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Risk assessment methodology for iron stability under water quality factors based on fuzzy comprehensive evaluation

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Abstract

Background: Changing water quality was prevalent in the current water supply. The fluctuation of iron stability due to changing water quality followed four characteristics: objectivity, relativity, predictability, and controllability. Therefore, it was necessary to study the stability of iron in the pipe network by integrating different water quality factors.

Results: The iron stability risk evaluation system was established according to the different water quality factors in the drinking water distribution systems (DWDSs). Meanwhile, an improved fuzzy comprehensive evaluation method was established to evaluate the risk of iron. Chloride, sulfate, dissolved organic matter (DOM) and pH were selected as the risk assessment index. The divisions of different evaluation levels were carried out through the values of water quality factor. On the basis of expert scoring, the weight and membership degree of water quality factors were analyzed by structural entropy method. In addition, risk analysis was established by using the optimized risk assessment system. According to the results of the comprehensive evaluation, DOM and pH were identified as two of the most important factors in the evaluation of the iron stability. In addition, compared with the traditional fuzzy comprehensive evaluation method, the optimized method had a higher degree of fit which could more clearly prove the relationship between the risk value and the iron concentration.

Conclusion: The uncertainty between the factors was eliminated by establishment of the fuzzy evaluation method combined with the different effects of water factors on iron stability. The method could be used as a comprehensive evaluation and be beneficial to the analysis of iron risk in water supply network.

Keywords: Risk assessment, Iron stability, Water quality factors, Fuzzy comprehensive evaluation

Background

Iron was often found in the water supply pipe network which could cause unpleasant metallic taste, water fouling and rusty color [1]. In the past few years, iron problems in the drinking water distribution systems (DWDSs) have attracted extensive attentions [2, 3]. Water supply pipes generally consist of metal pipes, plastic pipes and other types of pipes, meanwhile, metal pipes are the main ones [4]. However, the inner coating in metal pipes

gradually failed and flaked off for a long-time use, the pipe would be largely corrupted. The risk of iron stability was based on the changing of water quality conditions.

The fluctuation of iron stability produced by changing water quality followed the four characteristics: objectivity, relativity, predictability, and controllability. Objectivity referred to the phenomenon of the iron stability posed by different water quality conditions based on objective facts. Relativity was mainly due to the lag of the water quality information and the degree of accurate grasp on the mechanism of iron stability. Predictability meant the changes of iron stability could be predicted by the study of water quality in the pipe network. Controllability could be considered as the controlling of iron risk.

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Previous studies demonstrated that goethite ($\alpha\text{-FeOOH}$), lepidocrocite ($\gamma\text{-FeOOH}$), and magnetite (Fe_3O_4) are the main elements contained in iron scales on the inner walls of drinking pipes [5, 6]. The stability of iron in the DWDSs was affected by a variety of factors, especially the water quality factors including chloride, sulfate, dissolved organic matter (DOM), pH and so on. Each water quality factor showed different effect on iron stability. Chloride and sulfate were deemed to destroy the stability of iron in the DWDSs, increasing iron concentration in water [7, 8]. DOM played a key role in iron stability which was recorded to reduce ferric iron colloids to soluble ferrous iron [9, 10]. And the increasing of pH was demonstrated to enhance the iron stability and decrease the iron releasing in actual distribution systems [11].

At present, it is difficult to fully assess the iron pollution in the DWDSs for the limited number of detection points and the expensive costing. A method needs to be established to evaluate the stability of iron through conventional water quality parameters. Therefore, based on mathematical analysis, the evaluation method was established to evaluate the impact on iron pollution under different water quality conditions in the DWDSs. This research mainly focused on the four factors (chloride, sulfate, DOM and pH). The comprehensive risk assessment method should combine qualitative indexes and quantitative indexes. It was difficult to carry out an accurate quantitative analysis of the evaluation results for the ambiguous effect of different water quality conditions on iron stability. In addition, the relationships between the different water qualities factors were not clear which led to ambiguity in the set and calculation of indicators. Therefore, in view of the 'fuzzy' characteristics of the evaluation indexes, the fuzzy comprehensive evaluation method was used to evaluate the iron stability.

The fuzzy comprehensive evaluation method was a mathematical method which was proposed to evaluate and solve the problem with fuzziness of constrained boundary condition and unclear concepts [12–14]. The concept of fuzzy sets depicting imprecision and vagueness was introduced by Zadeh who defined the fuzzy mathematical theory in 1965 for the first time. The concrete analysis method of quantitative fuzzy problem made up the deficiency that classical mathematics could not quantify and analyze fuzzy things accurately. Fuzzy comprehensive evaluation was used to deal with the quantitative factors which were difficult to quantify based on the fuzzy mathematics as the theoretical basis, such as water resources carrying capacity [15] and water quality risk assessment [16]. There were no clear boundaries between the conceptual nature and the specificity of the iron stability in the DWDSs. The fuzzy comprehensive evaluation and analysis method could be used to analyze the iron risk assessment under different

water quality conditions. However, in the previous process of calculating membership, the comprehensive evaluation would be uncertain under the case index of the membership degree is less than or greater than the minimum or maximum median. Therefore, this research considered to optimize this part and establish an optimized fuzzy method.

Methods

The results of the environmental risk assessment were not absolute [17], but the risk assessment of iron stability in this study was relative. The changing between the different water quality factors and the same water quality factors in different values had different effects on the iron stability. Thence, the evaluation variables were ambiguous and difficult to synthesize the accurate prediction results. However, the fuzzy evaluation method used the weighting principle to take full account of the factors. Different factors were evaluated through the subjective and objective steps, resulting in reducing the uncertainty of the variables. Finally, the corresponding risk of iron stability on the comprehensive evaluation results was obtained.

There were multiple uncertainties in the DWDSs. The water quality factors had fuzzy characteristic. Therefore, in order to deal with the problem on iron stability, this research developed a model by integrating analytic hierarchy process (AHP) method and fuzzy sets into risk assessment model. The model could be described as following: (1) establishing the evaluation object and the evaluation indexes; (2) analyzing the improved fuzzy evaluation system; (3) getting the weights of the comparison elements and the risk level to obtain the risk assessment value. The detailed solution process is explained as follows.

Establishing the evaluation system

The need to determine the evaluation objective and evaluation objects was the primary assignment of establishing an evaluation system. This research focused on the impact of the four water quality factors (chloride, sulfate, DOM and pH) on iron stability in the DWDSs. The evaluating index set $U = \{u_1, u_2, u_3, \dots, u_n\}$ for the iron stability was established, $u_1 - u_n$ represented as the evaluating index. All of the four types of water quality parameters were quantitative indicators.

$$U = \{u_{\text{Cl}}, u_{\text{SO}_4^{2-}}, u_{\text{DOM}}, u_{\text{pH}}\}. \quad (1)$$

Evaluating index weight method

In order to reflect the impacts of water quality factors on iron stability, the different weights of water quality factors were settled. The weighting method used in this section was the structural entropy method.

The entropy method was based on the subjective basis of the indicators' importance on the evaluation object [18]. It was used to analyze by the entropy and the blind analysis. Finally, the weight of the index was obtained by normalization [19, 20].

Expert order

The assessments in this section provided researchers in the field of environmental to get the scoring table according to the individual's understanding and experience of the evaluation index. The importance of the four water quality factors (chloride, sulfate, DOM and pH) was analyzed.

In this section of the analysis, experts were invited to participate in the questionnaire. Each row represented the importance of the same expert for the importance of the indexes, and each column indicated the importance of different experts to the same indicator in the index matrix formula (2):

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}. \quad (2)$$

Blind analysis

Blind analysis was used in order to eliminate the phenomenon of uncertainty which might be generated by the experts in the sorting process due to personal subjective reasons. Membership function could be transformed from the 'expert order' which established as:

$$\chi(I) = -\lambda p_n(I) \ln p_n(I). \quad (3)$$

I was the index of the indicator by experts, $I = 1, 2, \dots, j$ according to the importance of the indicator; $m = j + 2$, p_n and λ were the functions formed by m :

$$p_n(I) = \frac{m - I}{m - 1}, \quad (4)$$

$$\lambda = \frac{1}{\ln(m - 1)}. \quad (5)$$

Therefore, the membership function $\mu(I)$ could be established as:

$$\chi(I) / \left(\frac{m - I}{m - 1} \right) = -\frac{\ln(m - I)}{\ln(m - 1)} + 1, \quad (6)$$

$$\mu(I) = \frac{\ln(m - I)}{\ln(m - 1)} \in [0, 1]. \quad (7)$$

In addition, the overall degree of x_j of the experts on the indicator u_j could be expressed as:

$$x_j = b_j(1 - \sigma_j), \quad (8)$$

in which b_j was defined as the same scoring of indexes by the total k experts, $b_j = (b_{1j} + b_{2j} + \cdots + b_{kj})/k$, σ_j was the uncertainty of the indicators impacting on the evaluation object, $\sigma_j = \{[\max(b_{1j}, b_{2j}, \dots, b_{kj}) - b_j] + [\min(b_{1j}, b_{2j}, \dots, b_{kj}) - b_j]\} / 2$, b_{kj} could be calculated by $\mu(I)$, and k represented the number of the experts.

Normalization of weight vector

The weight needed to be normalized in the fuzzy comprehensive evaluation method in order to evaluate clearly. Normalize the degree of awareness α_j as following in this research. Therefore, the weight vector of different water quality indicators could be obtained by normalization.

$$\alpha_j = x_j / \sum_{j=1}^k x_j \quad (9)$$

Therefore, formula (10) showed the weight vector of the evaluation objectives which could be calculated after the process of expert order, blind analysis, and normalization:

$$W = \{W_{Cl^-}, W_{SO_4^{2-}}, W_{DOM}, W_{pH}\}. \quad (10)$$

Evaluation grade (V)

The evaluation grade referred to the classification of the evaluation object (iron stability) according to the impact of the evaluation objectives (water quality factors). The quantitative description of the four evaluation indexes (chloride, sulfate, DOM and pH) were described according to the actual situation of each evaluation index. The evaluation of the situation was divided into five grades (slight risks, small risks, general risks, greater risks, significant risks), which were commonly used in fuzzy comprehensive evaluation. The evaluating grade set $V = \{v_1, v_2, v_3, v_4, v_5\}$ was established, v_1-v_5 represented as the five grades of the evaluation which depended on water quality factors. The evaluation grade of the iron risk assessment system was shown as the following:

$$V = \{v_{slr}, v_{smr}, v_{ger}, v_{grr}, v_{sir}\}. \quad (11)$$

Degree of membership function (V_n)

Each evaluation factor had different influence on the evaluation result. Therefore, the membership degree of each evaluation factor corresponding to different evaluation grade was determined by setting membership

function, according to the characteristics of the evaluation factors.

Water quality factors were divided into incremental factors and descending factors according to the influence on iron stability. Incremental factor and descending factor represented the risk increased with the value of the factor increasing or decreasing. According to the previous researches [7–10], the increasing concentration of chloride, sulfate and DOM in pipeline water would lead to an increasing risk of iron, while increased pH would lead to decrease the risk [11]. The degrees of membership functions are shown in Table 1.

The risk of the iron stability under the different water conditions could be calculated synthetically based on the membership value and the weight of the four water quality factors shown in formula (12):

$$R_n = W_n \times V_n. \quad (12)$$

$$V_{Cl^-} = \{v_{slr}, v_{smr}, v_{ger}, v_{grr}, v_{sir}\} = \{(0, 50), (50, 100), (100, 150), (150, 200), (200, 250)\}, \quad (14)$$

$$V_{SO_4^{2-}} = \{v_{slr}, v_{smr}, v_{ger}, v_{grr}, v_{sir}\} = \{(0, 50), (50, 100), (100, 150), (150, 200), (200, 250)\}, \quad (15)$$

$$V_{DOC} = \{v_{slr}, v_{smr}, v_{ger}, v_{grr}, v_{sir}\} = \{(0, 4), (4, 8), (8, 12), (12, 16), (16, 20)\}, \quad (16)$$

$$V_{pH} = \{v_{slr}, v_{smr}, v_{ger}, v_{grr}, v_{sir}\} = \{(8.0, 8.5), (7.5, 8.0), (7.0, 7.5), (6.5, 7.0), (6.0, 6.5)\}. \quad (17)$$

The optimized model with value outside the range

In the traditional method, both the values under the condition of smaller than the middle of the minimum range and bigger than the middle of the maximum range were '1'. In order to distinguish the situation, the following calculating formulas were used to analyze the condition outside the range. W represented the weight vector of the considered water factor which is out of the evaluation grade (Table 2):

$$R'_n = W_n \times V_n \times \sum_n (1 + Q_i \times W_i). \quad (13)$$

Variable fuzzy evaluation model for iron stability

The four indicators (chloride, sulfate, DOM and pH) were figured in this research, all of which were quantitative parameters and could affect the iron stability in the DWDSs.

Index classification

Sulfate and chloride were the indication of iron shape variation leading to the high concentration of red water [7]. DOM plays a key role in iron stability, could form complicated complexes with iron, meanwhile, the phenomenon of reducing ferric iron colloids to soluble ferrous iron was also recorded [9, 10]. And pH was demonstrated to increase the iron stability in actual distribution systems [21]. Therefore, the numerical interval division of the four indicators on evaluation grade could be expressed as following. Formula (14)–(17) showed the corresponding grade for each water quality factors. Chloride, sulfate, dissolved organic carbon (DOC) (characterize DOM content) were the incremental factors, and pH was the descending factor:

The experts order

Table 3 shows the sorting of the four water quality factors (chloride, sulfate, DOM and pH). Table 3 is calculated by using the fuzzy comprehensive evaluation method according to four environmental experts in the basic evaluation index set on iron stability.

Weight analysis

The effect of the four water quality factors on iron stability could be transformed into one comprehensive evaluation value (weight analysis) using the fuzzy comprehensive evaluation method, which provided a relatively simple approach for analyzing the water quality factors.

Weight was the relative concept for one indicator. The weight of indicator was the relative importance of the indicators in the overall evaluation. The weights of the four water quality factors under the influence of iron stability obtained blindness analysis and normalization

Table 1 Application of two kinds of evaluation factor types in membership function

Membership function	Incremental factor	Descending factor
$\mu_{v_1}(u_i) = \begin{cases} 1 \\ 0.5 \times \left[1 + \frac{u_i - k_1}{k'_1 - k_1} \right] \\ 0.5 \times \left[1 - \frac{k_1 - u_i}{k_1 - k'_2} \right] \\ 0 \end{cases}$	$\mu_{v_1}(u_i) = \begin{cases} u_i < k'_1 \\ k'_1 \leq u_i < k_1 \\ k_1 \leq u_i < k'_2 \\ u_i \geq k'_2 \end{cases}$	$\mu_{v_1}(u_i) = \begin{cases} u_i \geq k'_1 \\ k'_1 > u_i \geq k_1 \\ k_1 > u_i \geq k'_2 \\ u_i < k'_2 \end{cases}$
$\mu_{v_2}(u_i) = \begin{cases} 0 \\ 0.5 \times \left[1 - \frac{u_i - k_1}{k'_1 - k_1} \right] \\ 0.5 \times \left[1 + \frac{k_1 - u_i}{k_1 - k'_2} \right] \\ 0.5 \times \left[1 + \frac{u_i - k_2}{k'_2 - k_2} \right] \\ 0.5 \times \left[1 - \frac{k_2 - u_i}{k_2 - k'_3} \right] \\ 0 \end{cases}$	$\mu_{v_2}(u_i) = \begin{cases} u_i < k'_1 \\ k'_1 \leq u_i < k_1 \\ k_1 \leq u_i < k'_2 \\ k'_2 \leq u_i < k_2 \\ k_2 \leq u_i < k'_3 \\ u_i \geq k'_3 \end{cases}$	$\mu_{v_2}(u_i) = \begin{cases} u_i \geq k'_1 \\ k'_1 > u_i \geq k_1 \\ k_1 > u_i \geq k'_2 \\ k'_2 > u_i \geq k_2 \\ k_2 > u_i \geq k'_3 \\ u_i < k'_3 \end{cases}$
$\mu_{v_3}(u_i) = \begin{cases} 0 \\ 0.5 \times \left[1 - \frac{u_i - k_2}{k'_2 - k_2} \right] \\ 0.5 \times \left[1 + \frac{u_i - k_3}{k'_3 - k_3} \right] \\ 0.5 \times \left[1 - \frac{k_3 - u_i}{k_3 - k'_4} \right] \\ 0 \end{cases}$	$\mu_{v_3}(u_i) = \begin{cases} u_i < k'_2 \\ k'_2 \leq u_i < k_2 \\ k_2 \leq u_i < k'_3 \\ k'_3 \leq u_i < k_3 \\ k_3 \leq u_i < k'_4 \\ u_i \geq k'_4 \end{cases}$	$\mu_{v_3}(u_i) = \begin{cases} u_i \geq k'_2 \\ k'_2 > u_i \geq k_2 \\ k_2 > u_i \geq k'_3 \\ k'_3 > u_i \geq k_3 \\ k_3 > u_i \geq k'_4 \\ u_i < k'_4 \end{cases}$
$\mu_{v_4}(u_i) = \begin{cases} 0 \\ 0.5 \times \left[1 - \frac{u_i - k_3}{k'_3 - k_3} \right] \\ 0.5 \times \left[1 + \frac{k_3 - u_i}{k_3 - k'_4} \right] \\ 0.5 \times \left[1 + \frac{u_i - k_4}{k'_4 - k_4} \right] \\ 0.5 \times \left[1 - \frac{k_4 - u_i}{k_4 - k'_5} \right] \\ 0 \end{cases}$	$\mu_{v_4}(u_i) = \begin{cases} u_i < k'_3 \\ k'_3 \leq u_i < k_3 \\ k_3 \leq u_i < k'_4 \\ k'_4 \leq u_i < k_4 \\ k_4 \leq u_i < k'_5 \\ u_i \geq k'_5 \end{cases}$	$\mu_{v_4}(u_i) = \begin{cases} u_i \geq k'_3 \\ k'_3 > u_i \geq k_3 \\ k_3 > u_i \geq k'_4 \\ k'_4 > u_i \geq k_4 \\ k_4 > u_i \geq k'_5 \\ u_i < k'_5 \end{cases}$
$\mu_{v_5}(u_i) = \begin{cases} 0 \\ 0.5 \times \left[1 - \frac{u_i - k_4}{k'_4 - k_4} \right] \\ 0.5 \times \left[1 + \frac{k_4 - u_i}{k_4 - k'_5} \right] \\ 0 \end{cases}$	$\mu_{v_5}(u_i) = \begin{cases} u_i < k'_4 \\ k'_4 \leq u_i < k_4 \\ k_4 \leq u_i < k'_5 \\ u_i \geq k'_5 \end{cases}$	$\mu_{v_5}(u_i) = \begin{cases} u_i \geq k'_4 \\ k'_4 > u_i \geq k_4 \\ k_4 > u_i \geq k'_5 \\ u_i < k'_5 \end{cases}$

k_1, k_2, k_3, k_4, k_5 represented the critical value of the adjacent classification interval; k'_1, k'_2, k'_3, k'_4 and k'_5 were the midpoint of the rank of the corresponding level v_1, v_2, v_3, v_4 , and v_5 , respectively

Table 2 Optimized method of calculating membership

K_n	Incremental factor	Descending factor
$u_i < k'_1$	$Q_i = \frac{k'_1 - u_i}{v_{\max}}$	$Q_i = \frac{u_i - k'_1}{v_{\max}}$
$u_i < k'_5$	$Q_i = \frac{u_i - k'_5}{v_{\max}}$	$Q_i = \frac{k'_1 - u_i}{v_{\max}}$

analysis according to the results of the expert sorting. W formula (18) represented the weight vector of the four water quality evaluation indicators could be calculated by formula (2) to formula (10):

Table 3 The sorting table of the four water quality factors

Case	Chloride	Sulfate	DOM	pH
1	4	3	1	2
2	3	4	1	2
3	4	2	1	3
4	4	3	2	1

Table 4 Different water cases under four water quality factors

Condition	Chloride (mg/L)	Sulfate (mg/L)	DOC (mg/L)	pH
1	857.5	43.00	9.399	6.06
2	1057	140.53	33.307	6.25
3	1808.2	267.99	3.828	5.84
4	159.2	132.69	5.348	6.85

The data of four water quality indicators are from the hollows located between tubercles at the bottom of four different pipe fragments [23]

The content of DOM was characterized using DOC

$$W = [0.1444, 0.2521, 0.3126, 0.2909]. \quad (18)$$

Although the basic evaluation indexes were different according to the different experts' order, the sorting of the weights on the iron stability could also be calculated after the process of expert order, blind analysis, and normalization. The sorting of the weights on the iron stability was $\text{DOM} > \text{pH} > \text{sulfate} > \text{chloride}$ in this research, which was similar to the previous research [22].

Results

Different water quality has a good correlation with the stability of iron in the DWDSs. In the case study, four kinds of water factors about the steady water in the DWDSs were considered according to Swietlik et al. [23], which is used to explain the effects of water quality factors and iron stability. Four conditions of steady water were collected from the black water surrounding and partly filling the tubercles in the different parts of pipes [23]. The details of the water factors are shown in Table 4.

Table 5 Membership calculation (condition 1)

Water quality factor	Value	Slight risk (v_{slr})	Small risk (v_{smr})	General risk (v_{ger})	Greater risk (v_{grr})	Significant risk (v_{sir})
Chloride	857.5 mg/L	0	0	0	0	1
Sulfate	43.00 mg/L	0.6400	0.3600	0	0	0
DOC	9.40 mg/L	0	0.1500	0.8500	0	0
pH	6.06	0	0	0	0	1

Table 6 Membership calculation (condition 2)

Water quality factor	Value	Slight risk (v_{slr})	Small risk (v_{smr})	General risk (v_{ger})	Greater risk (v_{grr})	Significant risk (v_{sir})
Chloride	1057 mg/L	0	0	0	0	1
Sulfate	140.53 mg/L	0	0	0.6894	0.3106	0
DOC	33.31 mg/L	0	0	0	0	1
pH	6.25	0	0	0	0	1

Table 7 Membership calculation (condition 3)

Water quality factor	Value	Slight risk (v_{slr})	Small risk (v_{smr})	General risk (v_{ger})	Greater risk (v_{grr})	Significant risk (v_{sir})
Chloride	1808.2 mg/L	0	0	0	0	1
Sulfate	267.99 mg/L	0	0	0	0	1
DOC	3.83 mg/L	0.5425	0.4575	0	0	0
pH	5.84	0	0	0	0	1

Table 8 Membership calculation (condition 4)

Water quality factor	Value	Slight risk (v_{slr})	Small risk (v_{smr})	General risk (v_{ger})	Greater risk (v_{grr})	Significant risk (v_{sir})
Chloride	159.2 mg/L	0	0	0.3160	0.6840	0
Sulfate	132.69 mg/L	0	0	0.8462	0.1538	0
DOC	5.35 mg/L	0.1625	0.8375	0	0	0
pH	6.85	0	0	0.2000	0.8000	0

Table 9 Water quality risk assessment

Water condition	Risk assessment	The optimized risk value	Iron concentration [23]
1	3.4103	3.5826	360 mg/L
2	4.5741	4.8780	1120 mg/L
3	3.8926	4.5621	960 mg/L
4	3.0069	3.0069	0.4 mg/L

Membership analysis

The membership degree of the four water quality factors were calculated in five grades based on the calculation method of the membership function, as shown in Tables 5, 6, 7 8. The content of DOM was characterized using DOC. The specific membership was calculated according to the different values of the water quality factors according to Table 1. In order to better evaluate the effect of water quality factors on iron stability, the weight coefficient of each index was given from 1 to 2, 3, 4, 5 which represented slight risk, small risk, general risk, greater risk, significant risk, respectively.

Risk assessment

Different water quality factors had different effects on the risk of iron stability. The risk value under the four water conditions could be calculated synthetically based on the membership value and the weight of the four water quality factors which showed in formula (12) and formula (13). The results of risk value and iron concentration in different conditions are shown in Table 9. The lower risk of iron stability appeared under the lower risk value; meanwhile, the greater risk of iron stability appeared under the higher value, respectively. 'Iron concentration' in Table 9 meant iron concentration in water which surrounding and partly filling the tubercles in the pipes in the four conditions. The concentrations of iron were 360 mg/L, 1120 mg/L, 960 mg/L and 0.4 mg/L in conditions 1 to 4, which meant the iron risk could be described as the order of condition 4, condition 1, condition 3, and condition 2 from low to high.

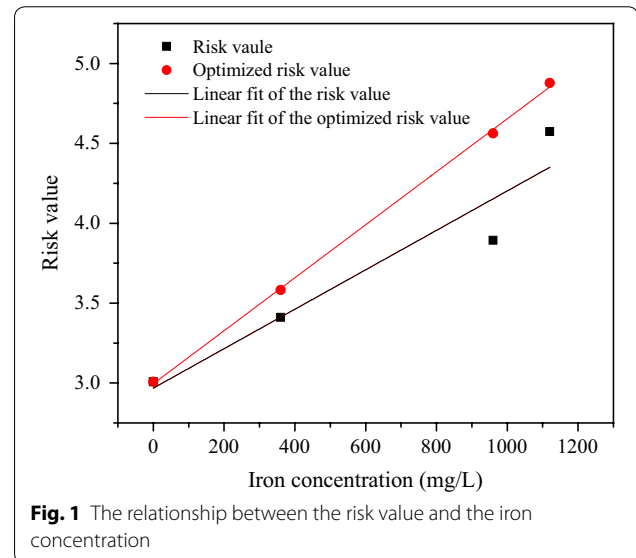


Fig. 1 The relationship between the risk value and the iron concentration

However, for the chloride and sulfate values in water quality conditions 1, 2 and 3, they were all larger than the median value of the significant risk. Therefore, the comprehensive risk score cannot be correctly judged. In order to solve the problem of membership degree, it was necessary to use the optimized calculation method for calculation by formula (13). The calculated value is shown by "The optimized risk value" in Table 9. The comparison of the two calculation conditions is shown in Fig. 1, which was used to illustrate the relationship between the risk value and the iron concentration. Compared with the traditional fuzzy comprehensive evaluation method, the optimized method had a higher degree of fit which could more clearly prove the relationship between the risk value and the iron concentration. The analysis suggested that the R^2 values of the traditional method and the optimized method were 0.869 and 0.999. Therefore, although the order of the risk was no different from before optimized, the revised risk values were significantly different from unrevised assessment, which coincided with the actual situation.

Discussion

The phenomenon was consistent with the result obtained by the risk assessment in this research, which demonstrates that, (1) the selection of water quality factors for iron risk assessment in water supply pipelines is scientifically reasonable; (2) this risk assessment method can be used to judge the different water quality conditions for the iron stability of the pipeline influences. As the result, although different water quality factors had different effects on the stability of iron, the comprehensive evaluation of water quality could be evaluated by the risk assessment under the improved fuzzy comprehensive evaluation, which would be beneficial to the analysis of iron risk in water supply network.

Conclusions

Iron was an important index which would cause turbidity, color and smell in water during the DWDSs. It was difficult to fully reflect iron concentration for the limited test points in the DWDSs. Different water quality factors had different influences on the iron stability. Therefore, the evaluation of the iron stability was complicated by the different of water quality parameters.

In this research, the optimized evaluation method was established to guide the iron stability under different water quality, especially under the condition that the values of water quality factors were out the median of the minimum/maximum risk range. The article provided the view that the iron stability could be assessed by the combination of different water quality factors. Meanwhile, for the formulated relevant management strategies, the water supply enterprises could obtain the reasons of the iron risk increasing from the assessment, and adopt active management measures to reduce the risk of iron stability. In addition, this research was particularly useful for assessing the iron stability in the evaluation of water quality mutations.

Abbreviations

DOM: Dissolved organic matter; DWDSs: Drinking water distribution systems; DOC: Dissolved organic carbon; AHP: Analytic hierarchy process.

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Authors' contributions

JW and HY were involved in the experiments and manuscript writing. JW and HY were responsible for the data analysis. KX and TT designed the study. TT contributed to correction of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets obtained and analyzed in the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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