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Determining the Quality of Mine Gushing and Mixed Water Using Coupled AHP and Fuzzy Comprehensive Evaluation Methods

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Abstract

This study focused on analysis of the chemical characteristics of mine waters. The aim of this study is to correlate the degree of different ionic components in mine water and the influence of their convergence using a combination of the three-scale AHP and fuzzy evaluation methods for the comprehensive evaluation of water quality. Ion chromatography (ICS 1100) has been used to analyze the content of the water sample while portable pH/EC/TDS/Temperature meters (SX 811 and SX 813) were used to test physical-chemical parameters. The results of this study show that chemistry of in No.11 gushing mine is dominated by HCO_3-Na and HCO_3-Ca, and had a pH between 7.1 and 8.00, belonging to neutral or slightly alkaline water. In addition, water were found to have the hardness between 18 mg/L and 542.5 mg/L. Results also show that the TDS of the roof sandstone and goaves water are higher than Cambrian limestone water, while the turbidity of the mixed water is 20 NTU in the sump, again higher than in other samples such as Cambrian limestone water. Total dissolved solids and the total hardness of Cambrian limestone groundwater mainly depend on the content of $K^+ + Na^+$, Ca^{2+}, $B = \{b_1, b_2, \cdots, b_j\}$ and SO_4^{2-}. Thus, chemical composition changes remarkably after mine water mixing. Results showed that the coal roof sandstone water is class V while that in the sump is class III, and the Cambrian limestone groundwater is class I. In gushing, the quality of water can vary greatly; thus, water from the coal face roof sandstone and the Cambrian limestone should be stored and treated separately before being utilized.

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1. Introduction

In the course of coal mining, a large amount of mine water needs to be drained to ensure the safety of underground production. In China's northern coalfields, the annual discharge of mine water is about 1.787 billion m^3 and the average discharge of mine water per ton of coal is about 1.29 m^3, but the average utilization rate is less than 25% [1] [2]. Due to the impact of coal mining activities, the water discharged can contain acidic substances, heavy metals, organic compounds, radioactive elements, bacteria, and other harmful substances that seriously pollute rivers and soils. Because this process also wastes huge volumes of water [3] [4] [5], appropriate strategies for treatment and reuse are of great significance to coal mining ecological and environmental protection.

The key to effectively utilizing and managing mine water is understanding its quality [6]. A number of mathematical models have been proposed to comprehensively evaluate water quality, including the analytic hierarchy process (AHP) [7], entropy weight analysis [8], principal component analysis [9], multivariate statistical methods [10], fuzzy comprehensive evaluation methods [11], and artificial neural networks [12]. These methods compare measured data with water quality standards to enable comprehensive evaluation. Singh [13] compared water chemistry indexes of mine water with corresponding standard values to determine their effectiveness but did not comprehensively evaluate the influence of various indicators on mine water quality. In later work, Sun [14] applied the fuzzy comprehensive evaluation method to a comprehensive evaluation of coal mine water quality in the arid area of western Chongqing; the results of this study are problematic, however, because this complex method requires the weight determination of each water sample separately. Similarly, Liu [15] used the gray clustering method to evaluate environmental water quality in the Dongsheng coal field, Inner Mongolia. This method applies threshold values to determine the weight value of each index, and therefore does not take into account changes in factors within the same level and their influence on water quality evaluation. Most recently, Gao [16] utilized a SPA-ITFN(Set Pair Analysis-Interval Triangular Fuzzy Numbers) coupling model for coal mine groundwater quality evaluation and showed that when the value for a measured factor is larger, weight will also increase; these results are therefore of importance for water quality evaluation.

Mine water gushing contact with coal and rock formations, A series of physical, chemical and biological reactions occur, coupled with the impact of mixed

with the production of waste water, which dissolved the chemical composition becomes very complicated [17]. Due to the limitations of the existing discriminant models, the evaluation results of mine drainage water quality often do not accord with the actual situation, which limits its scientific utilization. It is necessary to find a discriminant model that can be realized automatically and the evaluation results conform to the reality.

This paper evaluates mine water gushing from Pingdingshan No. 11 coal mine. A quality evaluation was conducted using AHP (Analytic Hierarchy Process) in tandem with the fuzzy comprehensive evaluation method, and the characteristics of mine water chemistry, ion composition, and confluence were analyzed. The AHP simplifies the process of determining the weight of the fuzzy comprehensive evaluation method and avoids human factor interference; this approach therefore makes the evaluation of mine water quality more scientific and provides a more reliable evaluation. The results of this paper provide a reference method for the automatic and reasonable evaluation of mine drainage water quality.

2. Overview of the Study Area

Pingdingshan No. 11 mine is located in the southwestern margin of this mining area, within the transitional zone between northern subtropical and warm temperate monsoonal climate. The annual average temperature is 15˚C and annual average rainfall is 747 mm. About 70 percent of annual rainfall occurs between July and September.

The water source within the Ji group of No. 11 mine is Cambrian and Carboniferous limestone, Permian sandstone, and old goaf water. No. 11 mine is located within the Cambrian limestone recharge area to the south of the Pingdingshan mining area; where the recharge water source is mainly groundwater, surface water, and shallow aquifer groundwater. As this recharge source is abundant and relatively close, this results in a large volume of water inflow during the mining process, more than 500 m^3/h on average. It is therefore of paramount importance to evaluate the water quality of mine and mixed water to enable the rational use of valuable resources.

3. Hydrochemical Characteristics

3.1. Water Sample Collection

The samples used in this study from No. 11 mine include mixed water from the sump (denoted C1, C2, and C3), drilling into Cambrian limestone (H1, H2, and H3), roof sandstone fissures water (D1) and goaf water (K1). The positions of these sampling points are shown (Figure 1 and Table 1); All samples were analyzed at the Henan Geological Environment Monitoring Institute. Simple analyses were performed on samples C2 and C3 and the remainder were subjected to full analysis. The simple analysis includes the common ions, and the full analysis includes all ions, etc.

Table 1. Conventional water chemical composition of mine water.

| Number	Source of water sample	Elevation (m)	K+ + Na+	Ca2+	Mg2+	Cl−	SO4^2−	HCO3−	TDS	Total hardness	pH	Turbidity
						(mg/L)						
H1	No. 10 observation hole	−593	73.67	173.95	26.37	61.68	219.98	413.82	982.88	542.54	7.15	<1
H2	No. 13 observation hole	−718	56.15	70.14	45.44	59.56	86.93	333.17	667.16	362.03	7.45	<1
H3	No. 15 observation hole	−880	53.36	74.95	43.98	63.46	86.93	341.71	683.30	368.20	7.10	<1
D1	roof water of working face	−610	771.52	4.81	1.46	72.32	109.99	1805.58	2777.83	18.30	8.00	<1
K1	The goaf water	−545	273.94	38.68	32.20	59.56	202.69	550.4	1,156.65	229.42	7.95	<1
C1	Central water sump	−593	197.88	89.38	26.37	67.36	202.69	474.13	839.77	331.52	7.80	20
C2	Ji 2 water sump	−880	92.46	82.16	46.90	79.05	179.63	366.73	663.56	398.07	7.80	/
C3	Ji 4 water sump	−800	128.80	45.89	26.37	56.01	127.28	355.75	562.22	223.00	7.75	/
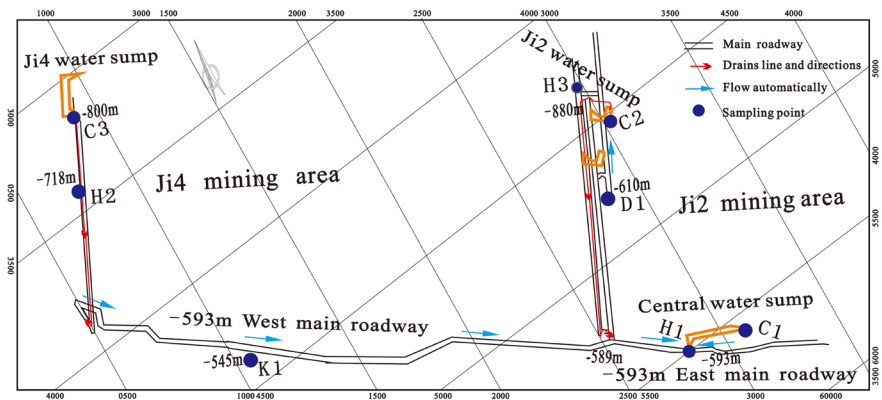
Figure 1. Distribution map of water samples collected from No. 11 mine.

3.2. Chemical Characteristics of Water

Test results of conventional hydrochemical components are shown Table 1. A piper diagram was constructed based on the six major ions was shown as Figure 2 [3]. Thus, four water sample groups within this analysis were characterized as HCO_3-Na (D1, K1, C1, and C3), three were HCO_3-Ca (H1, H3, and C2), and one was HCO_3-Mg (H2). The data presented in Table 1 shows that because the pH of all samples is between 7.1 and 8.0, this is neutral or weak alkaline water. In addition, the turbidity of mixed water in the central water sump (C1) is 20, while the remainder of samples are less than 1; this is because the central water sump contains a large volume of coal dust, which leads to an increase in turbidity. The TDS values for samples D1 and K1 were 2777.83 mg/L and 1156.65 mg/L, respectively, and so these are classified as brackish water (1000 mg/L < TDS < 3000 mg/L), while the rest of these samples have TDS values less than 1000 mg/L and so are classified as freshwater (TDS < 1000 mg/L) [18] [19]. The reason is that the D1 and K1 samples were taken from coal roof and goaf, respectively. The total hardness of these samples falls between 18 mg/L and 542.5 mg/L (average: 309 mg/L), within the range of hard water.
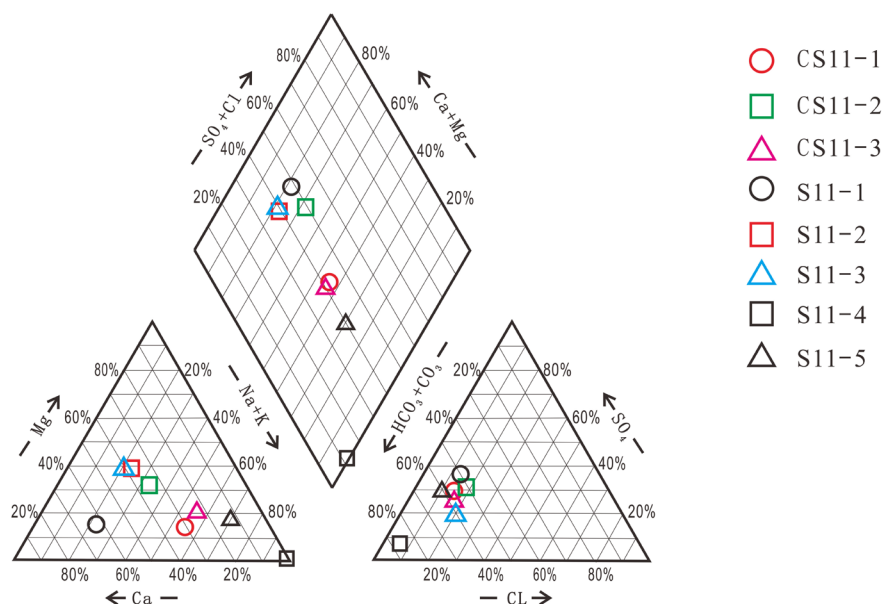
Figure 2. Piper chart of water samples.

The data presented in Table 2 shows the test results of trace components. Obviously, Trace component content of NO_3^- and F^- in Ordovician limestone water samples are far lower than that of other water samples (D1, K1 and C1). In addition, content of NH_4^+ in roof crack water samples is 70 times as other samples. Generally speaking, content of F^- in goaf (K1) and NH_4^+ and F^- in roof crack, all exceed class V water standards as defined by Chinese *Groundwater Quality Standards* (GB/T 14848-93).

3.3. Analysis of Ion Composition

A correlation analysis was performed to measure the relationship between two groundwater variables and to demonstrate source consistency and variability. According to mathematical statistics theory, when r > 0.9, it indicates that there is a significant correlation between the two variables; when 0.6 < r ≤ 0.9, it indicates moderatet correlation between the two variables; When 0.4 < r ≤ 0.6, it indicates low level correlation between the two variables, similar, When r ≤ 0.46, it indicates little correlation between the two variables [20] [21].

Pearson correlation coefficients for Cambrian limestone groundwater were calculated using the software SPSS (Table 3). These data show that the correlation coefficients of TDS and total hardness and K$^+$ + Na$^+$ are 0.985 and 0.988, respectively. The correlation coefficients of TDS and Ca^{2+} reached 1. And, the correlation coefficients of TDS and total hardness and HCO_3^- are 0.998 and 0.992, respectively. In addition, the correlation coefficients of TDS and total hardness and SO_4^{2-} are 0.999 and 1, respectively. This indicates that TDS and total hardness, K$^+$ + Na$^+$, Ca^{2+}, HCO_3^-, SO_4^{2-} are significantly correlated. In other words, The concentration of TDS and total hardness in Ordovician limestone groundwater is mainly determined by the content of K$^+$ + Na$^+$, Ca^{2+},

HCO_3^-, SO_4^{2-}. This is mainly because the several ions, $K^+ + Na^+$, Ca^{2+}, HCO_3^-, SO_4^{2-}, control the nature of groundwater.

3.4. The Influence of Confluence on Mine Water Quality

The data presented in Figure 1 show that mine water flows into a sump in the Ji 2 and Ji 4 mining areas. This flow then raises mine water into the −593 m west tunnel through the pump house, flows to the central water sump, and then into the ground. Results from the software Aq·QA used to study the water chemical ions in samples are shown in Table 4.

Simulation calculation value of a mixture of various sources of water (H2 + C3 + K1 + H3 + C2 + D1 + H1), based on Aq·QA software and measured value are shown in Table 4 and Figure 3. Obviously, except for SO_4^{2-} and HCO_3^-, the difference between the calculated value and the measured value of most ions is small. In addition, the trend of the connection between the simulated value and the measured value is consistent. This shows that the software simulation results of mine water confluence can be used to estimate the content of ion in mine water.

From Table 4, we know that values of TDS changed from 667.16 mg/L (H2) to 795.3 mg/L when Cambrian groundwater (H2) was mixed with water from the Ji 4 water sump (C3) and the goaf (K1). Thus, TDS increased from 683.3 mg/L (H3) to 1375 mg/L while water quality changed from freshwater to brackish when the Cambrian limestone groundwater (H3) was mixed with that from the Ji 2 water sump (C2) as well as 16,150 roof water from the working face (D1). In addition, TDS fell to 1071 mg/L and total hardness increased to 305.9 mg/L when this was mixed with water from H2 + C3 + K1 and Cambrian limestone groundwater (H1) as the latter was combined with sake. The above results comprehensively show that the mine water with different ion concentrations will change its ion concentration due to the confluence and affect the overall quality of the water, ultimately.

4. Comprehensive Evaluation of Water Quality

4.1. Establishment of a Fuzzy Relationship Matrix

A set of evaluation factors were created on the basis of the chemical composition of test results from sampling points. Thus, on this basis, those with greater impact on the water quality of chemical indicators were selected, as follows: U = {Cl^-, SO_4^{2-}, NH_4^+, NO_3^-, F^-, Ba, TDS, Total hardness, Turbidity}. Chinese *Groundwater Quality Standards* (GB/T 14848-93) have established a set of five evaluation factors V = {I, II, III, IV, V} [22]; Table 5 shows selected standard values for groundwater chemical grade classifications.

Take water sample H1 is as an example to state evaluation process. According to the comparison of the evaluation factor matrices and the evaluation rating matrices, the linear membership function is used to calculate the membership of each pollution factor [23], the applied formula as follows:
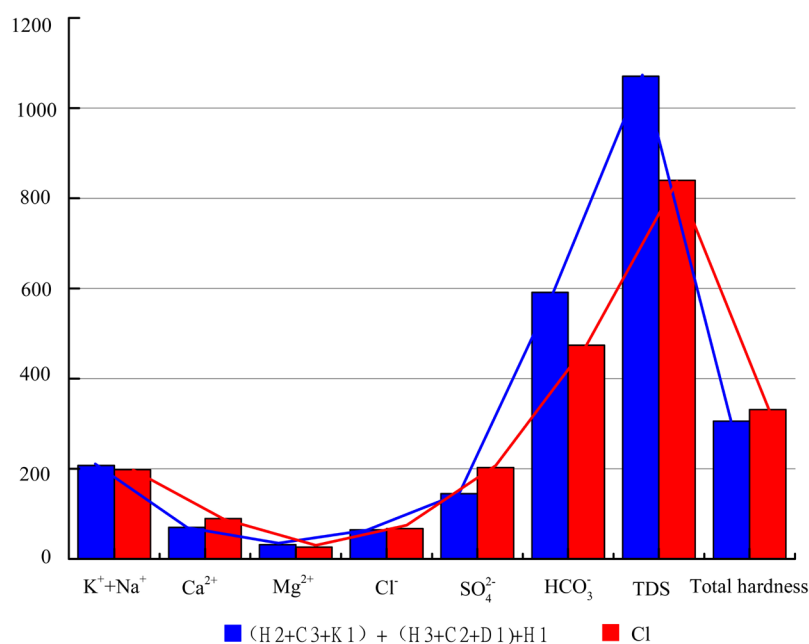
Figure 3. The comparison between the Aq·QA software simulation values and measured values.

Table 2. Chemical composition of trace water in mine water (mg/L).

Number	H1	H2	H3	D1	K1	C1
NO_3^-	0.33	0.33	0.37	3.29	10.54	15.61
NH_4^+	0.02	0.02	0.02	1.4	0.02	0.02
F^-	0.32	0.64	0.68	3.7	2.72	1.72
I^-	0.05	0.05	0.05	0.05	0.05	0.05
Li	0.025	0.035	0.033	0.03	0.18	0.06
Sr	0.66	0.71	0.66	0.44	2.18	1.2
Br^-	0.32	0.2	0.28	0.04	0.2	0.34
Ba	0.1	0.14	0.13	0.11	0.08	0.15
Volatile phenol	0.008	0.009	0.01	0.011	0.012	0.002

Table 3. Pearson correlation coefficients for Cambrian limestone groundwater.

Icons	$K^+ + Na^+$	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	TDS	TH
$K^+ + Na^+$	1							
Ca^{2+}	0.986	1						
Mg^{2+}	−0.981	−1.000	1					
Cl^-	−0.770	0.910	−0.119	1				
SO_4^{2-}	0.992	0.999	−0.998	0.050	1			
HCO_3^-	0.960	0.998	−0.996	0.207	0.988	1		
TDS	0.985	1.000	−1.000	0.096	0.999	0.998	1	
TH	0.988	1.000	−0.999	0.079	1.000	0.992	1.000	1

Table 4. The major ion changes under different water samples mixing (mg/L).

Number	Water source	$K^+ + Na^+$	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	TDS	TH
1	H2 + C3 + K1	153.2	51.6	34.7	58.4	139.1	413.1	795.3	271.5
2	H3 + C2 + D1	305.8	52.4	31.3	70.3	125.5	835.2	1375.0	261.3
3	1 + 2 + H1	207.1	70.1	31.8	64.5	144.8	591.0	1071.0	305.9
4	C1	197.88	89.38	26.37	67.36	202.69	474.13	839.77	331.52

Table 5. Water quality grading standards based on evaluation factors (mg/L).

Icons	I	II	III	IV	V
Cl^-	≤50	≤150	≤250	≤350	>350
SO_4^{2-}	≤50	≤150	≤250	≤350	>350
NH_4^+	≤0.02	≤0.02	≤0.2	≤0.5	>0.5
NO_3^-	≤2.0	≤5.0	≤20	≤30	>30
F^-	≤1.0	≤1.0	≤1.0	≤2.0	>2.0
Ba	≤0.01	≤0.1	≤1.0	≤4.0	>4.0
TDS	≤300	≤500	≤1,000	≤2000	>2000
Total hardness	≤150	≤300	≤450	≤550	>550
Turbidity	≤3	≤3	≤3	≤10	>10

$$\mu_i(x) = \begin{cases} 1 - (m_{i+1} - x)/(m_{i+1} - m_i) & m_{i-1} < x < m_i \\ (m_{i+1} - x)/(m_{i+1} - m_i) & m_i < x < m_{i+1} \\ 0 & x \le m_{m-1}, x \ge m_{i+1} \end{cases}$$

where x is the measured value; i is evaluation rank vaule, μ is the membership of the evaluation factor.

Thus, the corresponding Fuzzy relationship matrix is calculated as follows:

$$T_1 = [t_{ij}] = \begin{bmatrix} 0.883 & 0.117 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.300 & 0.700 & 0.000 & 0.000 \\ 1.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.000 & 0.000 & 1.000 \\ 1.000 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 1.000 & 0.000 & 0.000 & 0.000 \\ 0.000 & 0.034 & 0.966 & 0.000 & 0.000 \\ 0.000 & 0.000 & 0.075 & 0.925 & 0.000 \\ 1.000 & 0.000 & 0.000 & 0.000 & 0.000 \end{bmatrix}$$

And the membership matrix of other water samples are calculated as in sample H1.

4.2. Weight Determination Using AHP

The AHP method [24] was initially used to compare each element and to establish a comparison matrix, as follows:

$$P = \begin{bmatrix} p_{ij} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & -1 & -1 & 1 & -1 & -1 & 0 \\ 1 & 0 & 1 & -1 & -1 & 1 & -1 & -1 & 0 \\ 0 & -1 & 0 & -1 & -1 & 1 & -1 & -1 & 0 \\ 1 & 1 & 1 & 0 & -1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 \\ -1 & -1 & -1 & -1 & -1 & 0 & -1 & -1 & -1 \\ 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & -1 & -1 & 1 & -1 & 0 & 1 \\ 0 & 0 & 0 & -1 & -1 & 1 & -1 & -1 & 0 \end{bmatrix}$$

Thus, in this matrix $p_{ij} = \begin{cases} 1 & p_i \text{ is more important than } p_j \\ 0 & p_i \text{ and } p_j \text{ are just as important} \\ -1 & p_i \text{ is not important for } p_j \end{cases}$

The following formula is then used to build an optimal transfer matrix, q_{ik}, q_{jk} are the element in the comparison matrix Q.

$$q_{ij} = \frac{1}{n}\sum_{k=1}^{n}\left(p_{ik} - p_{jk}\right) = \frac{1}{n}\sum_{k=1}^{n}\left(p_{ik} + p_{jk}\right)$$

$$Q = \begin{bmatrix} 0.000 & -0.333 & 0.000 & -1.000 & -1.222 & 0.444 & -1.111 & -0.667 & -0.111 \\ 0.333 & 0.000 & 0.333 & -0.667 & -0.889 & 0.778 & -0.778 & -0.333 & 0.222 \\ 0.000 & -0.333 & 0.000 & -1.000 & -1.222 & 0.444 & -1.111 & -0.667 & -0.111 \\ 1.000 & 0.667 & 1.000 & 0.000 & -0.222 & 1.444 & -0.111 & 0.333 & 0.889 \\ 1.222 & 0.889 & 1.222 & 0.222 & 0.000 & 1.667 & 0.111 & 0.556 & 1.111 \\ -0.444 & -0.778 & -0.444 & -1.444 & -1.667 & 0.000 & -1.556 & -1.111 & -0.556 \\ 1.111 & 0.778 & 1.111 & 0.111 & -0.111 & 1.556 & 0.000 & 0.444 & 1.000 \\ 0.667 & 0.333 & 0.667 & -0.333 & -0.556 & 1.111 & -0.444 & 0.000 & 0.556 \\ 0.111 & -0.222 & 0.111 & -0.889 & -1.111 & 0.556 & -1.000 & -0.556 & 0.000 \end{bmatrix}$$

Next, after an optimal transfer matrix is established, a judgment matrix is calculated using the formula $r_{ij} = \exp\left(q_{ij}\right)$, as follows:

$$R = \begin{bmatrix} 1.000 & 0.717 & 1.000 & 0.368 & 0.295 & 1.560 & 0.329 & 0.513 & 0.895 \\ 1.396 & 1.000 & 1.396 & 0.513 & 0.411 & 2.177 & 0.450 & 0.717 & 1.250 \\ 1.000 & 0.717 & 1.000 & 0.368 & 0.295 & 1.560 & 0.329 & 0.513 & 0.895 \\ 2.718 & 1.948 & 2.718 & 1.000 & 0.801 & 4.240 & 0.895 & 1.396 & 2.432 \\ 3.395 & 2.432 & 3.395 & 1.249 & 1.000 & 5.295 & 1.18 & 1.743 & 3.038 \\ 0.641 & 0.459 & 0.641 & 0.236 & 0.189 & 1.000 & 0.211 & 0.329 & 0.574 \\ 3.038 & 2.177 & 3.038 & 1.118 & 0.895 & 4.738 & 1.000 & 1.560 & 2.718 \\ 1.948 & 1.396 & 1.945 & 0.717 & 0.574 & 3.038 & 0.641 & 1.000 & 1.743 \\ 1.118 & 0.801 & 1.118 & 0.411 & 0.329 & 1.743 & 0.368 & 0.574 & 1.000 \end{bmatrix}$$

Finally, in order to determine the weight of water chemical indicators, the following formula is applied [25]:

$$w_i = \frac{\sqrt[n]{\prod_{k=1}^{n} r_{ik}}}{\sum_{k=1}^{n}\sqrt[n]{\prod_{k=1}^{n} r_{ik}}}$$

$$w_i = \left(0.062, 0.086, 0.062, 0.167, 0.209, 0.040, 0.187, 0.120, 0.069\right)$$

4.3. Comprehensive Evaluation of Water Quality

Based on $B = T_i \times w_i$, water quality can be evaluated as $B = \{b_1, b_2, \cdots, b_j\}$, where b_j is the corresponding grade corresponding to a maximum B value. T_i is the membership matrix of water sample, w_i is the weight of each evaluation factor [26]. On this basis, water quality evaluation of Cambrian limestone groundwater (H1) is $B_1 = \left(0.394, 0.079, 0.250, 0.111, 0.167\right)$ and can be classified as type I. All other results are shown in Table 6.

The water samples are all tested by Henan Provincial Geological Environment Monitoring Institute with Grade A qualification, and the test results are reliable. All water quality assessments are graded according to China's *Groundwater Quality Standard* (GB/T 14848-93), the criteria are consistent. The weights of the evaluation factors are determined using the AHP method, avoiding man-made influence. Based on the above three reasons, the evaluation results are reliable and can be used for the treatment and utilization of mine water.

Research indicates Cambrian limestone groundwater from NO. 11 mine is Class I, and the water quality is superior. This is mainly due to the excellent circulation of the Cambrian limestone groundwater. Then, roof water is Class V, inferiorin addition water from goaf and central water sump are Class III. This is because Sandstone fissure water has recharge and poor runoff conditions.

Data show that the large difference in water quality depends on gushing source. This means that roof water from the working face and Cambrian limestone groundwater should be stored separately before being distinctively treated and utilized according to their respective levels of quality. This approach will guarantee the direct use of Cambrian limestone water and will also reduce mine drainage treatment costs.

5. Conclusions

1) The results of this study show that the chemistry of mine drainage water within the No. 11 mine in the Pingdingshan area mainly consists of HCO_3-Na and HCO_3-Ca and that pH is between 7.1 and 8.0. This means that the drainage water in this region is either neutral or weakly alkaline, has a hardness between 18 mg/L and 542.5 mg/L, and can be classified as hard. Data show that TDS values for the top sandstone and goat water samples are higher than others, and that the turbidity of mixed water in the central water sump is 20, again higher than all other samples.

2) A Pearson correlation coefficient analysis of hydrochemical parameters from the observation hole revealed significant relationships between Ca^{2+}, HCO_3^-, and SO_4^{2-} versus TDS and total hardness. At the same time, the correlation coefficients between Ca^{2+} and HCO_3^- versus SO_4^{2-} are significant related, too. The TDS and total hardness of groundwater in the Cambrian limestone are mainly determined by the content $K^+ + Na^+$, Ca^{2+}, HCO_3^- and SO_4^{2-}.

Table 6. Comprehensive evaluation of water quality from No. 11 mine samples.

Number	I	II	III	IV	V	Evaluation
H1	0.394	0.079	0.250	0.111	0.167	I
H2	0.616	0.270	0.114	0.000	0.000	I
H3	0.614	0.262	0.124	0.000	0.000	I
D1	0.438	0.404	0.000	0.000	0.457	V
K1	0.251	0.246	0.265	0.030	0.209	III
C1	0.112	0.351	0.469	0.000	0.069	III

3) Results show that subsequent to mixing with mine water, TDS values increased from an initial level of 683.3 mg/L to 1375 mg/L within the Ji 2 mining area, and from 667.16 mg/L to 795.3 mg/L within the Ji 4 mining area. This results show that the composition and quality of mine water significantly changes following confluence.

4) Use of the AHP and fuzzy comprehensive evaluation methods to comprehensively evaluate water quality show that samples from the roof sandstone within the working face are class V, while those from the goaf and central sump are class III, and Cambrian limestone groundwater can be classified as class I. Thus, the Cambrian limestone groundwater quality is superior and roof water quality is inferior.

5) Due to the great difference in water quality between gushing water sources of mines, the water from roof and Cambrian limestone should be separately stored, and then be treated and used respectively. This can ensure the rational allocation of mine drainage water resources and scientific use.

Acknowledgments

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] He, X.W., Yang, J., Shao, L.N., Li, F.Q. and Wang, X. (2008) Problem and Counter Measure of Mine Water Resource Regeneration in China. *Journal of China Coal Society*, **33**, 63-66.

[2] Lu, T., Liu, S.D., Wang, B., Wu, R.X. and Hu, X.W. (2017) A Review of Geophysical

Exploration Technology for Mine Water Disaster in China: Applications and Trends. *Mine Water & the Environment*, No. 5, 1-10.

[3] Batsaikhan, B., Kwon, J.S., Kim, K.H., Lee, Y.J., Lee, J.H., Badarch, M. and Yun, S.T. (2016) Hydrochemical Evaluation of the Influences of Mining Activities on River Water Chemistry in Central Northern Mongolia. *Environmental Science and Pollution Research*, 1-16.

[4] Li, S.J., Wu, Q., Cui, F.P., Zeng, Y.F. and Wang, G.R. (2014) Major Characteristics of China's Coal Mine Water Disaster Occurred in Recent Years. *Applied Mechanics & Materials*, **501-504**, 336-340.
https://doi.org/10.4028/www.scientific.net/AMM.501-504.336

[5] Nordstrom, D.K., Blowes, D.W. and Ptacek, C.J. (2015) Hydrogeochemistry and Microbiology of Mine Drainage: An Update. *Applied Geochemistry*, **57**, 3-16.
https://doi.org/10.1016/j.apgeochem.2015.02.008

[6] He, X.W. and Li, F.Q. (2010) New Technology and Development Tendency of Mine Water Treatment. *Coal Science and Technology*, **38**, 17-22.

[7] Aryafar, A., Yousefi, S. and Ardejani, F.D. (2013) The Weight of Interaction of Mining Activities: Groundwater in Environmental Impact Assessment Using Fuzzy Analytical Hierarchy Process (FAHP). *Environmental Earth Sciences*, **68**, 2313-2324.
https://doi.org/10.1007/s12665-012-1910-x

[8] Wu, J.H., Li, P.Y., Qian, H. and Chen, J. (2015) On the Sensitivity of Entropy Weight to Sample Statistics in Assessing Water Quality: Statistical Analysis Based on Large Stochastic Samples. *Environmental Earth Sciences*, **74**, 2185-2195.
https://doi.org/10.1007/s12665-015-4208-y

[9] Ouyang, Y. (2005) Evaluation of River Water Quality Monitoring Stations by Principal Component Analysis. *Water Research*, **39**, 2621-2635.
https://doi.org/10.1016/j.watres.2005.04.024

[10] Chow, M.F., Shiah, F.K., Lai, C.C., Kuo, H.Y., Wang, K.W., Lin, C.H., Chen, T.Y., Kobayashi, Y. and Ko, C.Y. (2016) Evaluation of Surface Water Quality Using Multivariate Statistical Techniques: A Case Study of Fei-Tsui Reservoir Basin, Taiwan. *Environmental Earth Sciences*, **75**, 1-15. https://doi.org/10.1007/s12665-015-4922-5

[11] Lu, X.W., Li Loretta, Y., Lei, K., Wang, L.J., Zhai, Y.X. and Zhai, M. (2010) Water Quality Assessment of Wei River, China Using Fuzzy Synthetic Evaluation. *Environmental Earth Sciences*, **60**, 1693-1699.
https://doi.org/10.1007/s12665-009-0303-2

[12] Singh, K.P., Basant, A., Malik, A., *et al.* (2009) Artificial Neural Network Modeling of the River Water Quality—A Case Study. *Ecological Modelling*, **220**, 888-895.
https://doi.org/10.1016/j.ecolmodel.2009.01.004

[13] Singh, A.K., Mahato, M.K., Neogi, B. and Singh, K.K. (2010) Quality Assessment of Mine Water in the Raniganj Coalfield Area, India. *Mine Water & the Environment*, **29**, 248-262. https://doi.org/10.1007/s10230-010-0108-2

[14] Sun, H.F., Zhao, F.H., Zhang, L., Liu, Y.M., Cao, S.H. and Zhang, W. (2014) Comprehensive Assessment of Coal Mine Drainage Quality in the Arid Area of Western Chongqing. *Journal of China Coal Society*, **39**, 736-743.

[15] Liu, Y.F., Wu, Q. and Zhao, X.N. (2013) Mine Water Quality Characteristics and Water Environment Evaluation of Inner Mongolia Dongsheng Coal Field. *Clean Coal Technology*, **19**, 101-106.

[16] Gao, X.X., Nie, Y. and Dong, D.W. (2015) Evaluation of Coal Mine Groundwater Quality with Coupling Model Based on SPA-ITFN. *Mining Safety and Environ-*

mental Protection, **42**, 68-71.

[17] Favas, P., Sarkar, S.K., Rakshit, D., *et al.* (2016) Acid Mine Drainages from Abandoned Mines: Hydrochemistry, Environmental Impact, Resource Recovery, and Prevention of Pollution. Environmental Materials and Waste. Elsevier Inc., 413-462.

[18] Tikhomirov, V.V. (2016) Hydrogeochemistry Fundamentals and Advances, Volume 1, Groundwater Composiiton and Chemistry. Hydrogeochemistry Fundamentals and Advances: Groundwater Composition and Chemistry, Volume 1.

[19] Wang, X.Y. (2011) Applied Hydrogeology. China University of Mining and Technology Press.

[20] Guo, Q.L., Xiong, X.Z. and Jiang, J.R. (2016) Hydrochemical Characteristics of Surface and Ground Water in the Kuye River Basin. *Environmental Chemistry*, **35**, 1372-1380.

[21] Labar, J.A. and Nairn, R.W. (2017) Evaluation of the Impact of Na-SO4, Dominated Ionic Strength on Effluent Water Quality in Bench-Scale Vertical Flow Bioreactors Using Spent Mushroom Compost. *Mine Water & the Environment*, 1-11.

[22] Tiwari, A.K., Singh, P.K. and Mahato, M.K. (2016) Environmental Geochemistry and a Quality Assessment of Mine Water of the West Bokaro Coalfield, India. *Mine Water & the Environment*, 1-11. https://doi.org/10.1007/s10230-015-0382-0

[23] Han, L., Song, Y.H., Duan, L. and Yuan, P. (2015) Risk Assessment Methodology for Shenyang Chemical Industrial Park Based on Fuzzy Comprehensive Evaluation. *Environmental Earth Sciences*, **73**, 5185-5192. https://doi.org/10.1007/s12665-015-4324-8

[24] Ren, X. (2016) Application of Three Scale AHP Method in Nuclear Accident Emergency Decision Making of Equipment System. *International Conference on Advances in Energy, Environment and Chemical Science*.

[25] Xue, X.H. and Yang, X.G. (2014) Seismic Liquefaction Potential Assessed by Fuzzy Comprehensive Evaluation Method. *Natural Hazards*, **71**, 2101-2112. https://doi.org/10.1007/s11069-013-0997-z

[26] Lai, C.G., Chen, X.H., Chen, X.Y., Wang, Z.L., Wu, X.S. and Zhao, S.W. (2015) A Fuzzy Comprehensive Evaluation Model for Flood Risk Based on the Combination Weight of Game Theory. *Natural Hazards*, **77**, 1243-1259. https://doi.org/10.1007/s11069-015-1645-6