Risk Analysis of Water Reuse for Industrial Cooling Water Consumptions

Salma Arjmandi[1]; Massoud Tabesh[2]; and Saleh Tarkesh Esfahani[3]

Abstract: Limited qualified water resources have necessitated industries to use unconventional water resources such as wastewater. The aim of this study is to evaluate the risk of using urban treated wastewater to replace freshwater as a water source of cooling systems for industrial cooling water consumptions considering three main risks: corrosion, scaling, and biofouling. To perform this research, a risk analysis framework has been developed in three stages: identification of risks and the influential parameters, evaluation of the consequences of failure, and calculation of the probability of failure. The identified parameters were weighted using a paired comparison matrix, and the consequences of failure have been calculated using defined criteria. Questionnaires were used for scoring risks. In this research, the Isfahan Mobarakeh Steel Complex was chosen as the case study. The results of the risk assessment indicated that biofouling failure had the largest score. Furthermore, among the influential major failures, ammonium, phosphate, and chlorine, respectively, had the maximum risk. Based on the results, the developed framework can be used for ranking the risks of using urban treated wastewater instead of freshwater in industrial cooling systems.
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Introduction

Severe water shortage is one of the global challenges threatening human life (Karagiannis and Soldatos 2008). Reduction of natural water resources such as drying lakes and rivers and the decline groundwater resources and the quality reduction and disruption to water supplies are among recent environmental challenges (Hadipour et al. 2016). On the other hand, urbanization, population growth, industrial development, and the change of people's lifestyle have led to growing water demand. All of the mentioned factors can exacerbate water supply challenges (Kayhanian and Tchobanoglous 2016).

As one of the developing countries located in dry and semidry regions, Iran is a country whose annual average scaling is less than one-third of the average scaling in the world (Madani 2014). On the other hand, in recent decades in Iran, sustainable management of water resources has not been a priority, which has resulted in the severity of the water deficit crisis (Kayhanian and Tchobanoglous 2016). Furthermore, the inevitable industrial development in this country has led to the use unconventional water resources in industries.

Reusing wastewater is considered as a strategy for sustainable management of water resources around the world (Miller 2006; Asano et al. 1996). Nevertheless, wastewater may be largely used as an alternative source of water for agricultural irrigation. The concern about using wastewater for agricultural irrigation is related to the introduction of unknown pathogens and chemicals into food, which can cause unknown diseases for farmers and product consumers (Shuval et al. 1997; Keraita and Drechsel 2016).

Therefore, wastewater reuse in other applications like industry is more sustainable as a matter of health (Eslamian et al. 2013). Among the industries, utility power plants, oil refineries, petrochemical, and steel industries are among those proposed for water reuse considering their huge water consumption. Cooling purposes account for the largest water volume required by industries. Although wastewater reuse in industrial cooling water usage is a suitable decision for sustainable management of water resources (Eslamian et al. 2013), it has some risks. Integrated risk analysis is one of the solutions for safe reuse of treated wastewater.

Previously, statistical methods have been used to assess reuse of treated wastewater in cooling systems. Zhang et al. (2014) proposed a statistical model to evaluate the probability of scaling and corrosion in power plant cooling systems across multiple samples of water sources (freshwater and treated wastewater). The Langelier Saturation Index (LSI) and the Aggressive Index (AI) were computed to determine the probability of corrosion and scaling. Results show that secondary treated municipal wastewater is the best source to be used as cooling system makeup water. However, this study does not consider the biological problems, which are the most important threat in the reuse of municipal wastewater in a cooling system.

A pilot-scale cooling system was designed to evaluate of changing water conditions and to test control strategies for corrosion, scaling, and biofouling due to reuse of treated municipal wastewater as cooling system makeup water (Chien et al. 2012b). Researes on this pilot-scale system showed that recirculating cooling systems using treated municipal wastewater causes severe scaling (Chien et al. 2013) and biological growth is one of the major associated challenges (Chien et al. 2012a).

Researchers have used various methods for risk analysis of water and wastewater infrastructure. They are different in scope and

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[1] Master of Science Graduated in Civil-Environmental Engineering, School of Civil Engineering, College of Engineering, Univ. of Tehran, Tehran 11155-4563, Iran.

[2] Professor, Center of Excellent for Engineering and Management of Civil Infrastructures, School of Civil Engineering, College of Engineering, Univ. of Tehran, Tehran 11155-4563, Iran (corresponding author). Email: mtabesh@ut.ac.ir

[3] Master of Science Graduated in Environmental Engineering, Environmental Engineering, Science and Research Branch, Islamic Azad Univ., Tehran 1477893855, Iran.

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complexity, such as Monte Carlo simulation, multicriteria decision-making, and fuzzy logic methods. Shakeri and Nazif (2018) used a risk analysis algorithm of different water reuse applications using fuzzy logic for managing different wastewater reuse options. Similarly, various risk analysis models have been developed for water distribution and wastewater collection systems. These models recommended that the risk and the failure consequences be determined (Shahata and Zayed 2016; Elsawah et al. 2014).

Ganoulis (2012) used an integrated framework for the sustainable use of wastewater in agriculture and the control of the associated risks. This model took economic and environmental risk into account, but probability of failure (POF) was not considered. The risk concept is key to guiding and facilitating equipping industries for safe wastewater reuse.

As mentioned previously, most risk analysis studies have focused on the identification of the risks of reusing treated wastewater. In particular, risk analysis for using wastewater in special consumptions such as industrial cooling water has not been performed so far. Although some research has been performed regarding risk analysis of water infrastructures (Roozbahani et al. 2013; Torres et al. 2009; Ganoulis 2012; Shakeri and Nazif 2018), to fully understand the risks and consequences of wastewater use in industrial cooling consumptions more accurate research should be performed. Risk prioritization for reusing wastewater as a cooling water source is crucial and should be conducted. This study shows the numerical criteria of risks and their ranking.

The main aim of this research is to integrate a framework to identify the failure of using urban treated wastewater as an alternative source of water instead of freshwater for cooling systems considering risk management process in the predesign phase. In this framework, a model is presented for assessing the current status in line with equipping a system considering the characteristics of the cooling system and the risk consequences resulting from the urban treated wastewater used as an alternative source of freshwater. This approach provides the possibility of relative confidence for decision makers to equip the industry for using urban treated wastewater. To achieve this aim, first the influential characteristics between urban treated wastewater and freshwater in the cooling system are identified, and their probabilities of failure are calculated. Thereafter, the measurement criteria for the consequences resulting from failures in the cooling system are developed. The risk index is calculated considering the two factors of probability of failure and the consequences of failures. Next, the suitable solutions for managing the system risk are presented in the preimplementation phase. Finally, the Isfahan Mobarakeh Steel Complex is used as case study.

Material and Methods

Integrated Risk Analysis Framework

Risk analysis based on the probability of failures and their consequences includes three stages: (1) identifying failures, (2) calculating the consequences of failure, and (3) calculating the probability of failures (Vose 2008). The risk analysis framework in this research allows ranking failures for decision-making based on the risk of using urban treated wastewater instead of freshwater in industries. Fig. 1 demonstrates the framework used in this study.

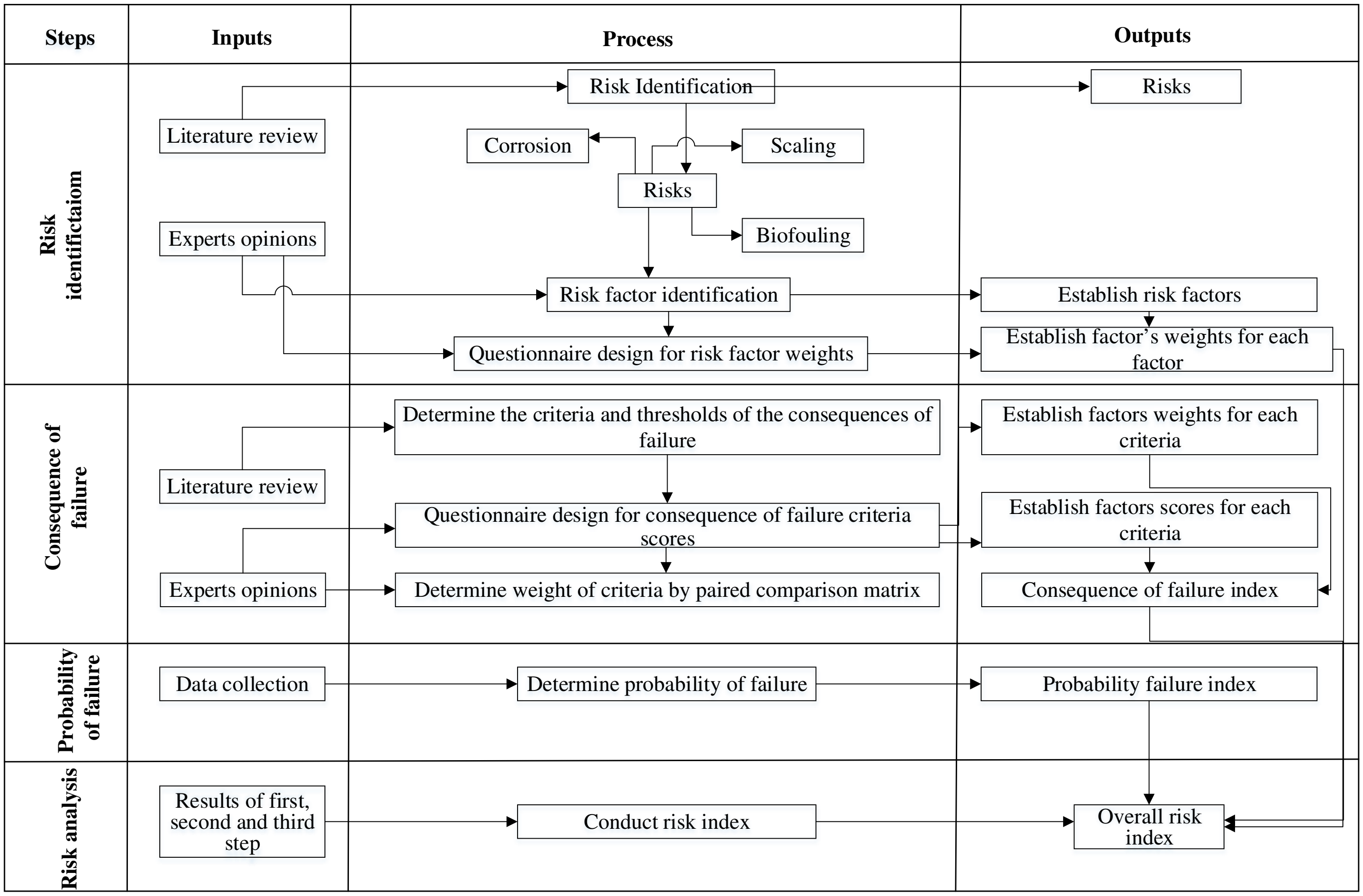

Fig. 1. Integrated risk analysis framework of using treated municipal wastewater in industrial cooling consumptions instead of freshwater.

Table 1. Main risks, their descriptions, and the effective parameters

Main risks	Description	Influential parameters
Corrosion	Corrosion in the cooling system causes damage and loss of the system equipment over time. Usage of wastewater as compensation water in closed-loop cooling systems affects the concentration of soluble solids in heat exchange systems (Rebhun et al. 1988). Exceeding the desirable limit of the concentration of the materials in wastewater causes corrosion.	Chlorine (Cl), pH, total dissolved solids (TDS), phosphate (PO_3), dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), copper (Cu), sodium (Na), magnesium (Mg), iron (Fe), total hardness (TH), NH_3, and sulfate (SO_4)
Scaling	Scaling in a closed-loop cooling system causes fouling and diminishes heat exchange efficiency (GE Water and Power 2007).	Ca, ammonia, DO, TDS, COD, BOD, Na, Mg, Fe, TH, SO_4, and PO_3
Biofouling factor	Presence of nutrients including nitrogen and phosphate, which contribute to microbiological growth, is the cause of growth of microorganisms. Biological materials (biofilms) attached to surfaces cause fouling of nozzles and heat exchangers. Further, it causes the membrane of cooling towers to fill. The concern of biofouling when using wastewater in addition to nutrients that participate in the biological growth also includes the microorganisms that cause microbiological scaling and corrosion.	N, PO_3^{-3}, TDS, temperature (°C), Cl, BOD, COD, and total suspended solids (TSS)

For this purpose, a hierarchy of criteria should be defined, through which one can determine the consequences of failures and damages incurred to the cooling system. Thereafter, by combining the probabilities of failures and their consequences, the risk number of the failures is presented as well as the weight of each failure (Shahata and Zayed 2016) (Fig. 1).

Risk Identification

The first step in this framework is identifying the failures. The risk factor is a combination of quantitative and qualitative factors. Two approaches are used in this stage: (1) reviewing the technical literature, and (2) benefiting from the experts' opinions. To calculate the weight of each parameter of failures, the paired comparisons matrix method has been used (Saaty 1990).

Risk Factor Identification

To determine the risks and prevent consequences of using urban treated wastewater as industrial cooling water, the influential parameters of each main failure should be identified. The effective weight of each should be calculated (Rebhun and Engel 1988; Selby et al. 1996; GE Water and Power 2007; USEPA 2012). The selection of numerous failures causes complication in the risk analysis trend. Furthermore, some of the identified risks can be examined in a single group. Selection of risk is contingent on the technical and economic characteristics of the specific industry. In the literature, various risks such as economic, environmental, human health, technical, and others were considered. In this study, corrosion, scaling, and biofouling, which threaten the cooling systems, were considered. Considering the importance of the corrosion, scaling, and biofouling risks of equipment exposed to treated wastewater in cooling systems (Rebhun and Engel 1988), these risks have been considered as the main risks in this research and are influenced by the qualitative properties of the wastewater (Crook 1991). Table 1 presents the main failures and the influential parameters in risks. Precise understanding of the influential parameters and wastewater properties help the decision makers to equip the wastewater treatment plant in order to prevent the risks of using urban treated wastewater in industries.

Consequence of Failure

The consequence of failure (COF) is a parameter of risk that is used for evaluating the response to the questions of how much damage was incurred to the capital, the extent of the damages incurred to the system, and to which failure is the system more vulnerable. This parameter depends on the risk and also on the system itself (Shakeri and Nazif 2018). The second step involves assessing the consequences of failure from the risk. At this step, some criteria are developed resulting from the failures and scored based on the defined thresholds. In addition, the effective weight of each criterion has been determined to calculate COF index.

To calculate the consequence of the identified failures of the system, a set of criteria should be developed (FEMA 2005; USEPA 2012; Roozbahani et al. 2013). Determination of the criteria requires precise identification of the cooling system and understanding the effects of corrosion, scaling, and biofilm growth on the cooling system. In this research, development of the criteria has been performed by investigating the studies conducted on the vulnerability and intensity of damages along with the consultation of experts. Table 2 indicates the developed criteria and the thresholds related to the scoring.

To determine the score of questionnaires and their ranking, the classic sensitivity analysis of simple additive weighting (SAW) as a multicriteria decision-making method has been used (Fortemps and Roubens 1996). In this method, assuming a **W** vector (the weights of the importance of criteria), the most suitable option A^* is calculated by Eq. (1). After calculating A_i, which is the weight of questionnaire i, a score is assigned to determine their superiority

$$A^* = \left\{ A_i \,\middle|\, \max \frac{\sum_j w_j \cdot r_{ij}}{\sum\limits_j w_j} \right\} \tag{1}$$

where r_{ij} = score of criterion j; w_j represents the weight of criterion j; and i = number of questionnaires.

For ranking the degree of importance of criteria and specifying their weight, a paired comparison matrix is used in analytical hierarchy process (AHP). The calculated weights are exact if the paired comparison matrix is consistent. Therefore, in this research Expert Choice, a user-friendly software for the AHP method (Ishizaka and Labib 2009), was used to specify the inconsistency of the matrices. The score such as consequence of each failure is obtained through simple weighted summation of the criteria according to Eq. (2)

$$U_i = \sum w_j \times r_{ij} \tag{2}$$

where U_i = score related to the failures; r_{ij} = score of each criterion in the intended failure; and w_j = weight of each criterion.

Probability of Failure

In the third step, the probability of failures is calculated considering the factors affecting it and, finally, considering the risk definition,

Table 2. Criteria and thresholds of the COF index

Criteria	Description	Score
Physical equipment detect the risk and delay in its incidence	The system lacks physical equipment to control the qualitative parameters of the input water and warning under undesirable conditions	9–10
	The system has physical equipment to control some qualitative parameters of the input water and warning under undesirable conditions	6–8
	The system has physical equipment for controlling most qualitative parameters of input water and warning under undesirable conditions	3–5
	The system has integrated and very suitable physical equipment to control all qualitative parameters of input water and warning under undesirable conditions	1–2
Detecting the damaged components	Identifying the damaged area is very difficult and needs special equipment and specialists	7–10
	Identifying the damaged area is difficult and needs a specialist	3–6
	Identifying the damaged area is easy and can be easily done by an operator	1–2
Reversibility to normal state	Repairing or replacing the damaged components and the return to the normal status occur over a long time	9–10
	Repairing or replacing the damaged components and the return to the normal status occur over a relatively long time	5–8
	Repairing or replacing the damaged components and the return to the normal status occur over a short time	3–5
	Repairing or replacing the damaged components and the return to the normal status occur very quickly	1–2
Flexibility in design and operation	No source has been designed and devised for water supply in the system under undesirable conditions of the wastewater	5–10
	Some sources with suitable quality and quantity (raw water) have been designed and devised for water supply of the system under undesirable conditions of the wastewater	1–5
Functionality	In case of incidence of failure, the cooling system performance efficiency declines to a very considerable extent	9–10
	In case of incidence of failure, the cooling system performance efficiency declines to a considerable extent	5–8
	In case of incidence of failure, the cooling system performance efficiency declines to a some extent	3–5
	In case of incidence of failure, the cooling system performance efficiency declines slightly	1–2
Economic	Repairing or replacing the damaged area of the system component is expensive	7–10
	Repairing or replacing the damaged area of the system component is relatively expensive	3–6
	Repairing or replacing the damaged area of the system component is inexpensive	1–2
Impairment time	In case of failure, the cooling system is impaired quickly	9–10
	In case of failure, the cooling system is impaired in the short term	5–8
	In case of failure, the cooling system is impaired in the long term	3–5
	In case of failure, the cooling system does not experience impairment	1–2
Vulnerability of the system against failure	More than 75% of the cooling system components are vulnerable to failure	9–10
	50%–75% of the cooling system components are vulnerable to failure	5–8
	25%–50% of the cooling system components are vulnerable to failure	3–5
	Less than 25% of the cooling system components are vulnerable to failure	1–2
Sensitivity for components	The components vulnerable to failure are housed in very sensitive parts of the cooling system	9–10
	The components vulnerable to failure are housed in sensitive parts of the cooling system	5–8
	The components vulnerable to failure are housed in low-sensitive parts of the cooling system	3–5
	The components vulnerable to failure are housed in slightly sensitive parts of the cooling system	1–2
Controlling water control using chemicals	Chemicals are not used	9–10
	Yes, the concentration of chemicals is controlled automatically on a monthly basis	5–8
	Yes, the concentration of chemicals is controlled automatically twice or more in the month	3–5
	Yes, the concentration of chemicals is controlled automatically everyday	1–2

the risk value is determined. The probability of failure is a parameter that specifies the frequency of the system failures (Vose 2008). Currently, the treatment systems in industries have been designed to bring the quality of raw water to the industrial water, but the quality of treated urban wastewater is different compared to freshwater. Accordingly, for risk analysis of replacing the treated wastewater as a water source of cooling systems, the parameters of wastewater that influence the failures should inevitably be compared with corresponding parameters in freshwater, which is calculated through POF.

The numerical value of POF of each influential factor in the main risk is determined by investigating the data measured from wastewater and raw water. In this research, to determine the probability of failure of each influential factor, the number of times the studied parameter has been larger than the corresponding parameter in freshwater was used. This method was previously reported by Vose (2008). In other words, the number of times the influential parameter in the treated wastewater exceeds its mean corresponding value in the raw water is considered as a criterion for determining the POF. To calculate the POF, Eqs. (3) and (4) are used

$$\mathrm{RWC}_{\mathrm{ave}(j)} = \frac{\sum_{i=1}^{n} C}{n} \tag{3}$$

$$\mathrm{POF}_{(j)} = \frac{\{N \mid N = \text{number of}(\mathrm{ReWC}_{(j)} > \mathrm{RWC}_{\mathrm{ave}(j)})\}}{n'} \tag{4}$$

in which $\mathrm{RWC}_{\mathrm{ave}(j)}$ = mean concentration of parameter j in freshwater; n = number of times freshwater properties were measured; C = concentration of parameter j in the freshwater; $\mathrm{POF}_{(j)}$ = probability of incidence of parameter j is the probability when parameter j exceed from the mean value of the parameter j in

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Table 3. POF scale

Comments	Description of probability of failure	Numerical value of ability of failure
It is almost definite that the intended parameter exceeds the allowable limit	Almost definite	0.77–1
It is very probable that the intended parameter exceeds the allowable limit	Very probable	0.60–0.77
It is probable that the intended parameter exceeds the allowable limit	Probable	0.17–0.60
It is not very probable that the intended parameter exceeds the allowable limit	With a low probability	0.13–0.17
The intended parameter rarely exceeds the allowable limit	Rare	0–0.13

freshwater; N = number of times parameter j in the wastewater is larger than the mean value of the jth parameter in the freshwater; $\mathrm{ReWC}_{(j)}$ = concentration of parameter j in wastewater; and n' = number of times of wastewater properties were measured. Table 3 gives a description related to the probability of failures and the relevant scores. The scores have been categorized from the quintiles of the data related to the probability of failures.

Overall Risk Index

The approach of calculating risk analysis of using treated wastewater as an industrial cooling system has been considered as a function of POF and COF (Vose 2008). Any infrastructure plan has some degree of risk. Risk management has a major role in the plan of asset management (Roozbahani et al. 2012). Because the degree of significance of each of the parameters identified in the failures of corrosion, scaling, and biofouling is varied, for greater accuracy in calculation of risk the weight of the influential parameters of the failure has also been taken into account in defining the risk. The integrated risk index in this research has been defined according to Eq. (5)

$$\mathrm{RI} = W \times \mathrm{POF} \times \mathrm{COF} \tag{5}$$

where RI = integrated risk index; and W = weight of each parameter.

Classification of the Failures

Representation of the risks in a three-dimensional space in Table 4 will indicate the status of failures in relation to each other. It also allows for comparing and prioritizing them for suitable decision-making and development of proper managerial policies. Considering the maximum and minimum values of the failures calculated in the previous step, the failures are categorized into five ranges. Fig. 2 reveals the three-dimensional matrix of the numerical risk index. The matrix elements are the result of multiplying POF by COF and by the weight of parameters. The colors of the elements of this matrix were chosen based on the coding introduced in Table 4.

Table 4. Classification of the integrated risk index scale

Classification	Description
Severe risk	This group of failures should be investigated quickly and carefully, and suitable solutions should be applied accordingly to improve the conditions.
Moderate risk	Risk management solutions are presented for removing or mitigating this group of failures, then prioritized, and after selection, implemented.
Mild risk	Risk management solutions for mitigating this group of failures are presented. Then, based on the limitations, the option of reduction or approval of risk is chosen.
Slight risk	The disorder developed by this type of failures in the system performance is less than the minimum desirable performance threshold.

According to the technical literature, some of the overall risk index ranges were divided into three parts (FEMA 2005), while some others were broken down into five parts. In this research, according to Shahata (2013), the failures are categorized into four parts including very severe, severe, moderate, and mild considering the integrated risk index. The proposed classification has been coded by four colors or shades for better understanding. Fig. 3 provides the classification of risks considering the integrated risk index scale. The proposed integrated risk index has been developed between 0 and 10.

Risk Mitigation Approach

The introduced classification in Table 4 is a basis for determining the points of failure considering their integrated risk index. The failure management policy should be different based on the risk location areas. Therefore, each color of risk determines the risk management policy of that failure. For example, transfer of one failure from the extreme risk area to the low risk or moderate risk area is applying a policy to mitigate the risk. For instance, in the two-dimensional space of risk for the parameters with the weight of 1, the failures in the extreme risk area are transferred to the trivial risk area as much as possible; otherwise, they are transferred to the low risk area, as schematically shown Fig. 3.

The primary attempts in risk management include mitigating the probability of failure. However, if this is not possible, the system should be equipped against failure. The most important activity can

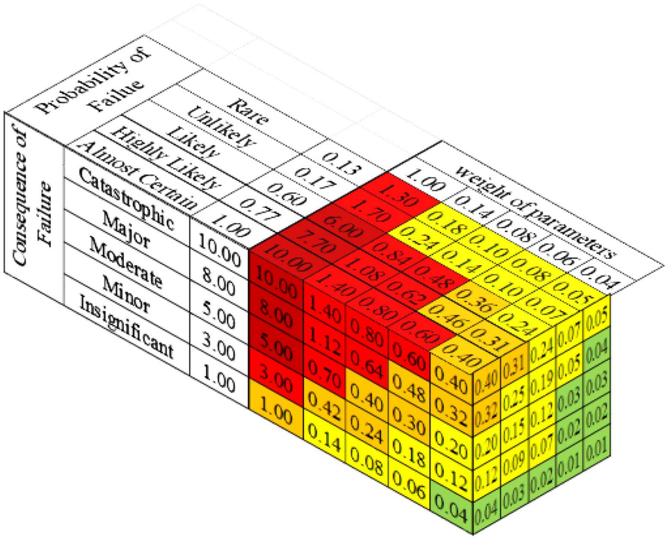

Fig. 2. Three-dimensional integrated risk index matrix of using treated municipal wastewater in industrial cooling consumptions instead of freshwater.

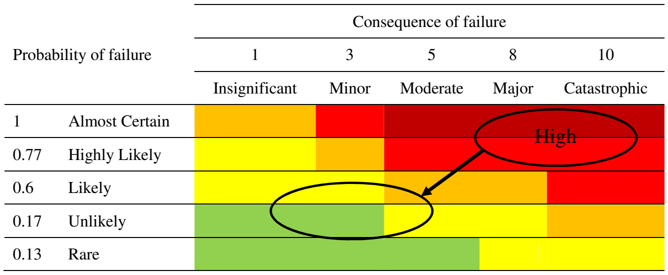

Fig. 3. Risk index and asset risk evaluation matrix.

be reducing the vulnerability of the system components (Roozbahani et al. 2013).

Fuzzy Risk Index

Determining the Fuzzy Score of Consequences of Failures

The threshold of the defined criteria is converted to fuzzy numbers ($\tilde{r}$). The weight of each criterion ($\tilde{W}$) is determined according to the AHP method. Thereafter, the score related to each criterion ($\tilde{U}$) is calculated according to Eq. (6)

$$\tilde{U}_i = \tilde{W}_i \times \tilde{r}_i \tag{6}$$

where $\tilde{U}$ = fuzzy score of consequence of failures; $\tilde{r}$ = fuzzy score of each criterion in the intended failure; $\tilde{W}$ = fuzzy weight of each criterion; and i is related to the criterion.

Evaluating the Fuzzy Risk Value

Eq. (7) is used to determine the fuzzy risk value. The parameter of probability of failure has been determined using the experimental data. Therefore, in the calculations, that parameter has been treated as a nonfuzzy number

$$\tilde{R} = \text{POF} \odot \tilde{W} \otimes \tilde{U} \tag{7}$$

where $\tilde{R}$ = fuzzy risk value; POF = probability of failure; $\tilde{W}$ = fuzzy weight of each parameter; and $\tilde{U}$ = fuzzy score of consequence of failures.

Defuzzification

Among the methods for converting a fuzzy quantity to a crisp value, the surface center method has less limitation and higher accuracy, which is calculated by Eq. (8) (Fortemps and Roubens 1996)

$$Z = \frac{\int_z \mu_A(z) z dz}{\int_z \mu_A(z) dz} \tag{8}$$

where Z = defuzzified value of $\tilde{A}$; $\mu_A(z)$ is the fuzzy membership function; and z = parameter of the fuzzy function. In this nonfuzzy research, considering the high accuracy, the surface center method is used.

Case Study

The studied region to evaluate the proposed methodology is the Isfahan Mobarakeh Steel Complex (the largest producer of flat steel in the middle east), located 75 km southwest of Isfahan, Iran. This complex is located alongside the Zayandehroud River, which is the source of industrial and drinking water for the Isfahan Mobarakeh Steel Complex.

Table 5. Qualitative standards of the cooling water in the Mobarakeh Steel Complex

No.	Parameter	Limit	Unit
1	Total suspended solids (TSS)	<5	ppm
2	Total dissolved solids (TDS)	<300	ppm
3	Total hardness	<200	ppm
4	Total alkalinity (methyl orange)	50–70	ppm
5	Chloride	<90	ppm
6	Sulfate	<120	ppm
7	pH	8.2–8.7	—

Table 5 provides the quality of the water required by the cooling system, which after the treatment operations and adding chemicals in the water treatment plant unit is used as industrial water in this complex.

The shop and small factory industrial wastewaters, entering the urban collection wastewater network, are the main risk factor for reusing wastewater in the industry. The entrance of materials such as heavy metals and industrial organic compounds whose treatment system is not in urban treatment plants can be very hazardous. Therefore, the differences between two water sources and their effects must be evaluated.

Results and Discussion

Risk Parameter Weights

After identifying the main failures and their influential parameters by using a paired comparisons matrix, the effect of weight of the parameters was calculated (Tables 6–8). The results for the weight of the influential parameters show that ammonium, dissolved oxygen, and iron have the maximum effect on corrosion (Table 6). Further, total hardness, calcium, sulfate, and phosphate have the greatest impact on scaling (Table 7). Finally, chloride, total suspended solids (TSS), phosphate, and nitrogen have the greatest effect on biofouling. In addition, using Expert Choice software, the inconsistency rate of the matrices was calculated. Considering the special characteristics and different degrees of sensitivity of industries, some of the previously mentioned parameters that were not sensitive to steel industries were removed from the risk assessment framework. Through the sensitivity of cooling systems in other industries, some other failures may also be considered.

Table 6. Weight of the corrosion risk parameters

Parameter	Risk variable weight
SO_4	0.045
Ammonia	0.175
Total hardness (TH)	0.040
Fe	0.129
Mg	0.079
Na	0.072
Cu	0.062
Chemical oxygen demand (COD)	0.023
Biological oxygen demand (BOD)	0.023
Dissolved oxygen (DO)	0.151
PO_3	0.034
Total dissolved solids (TDS)	0.026
pH	0.087
Cl	0.055

Table 7. Weight of the scaling risk parameters

Parameter	Risk variable weight
PO_3	0.114
SO_4	0.105
Total hardness (TH)	0.228
Fe	0.067
Mg	0.082
Na	0.057
Biochemical oxygen demand (BOD)	0.023
Chemical oxygen demand (COD)	0.022
Total dissolved solids (TDS)	0.084
Alkalinity	0.037
Ammonia	0.039
Ca	0.141

Table 8. Weight of the biofouling risk parameters

Parameter	Risk variable weight
TSS	0.164
Chemical oxygen demand (COD)	0.059
Biochemical oxygen demand (BOD)	0.056
Cl	0.309
Temperature	0.085
Total dissolved solids (TDS)	0.049
PO_3	0.172
N	0.107

The inconsistency rates of paired comparisons matrix of the parameters affecting corrosion, scaling, and biofouling were 0.08, 0.03, and 0.04, respectively. The acceptable range of consistency in any system according to experts' opinions can be different. However, generally Saaty (1996) suggests that if the inconsistency of the decision is higher than 0.01, it is better for decision makers to reconsider their judgment. Considering the inconsistency rate of the paired comparisons matrices on the factors affecting corrosion, it can be concluded that the consistency of the group decision is suitable.

Consequence of Failure

The second stage of the integrated risk assessment framework for using treated wastewater in the cooling systems of the Isfahan Mobarakeh Steel Complex was assessing the consequences of the identified failures. To calculate this stage, first the criteria and thresholds were used to estimate the consequences resulting from the three risks, corrosion, scaling, and biofouling (FEMA 2005; Roozbahani et al. 2013; UEPA 2012). Thereafter, the weight of each criterion was determined based on the paired comparisons matrix performed by Saaty (1990). Then the inconsistency rate of the matrices was specified using Expert Choice software. The weights of the water quality control criteria with chemicals, economics, impairment time, and vulnerability were higher than other criteria, suggesting their importance to others. Furthermore, the score of the failure consequences of growth of biological materials (7.92) was larger than that of scaling (5.66) and corrosion (5.32). This suggests that biofouling is the principal failure threatening the cooling system (Table 9).

Table 9. Calculation of the COF index for corrosion, scaling, and biofouling risks

Criterion	Criterion weight	Failure		
		Corrosion	Scaling	Biofouling
Physical equipment	0.023	6.81	4.82	9.04
Identification	0.016	3.08	3.38	8.43
Reversibility	0.038	2.71	7.89	5.57
Flexibility	0.070	3.85	4.86	4.82
Functionality	0.056	4.54	8.62	7.80
Economics	0.171	8.08	3.71	9.76
Impairment time	0.165	4.05	5.34	9.17
Vulnerability	0.159	6.27	7.89	7.83
Sensitivity of components	0.113	7.49	5.29	9.11
Controlling water quality with chemicals	0.188	3.14	5.32	5.98
Total score	—	5.32	5.66	7.92

Overall Risk Index

The last step after determining the indexes of consequences of failure and the probability of failure within the integrated risk assessment framework of using treated wastewater instead of freshwater as cooling water in industry was calculating the overall risk index. After specifying the weight of each parameter affecting the three main failures, the probability, and the consequences of failure resulting from them, the risk index value was obtained according to Eq. (5). Table 10 provides the results of calculating the risk of each parameter. The risk calculation results indicate that ammonium with the risk score of 0.931 poses the maximum risk of the parameters affecting corrosion. Phosphate with the risk score of 0.647 poses the maximum risk of the parameters affecting scaling. Finally, chlorine with the risk score of 2.139 poses the maximum risk of the parameters affecting the biofouling failure.

Figs. 4–6 reveal the percentage of parameters with extreme to partial risks for corrosion, scaling, and biofouling failures. Biological failures have the maximum risk for the cooling systems considering the high score of failure consequences and probability of incidence. As can be seen in Fig. 4, 14.29% of the parameters affecting corrosion are extreme, 21.43% are moderate, 50% low, and 14.29% are trivial risk factors in the cooling systems.

As can be observed in Fig. 5, 8.33% of the parameters affecting scaling failure are extreme, 16.67% are moderate, 50% are low, and 25% are trivial risk factors in the cooling systems. These results suggest that the parameters affecting scaling have the minimum risk impact on using treated wastewater in cooling systems.

As can be seen in Fig. 6, 50% of the parameters affecting biofouling failure are extreme risk factors, while the other 50% of the parameters are moderate risk factors in the cooling systems. These results describe the significant role of the factors affecting biofouling in using treated wastewater in cooling systems. Accordingly, equipping systems with resistance against this failure is crucial and should be considered before using treated wastewater.

Model Test Process

In this research, the integrated risk model was recalculated using the fuzzy analytical hierarchy process (FAHP) to show the measurement accuracy of the data that is sourced by human decisions. Fuzzy logic can be used as a development tool of expert or human knowledge-based systems. It can make the communication of experts' knowledge more exact and qualitative and solve the problem of inexact description of the experts (Fares and Zayed 2010; Karray and de Silva 2004).

Table 10. Overall risk calculations for parameters of corrosion, scaling, and biofouling risk

Failure	Parameter	Weight	POF	COF	Risk	Risk color for management policy
Corrosion	Ammonium	0.175	1.000	5.322	0.931	Red
	Dissolved oxygen (DO)	0.151	1.000	5.322	0.803	Red
	Sodium	0.072	0.733	5.322	0.279	Orange
	Magnesium	0.079	0.625	5.322	0.262	Orange
	Chloride	0.055	0.875	5.322	0.255	Orange
	Phosphate	0.034	1.000	5.322	0.181	Yellow
	pH	0.087	0.313	5.322	0.145	Yellow
	Total dissolved solids	0.026	1.000	5.322	0.139	Yellow
	Biochemical oxygen demand (BOD)	0.023	1.000	5.322	0.124	Yellow
	Chemical oxygen demand (COD)	0.023	1.000	5.322	0.122	Yellow
	Copper	0.062	0.313	5.322	0.103	Yellow
	Iron	0.129	0.125	5.322	0.086	Yellow
	Sulfate	0.045	0.125	5.322	0.030	Green
	Total hardness	0.040	0.000	5.322	0.000	Green
Scaling	Phosphate	0.114	1.000	5.663	0.647	Red
	Total dissolved solids	0.084	1.000	5.663	0.476	Orange
	Magnesium	0.082	0.625	5.663	0.292	Orange
	Sodium	0.057	0.733	5.663	0.237	Yellow
	Ammonium	0.039	1.000	5.663	0.220	Yellow
	Alkalinity	0.037	1.000	5.663	0.209	Yellow
	Biochemical oxygen demand (BOD)	0.023	1.000	5.663	0.129	Yellow
	Chemical oxygen demand (COD)	0.022	1.000	5.663	0.124	Yellow
	Sulfate	0.105	0.125	5.663	0.074	Yellow
	Iron	0.067	0.125	5.663	0.047	Green
	Calcium	0.141	0.000	5.663	0.000	Green
	Total hardness	0.228	0.000	5.663	0.000	Green
Biofouling	Chlorine	0.309	0.875	7.919	2.139	Red
	Phosphate	0.172	1.000	7.919	1.364	Red
	Total suspended solids	0.164	1.000	7.919	1.298	Red
	Nitrogen	0.107	0.938	7.919	0.794	Red
	Chemical oxygen demand (COD)	0.059	1.000	7.919	0.467	Orange
	Biochemical oxygen demand (BOD)	0.056	1.000	7.919	0.441	Orange
	Total dissolved solids	0.049	1.000	7.919	0.389	Orange
	Temperature	0.085	0.500	7.919	0.335	Orange

Note: Red = extreme risk factor; orange = moderate risk factor; yellow = low risk factor; and green = trivial risk factor.

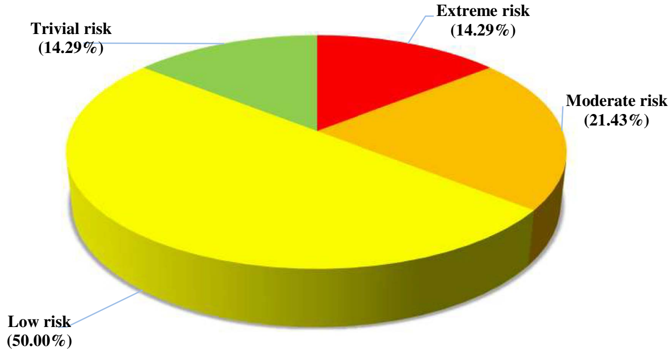

Fig. 4. Results of risk analysis of the parameters affecting corrosion risk of using treated municipal wastewater in industrial cooling consumptions instead of freshwater.

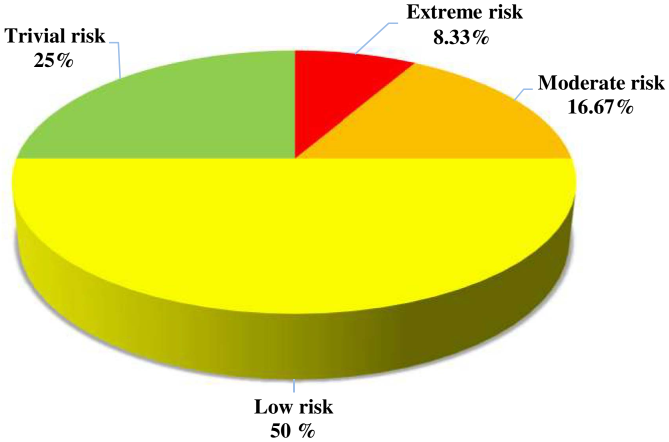

Fig. 5. Results of risk analysis of the parameters affecting scaling risk of using treated municipal wastewater in industrial cooling consumptions instead of freshwater.

For this purpose, first the effective weight of the scaling risk parameters and their related score was calculated through FAHP (Table 11).

According to Table 11, the order of risky parameters in the scaling failure in descending order are phosphate, total dissolved solids, magnesium, sodium, ammonium, alkalinity, biological oxygen demand (BOD), chemical oxygen demand (COD), sulfate, iron, calcium, and total hardness. In calculating the risk through the fuzzy method, the priority of 10 of the 12 parameters were exactly the same in the nonfuzzy method, and only two parameters, alkalinity and ammonium, are ranked differently: they are the fifth and sixth priorities in the fuzzy method, and the sixth and fifth priorities

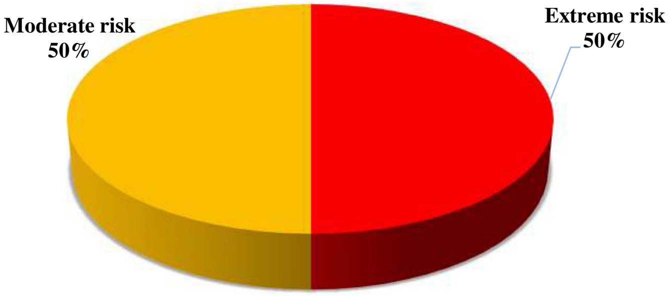

Fig. 6. Results of risk analysis of the parameters affecting biofouling risk of using treated municipal wastewater in industrial cooling consumptions instead of freshwater.

Table 11. Fuzzy and crisp values of the parameters of scaling risk calculated by FAHP method

Parameter	Crisp value	Fuzzy risk
Ca	0	(0,0,0)
Ammonia	0.481	(0.15,0.22,0.32)
Alkalinity	0.506	(0.13,0.21,0.33)
TDS	1.142	(0.29,0.47,0.75)
COD	0.282	(0.08,0.12,0.21)
BOD	0.308	(0.07,0.12,0.22)
Na	0.526	(0.12,0.22,0.39)
Mg	0.785	(0.16,0.3,0.55)
Fe	0.126	(0.02,0.05,0.1)
TH	0	(0,0,0)
SO_4	0.209	(0.04,0.08,0.17)
PO_3	1.809	(0.29,0.67,1.43)

in the nonfuzzy method. These results suggest that the accuracy of the response of the interviews is acceptable.

Conclusion

The results obtained from the risk analysis for using wastewater in industrial cooling systems show that the risks of the parameters of chlorine, phosphate, and total suspended solids are the largest among other risks. The parameters of ammonium, nitrogen, and dissolved oxygen stand in the second position. The sensitivity of cooling systems to parameters with extreme and moderate risk should be taken into account in the plan of designing and operating systems for using wastewater in industry. Also, some solutions should be presented to mitigate these values at the treatment stage. Furthermore, a plan should be developed to strengthen the system against the failures and the system should be equipped. Biofouling has acquired a larger value among the corrosion and scaling risks, which is logical. This is because biofouling can hardly be detected and there is no method for controlling it in industries. Biological risk at any time and in any sensitive parts threatens the cooling system.

The risk framework presented in this research provides the possibility of raising awareness about the main failures and the factors affecting them for using treated wastewater instead of freshwater in the Mobarakeh Steel Complex industry. In this way the system risks can be recognized before implementing the plan and suitable solutions can be employed to tackle it. Furthermore, this method and its results greatly help in developing the procedure of using treated wastewater as an industrial consumption instead of freshwater. Since the current research focused on corrosion, scaling, and biofouling risk, further research may enhance human health and environmental risks.

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