Evaluation of Mine Water Quality Based on Bayesian Theory MODEL of AHP-EWM Combined Weighting Method

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Abstract: In view of the fuzziness and randomness of groundwater quality evaluation and the rationality and scientificity of the weight in the evaluation process, in order to establish an objective, scientific and convenient mine water environment evaluation system and improve the accuracy of the evaluation results, AHP and EWM weight method are combined to obtain the weight value, which is coupled with Bayesian water quality evaluation model. In this paper, seven water quality evaluation factors and ten groups of water samples are selected to analyze the application of mine water in Shengquan coal mine, Shandong Province. At the same time, the single factor evaluation method, equal weight Bayesian model and fuzzy comprehensive evaluation method are used to compare with the evaluation results to verify the accuracy of the evaluation results of the model. The results show that the water quality evaluation model of combined weighted Bayesian model is reasonable for mine water quality evaluation, which not only distinguishes the difference of each evaluation factor's contribution to water quality, but also makes a more accurate evaluation of water quality, and the calculation process is simple, which avoids the complexity of multiple indicators of traditional methods, and provides a scientific basis for comprehensive utilization of mine water in mining area, so the evaluation method is practical.

Keywords: Water quality evaluation, entropy weight method, analytic hierarchy process, Bayesian theory.

1. INTRODUCTION

As a country with the largest coal resources in the world [1], China also needs to discharge a large amount of mine water [2, 3] to ensure the safety of underground production. The mining of mineral resources is often accompanied by a large amount of water production. For example, according to relevant research statistics, 2 tons of water will be produced for each ton of coal mined in the Netherlands [4], while 3 tons of water will be produced in the UK [5]. The pollution of surface water and groundwater caused by the drainage and leakage of mine water has become the main problem affecting the development of mining industry in the world. Strengthening the utilization of mine water can not only reduce the pollution, but also reduce the waste of water resources. Mine water has the characteristics of stable water source and wide distribution. The water quality is basically the same as that of groundwater in the area. It has little pollution and simple purification. It is a valuable unconventional water resource [6-9]. The utilization of mine water resources can be mainly used for production water, domestic water, and agricultural water around the mining area, so it can save surface and groundwater resource and reduce geological disasters in the mining area [10, 11]. Direct discharge of mine water may cause disasters such as land salinization and pollute the water source and ecological environment in mining areas. With the rapid growth of the demand for water resources and the aggravation of water environmental pollution, it is an inevitable way to turn waste into treasure and turn harm into benefit [12]. Therefore, water quality assessment [13, 14] is an indispensable preliminary basic work for water environment treatment and rational utilization in mining area.

Since the 1960s, various methods of water quality assessment at home and abroad have been developed and optimized, but there is still a lack of a unified and recognized assessment model. For example, the widely used fuzzy comprehensive evaluation method [15-17], the comprehensive index method [18, 19] with simple calculation and easy operation, mathematical statistics method [20], BP neural network method [21-24], grey correlation method [25, 26], cluster analysis method [27], etc. The algorithm of function evaluation method [28] is more complex; general statistics, grey clustering method and BP neural network method require a large number of samples and a large number of tasks. All the above methods have their advantages and limitations. The evaluation mode is single, and there are some defects in practical application. The evaluation of mine water quality has uncertainty, randomness and nonlinearity, so the evaluation needs to integrate all the evaluation factors that affect the water quality. A. K. Benson (1995) used geophysical and geochemical methods to survey and evaluate the mine site and its acid pit water (AMD) in the southeast of Salt Lake City in the United States [29]. Liu Wenming and Hexia (2001) analyzed and studied the type of water filling, the characteristics of water inflow, the water quality characteristics and its

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influencing factors in Xiejiaji mining area in Huainan, and evaluated the mine water quality in the mining area [30]. Yu Hao, Liu zhibin and Wang zhaojun (2003) evaluated the water quality of Fuxin mine by grey clustering method and determined the environmental quality grade of mine water [31]. Han Chenghui and Liu wensheng (2004) evaluated the groundwater quality in Huainan mining area with fuzzy comprehensive evaluation methods and put forward some suggestions to prevent the water quality from deteriorating [32]. Therefore, in order to better reflect the actual situation of mine water quality, classify the water quality of mine water and find out the main pollution factors, so as to make the process of water environment quality evaluation more simple and the results more scientific, this paper applies the mine water of Shengquan coal mine in Shandong Province as an example, uses the subjective analytic hierarchy process and objective entropy weight method to determine the evaluation index weight [33], and combines with Bayesian model In order to verify the applicability of the evaluation method.

2. WEIGHT DETERMINATION BASED ON COMBINATION WEIGHTING

Analytic hierarchy process (AHP) [34, 35] is widely used in weight determination, but it is greatly affected by subjective factors, which is not conducive to the accuracy of evaluation results [36, 37]. "Entropy weight" theory can be applied to the comprehensive evaluation of multiple objects and indicators, and its weighting is less affected by subjective factors. This paper compares the advantages and disadvantages of the two weighting methods, in order to obtain a reasonable and scientific weight, the AHP and entropy weight method are combined to weights the evaluation factors to make up for the shortcomings of the two single weighting methods.

2.1. AHP Analytic Hierarchy Process

Analytic hierarchy process (AHP) refers to simplifying complex problems into single-layer problems according to different levels of decision-making. The importance order of single-level indicators is compared by the expert advisory group to build a single-level judgment matrix A. the consistency of matrix A is tested after calculating the quantitative description. If CR < 0.1, it is judged to pass. Otherwise, the matrix is adjusted until it passes the test [38, 39].

2.2. Construct Judgment Matrix

Suppose that there are three indexes in the hierarchy (Table **1**), and then we analyze n_i(i=1, 2,…,n)and n_j(j=1,2,…,n) the matrix of order containing is formed **A**

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

Table 1: Value Table for Judging Matrix Importance

Important value	Index a is better than index B
1	Equally important
3	A little more important
5	Strong and important
7	Strongly important
9	Extremely important
2,4,6,8	Intermediate value of adjacent importance

2.3. Weight Vector

The product of each row of the matrix *A* is calculated *Ai*

$$\mathrm{A_i} = \prod_{i=1}^{n} \mathrm{a_{ij}} \ \ (j=1,2,\ldots,n) \quad (2)$$

To the nth power of the value of *Ai*:

$$\overline{M_\iota} = \sqrt[n]{A_i} \quad (3)$$

Take $\overline{M_\iota}$ The weight vector is obtained by normalization *Wi*

$$W_i = \frac{\overline{M_\iota}}{\sum_{i=1}^{n} \overline{M_\iota}} \quad (4)$$

The maximum eigenvalue λ Max is calculated according to *W* and *A*

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(AW)_i}{W_i} \quad (5)$$

2.4. Consistency Test

The average random consistency index *RI* (Table **2**) is introduced to calculate the verification coefficient *CR*. The test formula is as follows:

$$\mathrm{CR} = \frac{CI}{RI} = \frac{\lambda_{max}}{n-1}/RH \quad (6)$$

Where: *n* is the number of single level evaluation indexes.

Table 2: Average Random Consistency Index RI

Matrix order	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

2.5. Entropy Weight Method

The basic idea of entropy weight method [40, 41] is to determine the objective weight according to the variability of indicators, Generally speaking, if the smaller the entropy value of an indicator, the more information indicates the index value, the greater the role played in the evaluation, the greater the weight, and the smaller the weight [42, 43].

The steps of determining weight by entropy weight method are as follows [44, 45]:

(1) The original matrix of *m* evaluation indexes and *n* evaluation samples is established: $X=(x_{ij})_{m\times n,}$.

(2) The original matrix is normalized. The standardized formula is as follows:

$$\text{Positive indicators: } r_{ij} = \frac{x_{ij}-min(x_{ij})}{max(x_{ij})-min(x_{ij})} \quad (7)$$

$$\text{Negative indicators: } r_{ij} = \frac{max(x_{ij})-x_{ij}}{max(x_{ij})-min(x_{ij})} \quad (8)$$

(3) The factor information entropy was calculated

$$e_j = -k\sum_{i=1}^{n} p_{ij}\, ln(p_{ij}),$$

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}}(i=1,\cdots,n, j=1,\cdots,m),$$

$$k = 1/_{ln(n)} > 0, e_j \geq 0 \quad (9)$$

(4) The entropy weight is calculated

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, d_j = 1-e_j \quad (10)$$

2.6. Calculate Combination Weight

The difference coefficient method [46] is used to assign value. Let the weight of index obtained by analytic hierarchy process (AHP) be w_{j1}, the weight of evaluation index obtained by entropy weight method be w_{j2}, and the comprehensive weight be w_z, w_z is expressed linearly by w_{j1} and w_{j2}

$$w_z = (1-\alpha)w_{j1} + \alpha w_{j2} \quad (11)$$

Where: α is the proportion of the weight determined by entropy weight method in the combined weight, and the value is assigned by the difference coefficient method. The calculation formula is as follows:

$$\alpha = \frac{n}{n-1}\left[\frac{2}{n}(w_1 + 2w_2 + \cdots + nw_n) - \frac{n+1}{n}\right] \quad (12)$$

Where: $w_1, w_2, \ldots, w_n$ is the weight of the evaluation index determined by the analytic hierarchy process, which is increased and rearranged in turn, and *n is* the number of evaluation indexes determined by the analytic hierarchy process.

3. WATER QUALITY ASSESSMENT METHOD

Bayes theory [47] is a mathematical statistical method based on probability theory, which was put forward by British mathematician Bayes in 1763. It is a method to determine the probability of the water quality grade by calculating the posterior probability after empowerment and determining the probability of the maximum probability principle. Some scholars introduced entropy weight method into Bayesian model, and the results show that the Bayesian evaluation model based on entropy weight weighting is significantly better than equal Bayesian model in water quality evaluation [48]. Bayesian evaluation model takes all the parameters as a group of random variables, obtains the prior probability from the existing data, and then converts the prior probability into the posterior probability under the condition of new information for evaluation and prediction. The theory avoids the influence of incomplete data or subjective factor and makes the evaluation result reasonable and reliable [49, 50].

The calculation formula of Bayesian water quality assessment model is as follows [51, 52]:

$$P(y_{ij}|x_i) = \frac{P(y_{ij})P(x_i|y_{ij})}{\sum_{i=1}^{5} P(y_{ij})P(x_i|y_{ij})} \quad (13)$$

Where: *i* represents the sample index (*i*=1,2,…,n); *j* denotes water quality grade (*j*= 1,2,3,4,5); y_{ij} denotes water quality grade;

Calculation steps:

(1) The calculation of $P(y_{ij})$, a priori probability, under no precondition, the probability of the measured water samples belonging to any water quality grade is equal, $P(y_{i1})=P(y_{i2})=P(y_{i3})=P(y_{i4})=P(y_{i5})=1/5$.

(2) Calculate $P(x_i|y_{ij})$: According to the reciprocal of the absolute value of the distance between the water quality detection index and the standard water quality index, the following results can be obtained:

$$P(x_i|y_{ij}) = \frac{1/L_{ij}}{\sum_{j=1}^{5} 1/L_{ij}} \quad (14)$$

Where: $L_{ij} = |x_i - y_{ij}|$(j=1,2,…,5) (*i*=1,2,…,5), The smaller the L_{ij} index is, the higher the probability that it belongs to the corresponding water quality grade is.

(4) Calculate $P(y_{ij}|x_i)$

(5) The posterior probability of comprehensive water quality under multiple indicators is calculated P_j:

$$P_i = \sum_{i=1}^{n} w_i P(y_{ij}|x_i) \quad (15)$$

Where: w_i represents the weight of detection index *i*.

(6) Determine the final water quality grade:

$$P = \max_{i=1\sim 5} P_j \quad (16)$$

4. EXAMPLE APPLICATION

The evaluation area is located in the southern foothills of Lianhua Mountain, Shandong Province. The terrain is a typical hilly terrain, with high terrain in the middle and south and low-lying terrain in the north and the west. There are only two seasonal rivers in the area, and there is no large-scale ponding area. The main aquifers in the research area are Quaternary aquifer gravel layer, quaternary limestone, the first limestone of Taiyuan formation, Xujiazhuang limestone of Benxi Formation, Caobugou limestone and Ordovician limestone aquifer. The evaluation of water samples collection adopts a deep-hole water extractor, and then carries out the conventional hydrochemical test. The test results of the conventional hydrochemical components of the effluent were obtained by titration and conversion. Ten groups of water samples were collected from five sampling sites of 61505 transportation lane, Xuhui No.1 hole, Xuhui No.2 hole, Xuhui No.3 hole and Xuhui No.4 hole in Xujiazhuang limestone aquifer of Benxi Formation for water quality evaluation. Total hardness, TDS(total dissolved solids), pH (degree of acid or alkali), Cl^-(Chloride), SO_4^{2-}(Sulfate), Fe^{3+}(ferric ion) and Na^+(Sodium) were selected to evaluate the water quality. The original data of water quality are shown in Table **3**, the evaluation process is shown in Figure **1**, and the evaluation standard is in accordance with the groundwater quality standard (GB/T 14848-2017).

4.1. Combination Weighting

When there are many pollution factors in the evaluation of water body, the evaluation results of entropy weighting method assignment are more

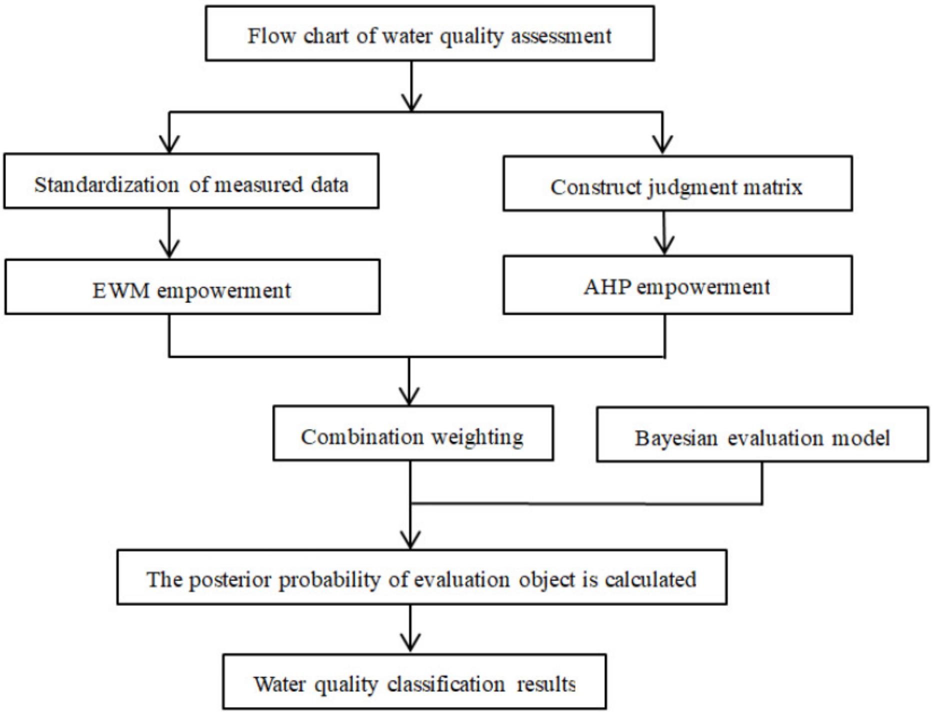

Figure 1: Flow chart of water quality assessment.

Table 3: Data of Mine Water Sampling Points in Shengquan Coal Mine (Unit: mg / L)

number	TDS	Total hardness	PH	Na^+	Fe^{3+}	Cl^-	SO_4^{2-}
XZ1	1958	823.59	8.0	302.08	0.8	86.99	1211.75
XZ2	1845	694.83	6.34	319.7	0.76	86.99	1119.55
XZ3	1686	699.54	5.35	259.3	0.64	76.75	1019.94
XZ4	1856	781.94	8.2	294.61	0.8	100.64	1132.31
XZ5	1916	857.63	7.4	284.95	0.9	81.89	1205.16
XZ6	1676	660.74	7.6	281.98	0.01	76.75	1027.77
XZ7	1907.21	751.35	7.77	286.97	0.14	140	1052.77
XZ8	1896.18	621.25	7.7	316.04	0.13	124	1008.32
XZ9	1788	702.56	8.3	286.93	0.1	81.64	1058.64
XZ10	1962	787.93	7.2	323.63	0.03	94.94	1195.7

Table 4: Calculation Results of Entropy Weight

Evaluation factors	TDS	Total hardness	PH	Na^+	Fe^{3+}	Cl^-	SO_4^{2-}
weight	0.1079	0.1039	0.0645	0.0813	0.2628	0.2066	0.1729

scientific and reasonable, and the objectivity of entropy weight method is too strong, so this paper uses AHP and entropy weight method to combine the objectivity and subjectivity of weighting to get a reasonable weight value for water quality evaluation. The combined weight is coupled by the difference coefficient method.

According to the formula (6) - (9), the information entropy and entropy weight of each evaluation factor are calculated by using MATLAB software [53]. The calculation results are shown in Table **4**.

Construct the judgment matrix as shown in Table **5**, and calculate its consistency test λ_{max}=7.3899, CR=0.0492＜0.1, so the judgment matrix passes the test, and the weight W_{AHP} results are shown in Table **6**.

The entropy weight method calculates the weight according to the discrete degree of the data itself, which can weaken the influence of outliers, but its weight is more objective. Therefore, the analytic hierarchy process is used to correct the shortcomings of the entropy weight method. In this paper, the difference coefficient method is used to calculate the combined weight according to equations (10) - (11). The calculation results are shown in Table **7**.

4.2. Bayesian Water Quality Assessment

According to the Bayesian water quality evaluation principle, the posterior probability of comprehensive water quality under multiple indexes is calculated, and the results are shown in Table **8**.

The equal weight Bayesian evaluation method and fuzzy comprehensive evaluation method are used to calculate the water quality grade of water samples, and the water quality grade of ten groups of water samples corresponding to each method is obtained. According to Table **3**, the single index evaluation grade is obtained. According to Table **8**, the combined weight Bayesian evaluation final water quality grade is determined by applying the maximum probability principle, and the water quality grade results of each group are obtained. Finally, the evaluation results are compared with the calculation results of equal weight Bayesian evaluation method, fuzzy comprehensive evaluation methods and single index evaluation method [54, 55]. The results are shown in Table **9**.

Table 5: Judgement Matrix

evaluating indicator	TDS	Total hardness	PH	Na^+	Fe^{3+}	Cl^-	SO_4^{2-}
Total soluble solids	1	1	1/5	1/2	1/2	1	1/3
Total hardness	1	1	1/5	1/3	1/3	1	1/3
PH	5	5	1	3	3	4	2
Na^+	2	3	1/3	1	1	1/2	1/2
Fe^{3+}	2	3	1/3	1	1	4	1/2
Cl^-	1	1	1/4	2	1/4	1	1/2
SO_4^{2-}	3	3	1/2	2	2	2	1

Table 6: AHP Weight Calculation Results

Evaluation factors	TDS	Total hardness	PH	Na^+	Fe^{3+}	Cl^-	SO_4^{2-}
weight	0.0639	0.0580	0.3343	0.1105	0.1521	0.0879	0.1932

Table 7: Comprehensive Weight Value

Evaluation factors	TDS	Total hardness	PH	Na^+	Fe^{3+}	Cl^-	SO_4^{2-}
weight	0.0808	0.0756	0.2308	0.0993	0.1946	0.1335	0.1854

Table 8: Posteriori Probability of Water Quality of each Sampling Point under Multiple Indicators

Sampling point	Membership of each level				
	I	II	III	IV	V
XZ1	0.1601	0.2201	0.1588	0.2670	0.1940
XZ2	0.1688	0.2297	0.1715	0.2310	0.1989
XZ3	0.1966	0.2131	0.1920	0.220	0.1779
XZ4	0.1242	0.2584	0.1444	0.2872	0.1858
XZ5	0.1896	0.2257	0.1798	0.2375	0.1672
XZ6	0.2593	0.2379	0.1757	0.1724	0.1547
XZ7	0.1704	0.3105	0.1728	0.1765	0.1697
XZ8	0.2036	0.2895	0.1631	0.1669	0.1769
XZ9	0.1196	0.1949	0.2710	0.2315	0.1829
XZ10	0.2250	0.2859	0.1637	0.1456	0.1798

Table 9: Comparison of Evaluation Results of Various Methods

Sampling point	Equal weight Bayesian	Combination weight Bayesian	Fuzzy comprehensive evaluation	Single index						
				TDS	Total hardness	PH	Na	Fe^{3+}	Cl^-	SO_4^{2-}
XZ1	IV	IV	IV	V	V	I	IV	IV	II	V
XZ2	V	IV	IV	V	V	I	IV	IV	II	V
XZ3	IV	IV	IV	IV	V	I	IV	III	II	V
XZ4	V	IV	V	V	V	IV	IV	IV	II	V
XZ5	IV	IV	IV	V	V	I	IV	IV	II	V
XZ6	IV	I	II	IV	V	I	IV	II	II	V
XZ7	II	II	II	V	V	I	IV	II	II	V
XZ8	V	II	III	V	V	I	IV	II	II	V
XZ9	IV	III	III	V	V	IV	IV	I	II	V
XZ10	II	II	II	V	V	I	IV	I	II	V

4.3. Result analysis and discussion

According to Table **9**, the water quality grade discrimination results of ten groups of water samples by various methods are drawn, and the broken line comparison chart of evaluation results is drawn, as shown in Figure **2** below. From the analysis in Table **9** and Figure **2**, it can be concluded that almost half of the results of the combined weighted Bayesian model are consistent with those of the fuzzy comprehensive evaluation method and the equal weight Bayesian model, which shows that the results of this method are reliable. However, there are also certain differences in the results of each sampling point. The evaluation results of equal weight Bayesian model at xz2, xz6, xz8 and xz9 sampling points are V, IV, V and IV, while the evaluation results of combination weighted Bayesian model at this point are IV, I, II and III,. The evaluation results of equal weight Bayesian model are conservative, while the evaluation results of combination weighted Bayesian model are optimistic.

The combined weight Bayesian model emphasizes the relationship between the evaluation factors and weakens the contribution value when the background values of total soluble solids, total hardness and sulfate ion are high, and distinguishes the difference of the contribution rate of each evaluation factor to water quality. The influence degree of each evaluation index on water quality is taken into consideration by AHP, which reduces the influence of abnormal values of sample indexes on the evaluation results, indicating that the evaluation result of this method is reasonable.

In the evaluation of combined weighted Bayesian model, there are advantages, disadvantages and errors. The advantages are that the evaluation results of this method are more scientific and reasonable, and the main pollution factors can be found out from the

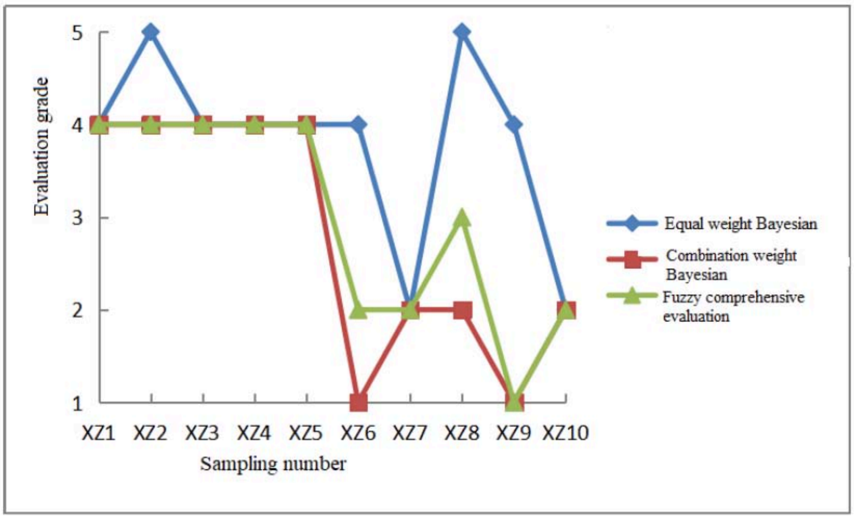

Figure 2: Comparison of Evaluation Results of each Method.

evaluation process to provide direction for the follow-up mine water purification treatment. The disadvantages and errors are that the problems in the determination of water quality grade can be found from the comprehensive water quality posterior probability (Table **8**). For example, the posterior probabilities of water quality grade II and IV at xz2 sampling point are only 0.0013, the posterior probabilities of water quality grade II and IV at xz3 sampling point are only 0.0069, and the posterior probabilities of water quality grade II and IV at xz5 sampling point are only 0.0118. The degree of belonging to water quality at these three points is very small. How to determine the water quality membership degrees of the three sampling points still needs to be integrated. The influence of other factors such as index on the membership degree of water quality grade needs further study to solve the fuzzy phenomenon of water quality grade.

5. CONCLUSION

(1) The evaluation results of Bayesian model show that the water quality of Xuhui aquifer in the region, except for xz1, xz2, xz3, xz4 and xz5, meets the class III water quality standard, and the main pollution factors are sodium ion and sulfate, which leads to poor water quality.

(2) The evaluation results of the combined weight Bayesian evaluation method are optimistic and reasonable compared with the fuzzy comprehensive evaluation method and the equal weight Bayesian method evaluation method, and the single factor evaluation method is more comprehensive..

(3) AHP and entropy weight method coupling weighted Bayesian evaluation model in mine water quality evaluation can achieve the purpose of comprehensive, reasonable and scientific evaluation of mine water quality. It can effectively provide scientific basis for whether the mine water can be directly discharged and whether the mine water resources need to be used. It can also provide reference for the adoption of purification methods and measures, so as to achieve targeted and rapid development Speed effect.

(4) The combination model Bayesian model also has shortcomings and drawbacks in the evaluation process. The disadvantage is that there will be grade ambiguity in the process of determining the water quality grade. How to avoid this phenomenon needs further study and improve the method.

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