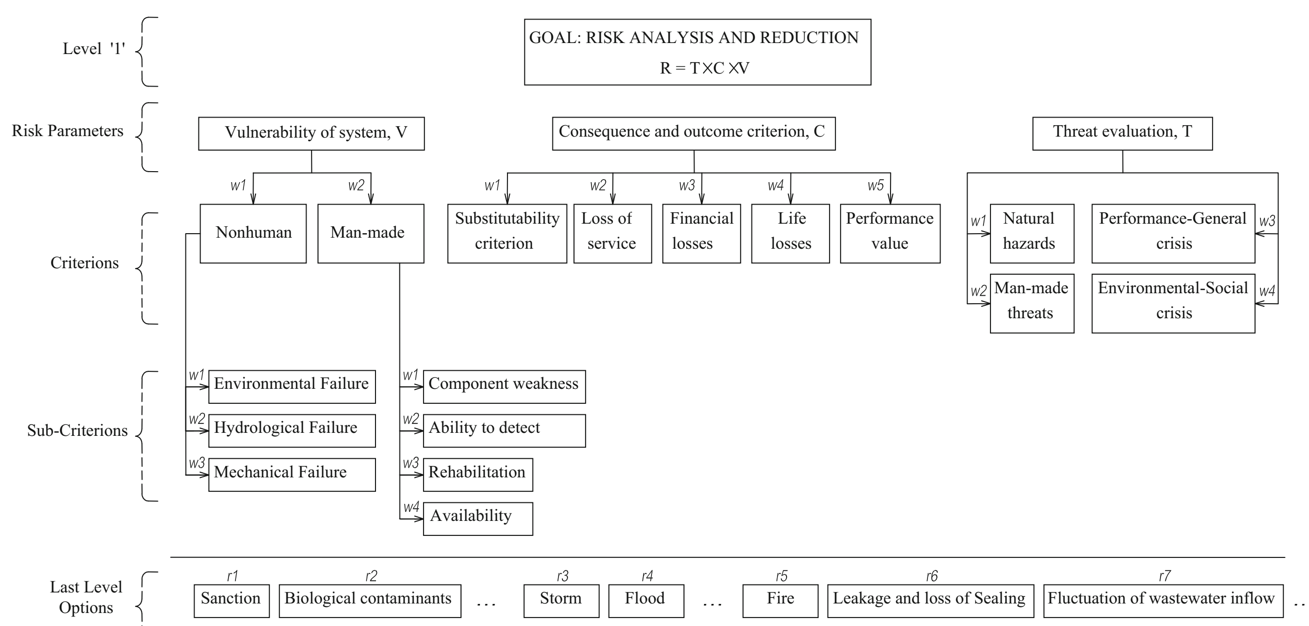

Fig. 5 Proposed risk assessment model's hierarchical process

Table 4 Matrix or paired comparison matrix (A), for threat groups by fuzzy numbers (a_{ij}, b_{ij}, c_{ij}, d_{ij})

Threat category	Man-made	Environmental-social	Performance-general	Natural
Man-made	(1, 1, 1, 1)	(3, 5, 5, 7)	(3, 5, 5, 7)	(5, 7, 7, 9)
Environmental-social	$\left(\frac{1}{7}, \frac{1}{5}, \frac{1}{5}, \frac{1}{3}\right)$	(1, 1, 1, 1)	(3, 5, 5, 7)	(1, 3, 3, 5)
Performance-general	$\left(\frac{1}{7}, \frac{1}{5}, \frac{1}{5}, \frac{1}{3}\right)$	$\left(\frac{1}{7}, \frac{1}{5}, \frac{1}{5}, \frac{1}{3}\right)$	(1, 1, 1, 1)	(1, 1, 1, 1)
Natural	$\left(\frac{1}{9}, \frac{1}{7}, \frac{1}{7}, \frac{1}{5}\right)$	$\left(\frac{1}{5}, \frac{1}{3}, \frac{1}{3}, 1\right)$	(1, 1, 1, 1)	(1, 1, 1, 1)

Similarly, values of '*d*, d_i, *c*, c_i, *b*, b_i' were obtained. In accordance with Buckley preference, values of threat groups were defined as follows:

Man-maid threats weight	$w_1 = \left(\frac{a_1}{d}, \frac{b_1}{c}, \frac{c_1}{b}, \frac{d_1}{a}\right) = (0.372,\ 0.643,\ 0.643,\ 1.086)$
Environmental-social threats weight	$w_2 = \left(\frac{a_2}{d}, \frac{b_2}{c}, \frac{c_2}{b}, \frac{d_2}{a}\right) = (0.102,\ 0.214,\ 0.214,\ 0.411)$
Industrial and process threats weight	$w_3 = \left(\frac{a_3}{d}, \frac{b_3}{c}, \frac{c_3}{b}, \frac{d_3}{a}\right) = (0.045,\ 0.067,\ 0.067,\ 0.113)$
Natural threats weight	$w_4 = \left(\frac{a_4}{d}, \frac{b_4}{c}, \frac{c_4}{b}, \frac{d_4}{a}\right) = (0.049,\ 0.076,\ 0.076,\ 0.149)$

After weighting threats group in a hierarchical tree of Fig. 5, the fuzzy utilities ($\tilde{U}_i$) or options scores are calculated by Bonissone FSAW relations. Utility function options for each option in Bonissone FSAW method same as SAW are $\tilde{\boldsymbol{U}}_i = \frac{\sum_{j=1}^{n} \tilde{w}_j \tilde{r}_{ij}}{\sum_j \tilde{w}_j}$.

Bonissone method was applied rather than Buckley method. Because of having many competing options, it was easier in order to fuzzy rank of options. Utility function $\tilde{\boldsymbol{U}}_i$ was determined from Eq. (3) and using arithmetic operators (Table 5).

Afterward,$\tilde{\boldsymbol{U}}_i$ was become a defuzzy number to do descent threats listing according to their ranking by Yager ranking index according to Eq. (10). So, the most important threats are listed in Table 6 and Fig. 6.

3.2 Consequence Assessment and Damage Intensity Evaluation

Damage intensity assessment is the second parameter in risk evaluation. In this case, five evaluation criteria were determined just like the applied method for threat evaluation (Fig. 5). Definition of each criterion and its scoring are presented in Tables 7 and 8. Weights of outcome and damage indices are shown in Table 9. Decision-making matrix for determining damage intensity is illustrated in Table 10. In this matrix, the final fuzzy score related to each threat is attained by FSAW method.

3.3 Vulnerability Assessment

In this study, different evaluation criteria were developed for vulnerability because of diverse nature among man-made and functional-natural threats as mentioned before. The vulnerability criteria in natural and functional threats were divided into three categories, mechanical, hydraulic and environmental. In accordance with FEMA, there are some determinants against man-made and terrorist threats such as (1) ability to identify the component, (2) component accessibility, (3) component weakness and (4) ability to rebuild and returning to normal position (FEMA 452 2005). Therefore, similar to the last two items the same procedure was applied and human and non-human vulnerability matrix was obtained by Bonissone FSAW method (Tables 11, 12).

3.4 Risk Assessment

After obtaining score of each risk parameter, the fuzzy risk value of each threat was attained by fuzzy multiplying these parameters through $R = T \times C \times V$ and using Bonissone operators as shown in Table 13. Then, defuzzy risk value of each threat was obtained through Eq. (10) using Yager defuzzification method and same as the applied calculation for last items.

3.5 Risk Control and Management

The last step of risk assessment and management of wastewater network is to control quantified risks. In this step, some coping strategies will be taken for each of those risks. Risk control stages are as follows:

1. Risk classification (low-risk threat $R < .2$, moderate-risk threat $.2 < R < .5$ and high risk threat $.5 < R$). These margins have been presented by experts and decision makers based on the situation of the project and relative considerations.
2. Policy and risk reduction strategies development to deal with each category (including risk compliance, risk transfer and risk confrontation)
3. Technical evaluation of those written policies and costs estimation

In this study, a questionnaire was prepared in order to present risk reduction solutions and economical-technical assessments. Risk reduction solutions along with concerned economical-technical justifications at $R > .2$, including contaminant entry (malicious or non-biased), are

Table 5 Decision matrix to assess threats in wastewater transmission and treatment system

Threat category	relative weight of groups	Threat name (i)	Probability criterion $\tilde{w}_j$							Final score ($\tilde{U}_i$)
			Very high (1, 1, .2, 0)	High (.9, 1, .2, 0)	Relatively high (.8, .8, .2, .2)	Appropriate (.5, .5, .2, .2)	Relatively low (.2, .2, .2, .2)	Low (0, .1, 0, .2)	Very low (0, 0, 0, .2)	
Human threats and malicious	$w'_1 = (0.643,\ 0.643,\ 0.271,\ 0.443)$	Cyber	–	–	–	–	–	–	*	(0, 0, 0, .22)
		Bombing	–	–	–	–	–	*	–	(0, .06, 0, .26)
		Biological contaminants	–	–	–	–	*	–	–	(.13, .13, .13, .31)
		Chemical contaminants	–	–	–	*	–	–	–	(.32, .32, .21, .44)
Environmental, social	$w_2 = (0.214,\ 0.214,\ 0.112,\ 0.197)$	Changes in the quality of wastewater (BOD_5)	–	*	–	–	–	–	–	(.19, .21, .12, .20)
		Excessive increase in wastewater inflow	–	–	*	–	–	–	–	(.17, .17, .11, .24)
		Excessive decrease in wastewater inflow	–	–	–	–	*	–	–	(.04, .04, .04, .12)
Performance-General	$w_3 = (0.067,\ 0.067,\ 0.022,\ 0.046)$	Industrial fire and explosion	–	–	–	–	*	–	–	(.01, .01, .01, .03)
		Leakage and loss of sealing	–	–	*	–	–	–	–	(.05, .05, .03, .06)
		Trash entry	–	–	–	*	–	–	–	(.03, .03, .02, .05)
		Equipment aging or corrosion	–	–	–	*	–	–	–	(.03, .03, .02, .05)
		Design flaws	–	–	–	–	–	*	–	(0, .01, 0, .03)
Natural	$w_4 = (0.076,\ 0.076,\ 0.027, 0.073)$	Earthquake	–	–	–	–	*	–	–	(.02, .02, .02, .04)
		Storm	–	–	–	–	–	*	–	(0, .01, 0, .04)
		Flood	–	–	–	–	*	–	–	(.02, .02, .02, .04)
		Landslides	–	–	–	–	–	–	*	(0, 0, 0, .03)
		Liquefaction	–	–	–	–	–	–	*	(0, 0, 0, .03)

Table 6 Five important fuzzy and defuzzy highest scores for evaluation threats forming the risk

Defuzzy number by Yeager $Y(\tilde{U}_i)$	Fuzzy number of threat final score $\tilde{U}_i$	Threat category	Threat name	Threat No.
0.398	(.32, .32, .21, .44)	Human and malicious	Chemical contaminants (malicious)	1
0.228	(.19, .21, .12, .20)	Environmental-social	Changes in quality of wastewater (non-biased)	2
0.215	(.17, .17, .11, .24)	Environmental-social	Excessive increase in wastewater inflow	3
0.069	(.04, .04, .04, .12)	Environmental-social	Excessive decrease in wastewater inflow	4
0.065	(.05, .05, .03, .06)	Performance-general	Leakage and loss of sealing	5

presented in Table 14. Also reduction strategies of some other risks (including fluctuations in wastewater volume inflow, boycott, bombing and earthquake) are presented by experts in this table.

4 Case Study 2: Wastewater Treatment Plant in South of Tehran

The same procedure of risk assessment and management for network was conducted for wastewater treatment plant in south Tehran. General characteristics of the wastewater treatment plant are as follows: The wastewater treatment plant is in Rey city (south of Tehran) and expected to be built in eight modules with a capacity of 4.2 billion people. Each of four current built modules covers a population of 525,000 people, and flow of 450,000 m^3/day can be refined. Land area of treatment plant is 110 hectares (Website of Tehran Wastewater Company 2015). The process of wastewater treatment is activated sludge along with nitrogen removal, and refined wastewater irrigates agricultural land of Varamin plain (Tehran Province Wastewater Company 2015).

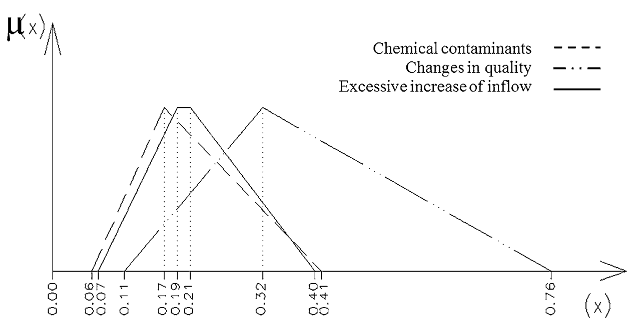

Fig. 6 Membership function of final scores of some threats

The main parts of wastewater treating system were detected. Those parts were included the site, administration office buildings, controlling systems, pump inlet station, pipes, trash screen, grease and grit chamber, aerating pool, primary and secondary sedimentation tanks, electrical facilities, sludge processing and refining unit, disinfection unit, biogas storage tank, utilization staff and returned sludge pumping station.

Detected threats were included natural disasters, man-made threats and functional-general threats. Again threat value was measured by multiplying threat group weight with its probability. Also the consequence and vulnerability of risks were measured through values weighing by AHP and paired comparison matrix measurement using SAW

Table 7 Description outcome and consequences analysis-related criterions (FEMA, 2005)

Criterion description	Criterion
In case of threat and damage to components, can the component be replaced? (entirely, in the short term, medium term, in the long run)	Substitutability criterion
What percentage is the reduction of service, in case of threat and damage to components? (Over 90% will be full service interrupted)	Loss of service
How much are estimated investment costs, in case of threat and damage to components? It is low and easy to pay, or as much as is reasonable and is payable by planning, or high	Financial losses
What are the consequences of life, in case of threat and damage to components? (Negligible and can lead to very low diseases and injuries, or severe disease, or catastrophic and leading to death)	Life losses
How much less is the main performance of the system, in case of threat and damage to components? (without any disturbance or in long term, or in short term or the operation of the system totally and immediately closed)	Performance value

Table 8 Performance value scoring

Criterion description	Ranking qualitative (r_{ij} in FSAW)	Trapezoidal fuzzy number (Bonissone)
When a threat occurs, how much disturbed the system operating is? (without any disturbance or in long term, or in short term or the operation of the system totally and immediately closed)	Very low	(0, 0, 0, .2)
	Low	(0, .1, 0, .2)
	Relatively low	(.2, .2, .2, .2)
	Appropriate	(.5, .5, .2, .2)
	Relatively high	(.8, .8, .2, .2)
	High	(.9, 1, .2, 0)
	Very high	(1, 1, .2, 0)

Table 9 Fuzzy-trapezoidal index weight

Fuzzy weight in Bonissone form (a, b, α, β)	Fuzzy weight in buckley form (a, b, c, d)	The consequence criterion
$\mathbf{w}'_1 = (.035,\ .035,\ .015,\ .044)$	(.020, .035, .035, .080)	Financial losses
$\mathbf{w}'_2 = (.550,\ .550,\ .255,\ .444)$	(.295, .550, .550, .994)	Life losses
$\mathbf{w}'_3 = (.177,\ .177,\ .084,\ .149)$	(.093, .177, .177, .326)	Performance value
$\mathbf{w}'_4 = (.072,\ .072,\ .038,\ .117)$	(.034, .072, .072, .190)	Substitutability
$\mathbf{w}'_4 = (.165,\ .165,\ .081,\ .145)$	(.084, .165, .165, .310)	Loss of service

method. Three steps of final results are presented in Table 15, and fuzzy and numerical risks were obtained. Then, risk confrontation and reduction strategies in most important sections of treatment plant are presented in Table 16. Because of the limited space of the paper, the description of other sections is avoided.

Results have revealed that "earthquake" risk has the highest score in biogas tanks, sludge processing unit and controlling system. So, obviously these parts are sensitive points in case of any earthquake. Thus, some particular preparations should be taken. Power outage and wornout equipment related to administration office buildings and controlling systems have the lowest score, respectively.

Confrontation strategies, risk reduction and economical-technical evaluation are presented for threats with a higher risk in Table 16. Risk compliance is a suggested strategy for threats with lower risks as well. Risk control process is a dynamic process whose results will be subjected to change over time.

5 Conclusion

In this study, a systematic approach was developed for risk management of wastewater collection network and treatment plant. FEMA suggested a framework for dealing with malevolent threats at infrastructures. This study was extended that framework, especially for wastewater collection network and treatment plants using fuzzy MADM. Also natural and functional threats were included, so it is a comprehensive risk assessment by fuzzy decision-making techniques and questionnaires as supporting tools.

First threats probabilities were detected in order to find and assess more likely threats. Then, the main parts of the system were evaluated in terms of effect intensities and threat consequences as well as vulnerabilities. Fuzzy and defuzzy values of system components risks were specified in the next phase of the algorithm, after obtaining damage intensity–consequences and vulnerability. For two case studies in Tehran, "entry of chemical contaminant" and "change in wastewater quality" were taken the highest score for west Tehran wastewater collection network and "earthquake" in processing units and sludge treatment and gas storages were taken the highest score in south Tehran wastewater treatment through expert's polls. After that, for most important risks the reduction strategies and technical evaluations were presented by experts based on situation.

It is pertinent to mention that these results driven from expert's polls and determined through FMDAM are reliable and valid like other similar researches introduced by authentic agencies like department of homeland security (DHS) in USA. Likewise, some points need to be addressed:

Table 10 Decision matrix for outcome analysis in wastewater network component

Sections	Threat	Financial losses $\boldsymbol{w'}_1 = (.035,\ .035,\ .015,\ .044)$	Life losses $\boldsymbol{w'}_2 = (.550,\ .550,\ .255,\ .444)$	Performance value $\boldsymbol{w'}_3 = (.177,\ .177,\ .084,\ .149)$	Substitutability $\boldsymbol{w'}_4 = (.072,\ .072,\ .038,\ .117)$	Loss of service $\boldsymbol{w'}_5 = (.165,\ .165,\ .081,\ .145)$	Final score $U_i = \frac{\sum_j \tilde{w}_j \tilde{r}_{ij}}{\sum_j \tilde{w}_j}$
Pipes and sewers	1	(1, 1, .2, 0)	(1, 1, .2, 0)	(.8, .8, .2, .2)	(.5, .5, .2, .2)	(.2, .2, .2, .2)	(.80, .80, .48, .86)
	2	(.9, 1, .2, 0)	(.5, .5, .2, .2)	(.5, .5, .2, .2)	(.5, .5, .2, .2)	(0, .1, 0, .2)	(.43, .45, .29, .54)
	3	(0, .1,0, .2)	(.5, .5, .2, .2)	(.9, 1, .2, 0)	(.8, .8, .2, .2)	(.5, .5, .2, .2)	(.57, .60, .38, .62)
	4	(.2, .2, .2, .2)	(0, 0, 0, .2)	(.5, .5, .2, .2)	(0, .1, 0, .2)	(0, 0, 0, .2)	(.10, .10, .68, .34)
	5	(0, 0, 0, .2)	(.5, .5, .2, .2)	(0, 0, 0, .2)	(.2, .2, .2, .2)	(.5, .5, .2, .2)	(.37, .37, .26, .46)
Pumping stations and facilities	1	(1, 1, .2, 0)	(.5, .5, .2, .2)	(.9, 1, .2, 0)	(.5, .5, .2, .2)	(.2, .2, .2, .2)	(.54, .56, .36, .80)
	2	(.9, 1, .2, 0)	(.5, .5, .2, .2)	(.5, .5, .2, .2)	(.2, .2, .2, .2)	(0, .1,0, .2)	(.41, .43, .28, .74)
	3	(0, .1, 0, .2)	(.5, .5, .2, .2)	(.5, .5, .2, .2)	(.8, .8, .2, .2)	(.2, .2, .2, .2)	(.45, .46, .32, .80)
	4	(.2, .2, .2, .2)	(0, 0, 0, .2)	(.5, .5, .2, .2)	(0, .1, 0, .2)	(0, 0, 0, .2)	(.10, .10, .07, .47)
	5	(0, 0, 0, .2)	(.2, .2, .2, .2)	(0, 0, 0, .2)	(0, 0, 0, .2)	(.2, .2, .2, .2)	(.14, .14, .14, .50)

Table 11 Analysis of vulnerability decision matrix due to man-made threats in different parts of West Tehran wastewater network

Sections	Threat	Ability to detect (.070, .070, .026, .062)	Availability (.080, .080, .032, .094)	Component weakness (.595, .595, .318, .568)	Rehabilitation (.255, .255, .147, .375)	Final score $U_i = \frac{\sum_j \tilde{w}_j \tilde{r}_{ij}}{\sum_j \tilde{w}_j}$
Pipes and sewers	*Chemical	(.8, .8, .2, .2)	(.9, 1, .2,0)	(.5, .5, .2, .2)	(.5, .5, .2, .2)	(.55, .56, .38,1.0)
	Biological	(.8, .8, .2, .2)	(.9, 1, .2, 0)	(.2, .2, .2, .2)	(.5, .5, .2, .2)	(.37, 1.66, .28, 2.71)
	Bombing	(.5, .5, .2, .2)	(.5, .5, .2, .2)	(.8, .8, .2, .2)	(.2, .2, .2, .2)	(.60, .60, .41,1.03)
	Cyber	(.2, .2, .2, .2)	(0, .1, 0, .2)	(0, 0, 0, .2)	(0, 0, 0, .2)	(.01, .02, .01, .44)
Pumping stations and facilities	*Chemical	(.5, .5, .2, .2)	(.5, .5, .2, .2)	(.2, .2, .2, .2)	(0, .1, 0, .2)	(.19, .22, .17, .65)
	Biological	(.5, .5, .2, .2)	(.5, .5, .2, .2)	(.2, .2, .2, .2)	(0, .1, 0, .2)	(.19, .22, .17, .65)
	Bombing	(.2, .2, .2, .2)	(.2, .2, .2, .2)	(1, 1, .2, 0)	(.2, .2, .2, .2)	(.68, .68, .45, .86)
	Cyber	(.2, .2, .2, .2)	(.2, .2, .2, .2)	(0, .1, 0, .2)	(0, 0, 0, .2)	(.03, .09, .03, .51)

*This item is original. Other ones have come as examples

Table 12 Analysis of vulnerability decision matrix due to non-human crises in different parts of west Tehran wastewater network

Sections	Threat	Mechanical failure (.158, .158, .077, .113)	Hydrological failure (.076, .076, .028, .083)	Environmental failure (.766, .766, .272, .408)	Final score $U_i = \frac{\sum_j \tilde{w}_j \tilde{r}_{ij}}{\sum_j \tilde{w}_j}$
Pipes and sewers	Changes in the quality of wastewater (BOD_5)	(.2, .2, .2, .2)	(0, .1, 0, .2)	(1, 1, .2, 0)	(.80, .81, .40, .52)
	Excessive increase in wastewater inflow	(0, .1, 0, .2)	(1, 1, .2, 0)	(.2, .2, .2, .2)	(.23, .24, .19, .46)
	Excessive decrease in wastewater inflow	(0, 0, 0, .2)	(.2, .2, .2, .2)	(.2, .2, .2, .2)	(.17, .17, .17, .42)
	Leakage and loss of sealing	(.2, .2, .2, .2)	(.5, .5, .2, .2)	(.5, .5, .2, .2)	(.45, .45, .29, .59)
Pumping stations and facilities	Changes in the quality of wastewater (BOD_5)	(.2, .2, .2, .2)	(0, .1, 0, .2)	(.9, 1, .2, 0)	(.72, .81, .37, .52)
	Excessive increase in wastewater inflow	(0, .1, 0, .2)	(.8, .8, .2, .2)	(.2, .2, .2, .2)	(.21, .23, .19, .48)
	Excessive decrease in wastewater inflow	(0, .1, 0, .2)	(.2, .2, .2, .2)	(0, .1, 0, .2)	(.02, .11, .02, .39)
	Leakage and loss of sealing	(0, .1, 0, .2)	(.2, .2, .2, .2)	(.5, .5, .2, .2)	(.40, .41, .25, .55)

Table 13 Fuzzy numerical risk in main parts of wastewater collection and transmission

Sections	Threat	T = threat	C = consequence	V = vulnerability	Fuzzy risk = $\tilde{R} = \tilde{T} \times \tilde{C} \times \tilde{V}$	R = numerical risk
Pipes and sewers	Chemical contaminants (malicious)	(.32, .32, .21, .44)	(.80, .80, .48, .86)	(.55, .56, .38,1.0)	(.14, .14, .13, .1.8)	0.704
	Changes in quality of wastewater (non-biased)	(.19, .21, .12, .20)	(.43, .45, .29, .54)	(.80, .81, .40, .52)	(.07, .08, .06, .47)	0.2045
	Excessive increase in wastewater inflow	(.17, .17, .11, .24)	(.57, .60, .38, .62)	(.23, .24, .19, .46)	(.02, .02, .02, .33)	0.1258
	Excessive decrease in wastewater inflow	(.04, .04, .04, .12)	(.10, .10, .68, .34)	(.17, .17, .17, .42)	(.0, .0, .0, .04)	0.0139
	Leakage and loss of sealing	(.05, .05, .03, .06)	(.37, .37, .26, .46)	(.45, .45, .29, .59)	(.01, .01, .01, .09)	0.0348
Pumping stations and facilities	Chemical contaminants (malicious)	(.32, .32, .21, .44)	(.54, .56, .36, .80)	(.19, .22, .17, .65)	(.03, .04, .03, .86)	0.3101
	Changes in quality in wastewater (non-biased)	(.19, .21, .12, .20)	(.41, .43, .28, .74)	(.72, .81, .37, .52)	(.06, .07, .05, .57)	0.2335
	Excessive increase in wastewater inflow	(.17, .17, .11, .24)	(.45, .46, .32, .80)	(.21, .23, .19, .48)	(.02, .02, .02, .35)	0.1279
	Excessive decrease in wastewater inflow	(.04, .04, .04, .12)	(.10, .10, .07, .47)	(.02, .11, .02, .39)	(.06, 4.4, 06, 45.5) $\times 10^{-3}$	0.0153
	Leakage and loss of sealing	(.05, .05, .03, .06)	(.14, .14, .14, .50)	(.40, .41, .25, .55)	(.0, .0, .0, .07)	0.0237

Table 14 Risk reduction strategies for wastewater collection network in west Tehran

Technical and economic evaluation	Reduction strategies	Risk	Section
Despite the low probability, the damage of malicious threats of chemical contaminants is so high. The coping measures are recommended Execute pretreatment hospitals and industrial wastewaters	*Use of control systems and camera to evaluate network performance *Increasing aeration to flow at sewage corridors *Wastewater quality control of places and industries in terms of chemical contamination (BOD, COD) *Monitoring the manhole *Preventing contaminated sewage entrance to downstream lands	*Contamination entrance and *Wastewater quality change	Wastewater collection system/ pipes and sewers
Pipes are the main components of the system, and coping measures are technically and economically justified	*Program to prepare for an earthquake. *The use of new technologies in earthquake resistant pipes *Forecast mobile pumps for transferring wastewater in locations where the pipes were fractured	Earthquake	
Pipes are the main components of the system, and coping measures are technically and economically justified	*The use of new technologies in earthquake resistant pipes *Predicts mobile pumps for transferring wastewater in locations where pipes were fractured and raising security systems for the prevention of threats	Bombing	
Integration of various types of industrial waste, hospital and surface water by municipal wastewater, the system has encountered a serious problem; coping measures are technically and economically justifiable	*Adjustment of pump performance. *Use the control systems to regulate the operation of pumps *Supervision to prevent bursting wastewater corridors with bare walls at high pressures	Fluctuations (*increase or *decrease) in wastewater inflow	Wastewater collection system/ pumping stations and facilities
Given the importance of this part of the system and the severity of the threat damage, coping measures are necessary	*Identify vulnerable points and strengthening them *Program to prepare for earthquakes *Design and execution of retrofitting plans against earthquakes	Earthquake	
Given the hostile policies of some countries toward Iran, coping measures are essential	*Identify indirect channels to purchase equipment through intermediaries *Provide adequate spare parts and identify alternative manufacturers	Boycott	

1. The presented process in this research is a modulation technique using both quantitative and qualitative methods of risk assessment which can be usefully applied by decision makers whenever laboratory data or actual pilot projects are not available.
2. Uncertainty of expert's opinions and their rating were reduced through "fuzzy" analysis of polls.
3. Developing risk assessment and management algorithms like what presented in this study to some sort of supporting and decision-making systems and software packages would definitely reduce the time of such studies and increase accuracy of the results.

For the future studies, it is suggested to use other hydro-systems risk assessment methods and compare them with the results of the approach presented in the current research. Also other fuzzy aggregation methodologies can be applied to integrate the risk parameters.

Table 15 Risk calculation of the main wastewater treatment components

Sections	Threat	T = threat	C = consequence	V = vulnerability	Fuzzy risk = $\tilde{R} = \tilde{T} \times \tilde{C} \times \tilde{V}$	R = numerical risk
Site	Bombing	(0, .003,0, .006)	(.48, .49, .2, .19)	(.62, .66, .2..13)	(0, 1, 0, 4)	0.18
	Earthquake	(0, .03, 0, .06)	(.75, .81, .2, .07)	(.42, .42, .2, .2)	(0, 10.2, 0, 39.2)	1.7
Control systems	Earthquake	(0, .03, 0, .06)	(.77, .79, .19, .17)	(.81, .81, .2, .2)	(0, 19.2, 0, 68.2)	3
	Explosion	(0, .006, 0, .012)	(.93, .94, .19, .04)	(.81, .86, .2, .12)	(0, 4.8, 0, 12.3)	0.61
Input pumping station	Boycott	(.03, .03, .012, .012)	(.47, .50, .19, .13)	(.49, .49, .2, .19)	(6.8, 7.4, 5.4, 10.5)	0.88
	Earthquake	(0, .03, 0, .06)	(.78, .81, .19, .12)	(.81, .81, .2, .2)	(0, 19.7, 0, 64.8)	2.9
	Fluctuations in wastewater	(.02, .02, .006, .006)	(.46, .49, .19, .13)	(.77, .77, .2, .2)	(7.1, 7.5, 5.0, 8.3)	0.84
Aerated pool	Boycott	(.03, .03, .012, .012)	(.29, .35, .08, .19)	(.65, .65, .2, .2)	(5.6, 6.7, 3.9, 12.3)	0.89
	Earthquake	(0, .03, 0, .06)	(.79, .85, .19, .08)	(.64, .64, .2, .2)	(0, 16.3, 0, 54.2)	2.5
Primary and secondary settling pool	Bombing	(0, .003, 0, .006)	(.88, .94, .19, .03)	(.65, .65, .2, .2)	(0, 2.0, 0, 6.0)	0.28
	Earthquake	(0, .03, 0, .06)	(.79, .83, .19, .14)	(.68, .68, .2, .2)	(0, 16.9, 0, 60.4)	2.7
Processing units and sludge treatment	Boycott	(.03, .03, .012, .012)	(.37, .43, .08, .13)	(.54, .54, .2, .2)	(5.9, 6.8, 4.1, 10.3)	0.83
	Earthquake	(0, .03, 0, .06)	(.90, .98, .19,0)	(.75, .75, .2, .2)	(0, 22.2, 0, 62.3)	3
	Explosion	(0, .006, 0, .012)	(.97, .98, .19,0)	(.79, .83, .2, .12)	(0, 4.8, 0, 11.8)	0.59
Storage gas tank	Bombing	(0, .003, 0, .006)	(.92, .93, .19, .05)	(.69, .73, .2, .14)	(0, 2.2, 0, 6.0)	0.29
	Earthquake	(0, .03, 0, .06)	(.89, .91, .19, .05)	(.85, .85, .2, .12)	(0, 23.3, 0, 60.8)	3
Return sludge pumping	Earthquake	(0, .03, 0, .06)	(.78, .81, .19, .12)	(.79, .81, .2, .16)	(0, 19.7, 0, 61.4)	2.8
	Fire	(.006, .006, .006, .006)	(.72, .74, .19, .15)	(.72, .72, .2, .2)	(3.3, 3.4, 3.3, 7.2)	0.47

Table 16 Risk confrontation and reduction strategies in most important components of treatment plant

Section	Risk	Reduction strategies	Technical and economic evaluation
Control systems	Earthquake	Identification of sensitive areas and establishing manual control systems instead of automatic controls, in conditions damage	Considering the important role of control systems, it is necessary to establish a backup system, along with other systems for critical time
	Explosion	The use of proper equipment, to prevent explosions in hazardous areas	Because the threat of explosion could bring damages to the area, coping measures are necessary
		Forecast firefighting equipment	
Input pumping station	Boycott	Identifying indirect channels to purchase equipment through intermediaries	Due to the hostile policies toward Iran of some countries, coping measures are essential
		Adequate supply of spare parts and identifying alternative suppliers	
	Fluctuations in wastewater	Setting the pump operation	During integration of hospital sewage and industrial wastewater, the system has encountered a serious problem. Coping measures are justifiable, technically and economically
		Use of control systems to adjust the operation of pumps in the best condition	
Primary and secondary settling pool	Earthquake	Earthquake preparedness plans	Coping measures are applicable and economically effective
		The use of portable pumps to discharge sludge	
	Bombing	Upgrading security systems, and the use of CCTV, for continuous monitoring component	Coping measures are applicable and economically effective
		Use of portable pumps to discharge sludge	

Table 16 continued

Section	Risk	Reduction strategies	Technical and economic evaluation
Processing units and sludge treatment	Earthquake	Program to prepare for an earthquake Use of portable pumps to transfer sludge Use of isolators and dampers to increase the seismic response of structures	Coping measures are applicable, and use of dampers and isolators instruments is helpful economically
	Explosion	Component equipped with firefighting equipment, Installation of temperature sensors and automatic fire extinguishing systems Forecast the control equipment to monitor key parameters to creating an explosion	60% costs of the treatment is allocated to sludge processing operations; therefore, coping measures justified technically and economically
Storage tank of gas	Earthquake	Plan to prepare for an earthquake Improvement of seismic structures Forecast firefighting equipment Use damper systems	Coping measures are applicable and economically effective
	Bombing	Upgrading security systems and CCTV Forecast firefighting equipment	Because in case of threat, explosion can occur and lead to serious damage, coping measures are necessary
	Explosion	Use of control systems to identify sensitive areas, and prevent the threat Forecast firefighting equipment	Because in case of threat, explosion can occur and lead to serious damage, coping measures are necessary

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