Research Article

Hydrogeochemical Evolution and Control Mechanism of Underground Multiaquifer System in Coal Mine Area

Qiding Ju,1,2 Yu Liu,1 Youbiao Hu,2 Yuquan Wang,3 Qimeng Liu,2 and Zitao Wang2

1State Key Laboratory of Mining Response and Disaster Prevention and Control in Deep Coal Mines, Anhui University of Science and Technology, Huainan 232001, China
2School of Earth and Environment, Anhui University of Science and Technology, Huainan 232001, China
3Wanbei Coal-electricity Group Company, Suzhou 234001, China

Correspondence should be addressed to Yu Liu; yliu@aust.edu.cn

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1. Introduction

Human activities have led to different deterioration trends in the global groundwater environment; this trend is developing in a negative direction [1–3]. The mine water inrush and water contamination are two common groundwater problems in mining areas of China. After mining, the chemical environment of the groundwater becomes complex, forming a multiaquifer system with different hydrogeochemical characteristics. This leads to a complex groundwater flow field and chemical field. As the aquifer connects with the structure, different aquifers connect to form a water filling channel, which causes water inrush accidents and water pollution [4, 5]. This highlights the importance of studying water quality types and the hydrogeochemical evolution characteristics of underground aquifers, which can provide the basis for the safe production of coal mines and the full utilization of water resources.

Variations in conventional ion levels in groundwater represent hydrogeochemical evolution processes. Hydrogeochemical analysis methods used to determine the evolution of groundwater chemical composition include: hydrogeochemical maps, multivariate statistical analysis, and GIS spatial analysis [6–8]. Huang et al. [9, 10] used a Piper diagram, Gibbs diagram, and Ion proportion coefficient diagram to analyse the chemical characteristics of groundwater. Multivariate statistical analyses were used to study the hydrogeochemical evolution process mainly include factor analysis, principal component analysis, and cluster analysis. Comprehensive consideration time and space indicators, Chen et al. [11] successfully revealed the chemical characteristics and spatiotemporal evolution mechanism of groundwater by
principal component analysis. Zhang et al. [12] studied the relationship between the hydrogeochemical characteristics of groundwater and the multilayer aquifer in a Karst subsided column mine, by combining a chemical analysis with a principal component analysis. Gomo et al. [13] used the traditional hydrochemical analysis method to describe the underground hydrogeochemical process of a submerged mine and analysed the groundwater chemical types and water quality evolution. Sunkari et al. [14] used factor analysis to transform original ion concentration data into a normal distribution, effectively explained the sourcing of groundwater ions. In recent years, based on GIS spatial interpolation analysis, some researchers studied the hydrochemical evolution process of underground aquifer, drew the hydrogeochemical action spatial map, and quantitatively described the hydrochemical spatial evolution process and control factors [15, 16]. In summary, hydrochemical analysis, factor analysis, and GIS spatial analysis can be combined to describe the hydrogeochemical evolution process and its controlling factors; this provides important information about the hydrogeological background.

The Hengyuan coal mine, operated by the Wanbei Coal Electricity Group, has complicated hydrogeological conditions. The mine is threatened by high-pressure limestone water and sandstone water from the coal seam roof and floor and poses potential safety hazards, such as the collapse of the karst column and water disasters in the loose layers. In this paper, factor analysis is used to name the main hydrogeochemical processes clearly and accurately, and then, it is combined with traditional hydrochemical methods. Finally, GIS spatial analysis reveals the hydrochemical evolution process of multiaquifer system. The study focused on identifying the hydrogeological and geochemical characteristics and control factors of water-filled aquifers. It provides a scientific basis for accurately identifying potential water inrush hazard sources and a basis for the rational protection and utilization of water resources. In addition, this method has a certain guiding significance for the concealed coalfields in North China.

2. Materials and Methods

2.1. Study Area and Hydrogeological Setting. The Hengyuan coal mine is located in Huaihe City in north of Anhui Province, China (Figure 1(a)). The geographical coordinates are 116°36′04″ -116°43′22″E and 33°54′30″ -34°0′59″N. The terrain in the mining area is flat, and the natural surface elevation is approximately 30 to 36 m, with a tendency to incline from the northwest to southeast. There is no bedrock outcrop; instead, the area is covered by an extremely thick Cenozoic loose layer. The climate in this area is mild, exhibiting a north temperate monsoon area marine continental climate. The annual average temperature is 16.8°C, the maximum temperature is 37°C (July 2019), and the minimum temperature is -7°C (January 2019). The average annual rainfall is 1067 mm, and the rainfall is mainly concentrated in July and August.

The strata in this area are rarely exposed and are mostly covered by Quaternary alluvial and proluvial plain materials (Figure 1(b)). Drilling records show that the strata, from old to new, are Ordovician (O1,2), Carboniferous (C2,3), Permian (P), Tertiary (N), and Quaternary (Q). The coal-bearing strata in the Hengyuan coal mine include the lower Permian Shansi Formation and Lower Shihezi Formation. There is no mineable coal seam in upper Shihezi Formation, so it was not studied. The coal-bearing strata are 343.20 m thick and include eight coal seams (formations) and 2-17 coal seams. The total thickness of the coal seam is 5.52 m. The average total thickness of the mineable or partially mineable coal seam is 4.82 m, accounting for 87.3% of the total thickness of the coal seam. For all the seams, 4 and 6 coal seams are the main mineable coal seams, with an average total thickness of 4.48 m, accounting for 81.2% of the total thickness of the mineable coal seams.

The Cenozoic unconsolidated aquifer can be divided into three aquifers groups from top to bottom. The Cenozoic bottom aquifer forms a “skylight,” due to the lack of aquiclude in local areas, which directly cover the coal-bearing strata. They may also become the water supply source into the Permian aquifer. The main source of recharge is the regional interlayer runoff; the lithology of the Permian aquifer is composed of sandstone, mudstone, siltstone, and coal seam, with mostly mudstone and silts. The Permian aquifer is approximately 240 m thick, with a buried depth of approximately 500 m. From the top to the bottom of the mine, the location and degree of fractures development in the main mining coal seams are divided across the fifth aquifer, the sixth aquifer, the seventh aquifer, and the eighth aquifer.

According to water level observations, the water level in 12 Carboniferous aquifer observation holes had dropped to -146.14 m by the end of 2006. The Carboniferous aquifer is the water supply source for coal seam mining and is one of the hidden dangers, as water may fill the 6 coal seams. The lithology of the Ordovician limestone karst fissure aquifer is light grey thick layered limestone, with different regular grey and light grey white stripes, and local dolomite. It is pure and brittle with a microcrystalline structure and high angle fractures. Under normal conditions, no direct water fills the mine pit. However, it is possible that a water inrush could occur, with Ordovician limestone water directly entering the mine pit. This could occur when the shaft and roadway engineering encounter a water-conducting fault or water flowing subsided column.

2.2. Methods. A total of 74 water samples were collected between January and July 2018 in the Hengyuan Coal Mine area. The samples included 9 samples from the Cenozoic aquifers, 35 samples from the Permian aquifers, and 30 samples from the carboniferous aquifers (Figure 1).

Before sampling, each clean 550 mL polypropylene bottle and cap was rinsed with water 3-5 times [17–19]. Each water sample was collected in a bottle, leaving a 5-10 ml space at the top of the bottle. The temperature and pH were maintained at stable levels after the water samples were collected; a previously calibrated Hanna portable pH meter was used to measure all the parameters within five minutes. The water samples were put through a 0.45 μm field filtering membrane, with each water sample divided into three bottles,
Figure 1: The map of the Hengyuan coal mine area, with the distribution of faults, folds, sampling sites, and cross section of the coal mine along line A–A′.
The mass concentration of K\(^{+}\)Na\(^{+}\) is 1.5 times and 2.8 times of HCO\(_3\) is highest for K\(^{+}\)Na\(^{+}\), followed in descending order by Ca\(^{2+}\) and Mg\(^{2+}\). The anion concentrations are the highest for CO\(_3\) weakly alkaline. In the weakly alkaline environment, the pH value of all samples varies from 7.10 to 8.32, making the entire underground aquifer weakly alkaline. In the weakly alkaline environment, the CO\(_3\)\(^{2-}\) levels are less than 5% of the sum of HCO\(_3\)\(^{-}\) and CO\(_3\)\(^{2-}\), making it unimportant to assess CO\(_3\)\(^{2-}\) levels.

The average salinity of the Cenozoic aquifers is 1058.24 mg/L. The cation concentrations in the water overall are the same as Cenozoic aquifers, and the anion concentrations are the highest for SO\(_4\)\(^{2-}\), followed in descending order by HCO\(_3\)\(^{-}\) and Cl\(^{-}\). The mass concentration of K\(^{+}\)Na\(^{+}\) is 1.9 and 3.3 times of the mass concentrations of Ca\(^{2+}\) and Mg\(^{2+}\), respectively. The mass concentration of SO\(_4\)\(^{2-}\) is 5.8 and 9.8 times of HCO\(_3\)\(^{-}\) and Cl\(^{-}\). The mass concentration of Ca\(^{2+}\) and Mg\(^{2+}\), respectively. The mass concentration of HCO\(_3\)\(^{-}\) is 1.5 times and 3.6 times of SO\(_4\)\(^{2-}\) and Cl\(^{-}\), respectively.

The average salinity of Permian aquifers is 3371.35 mg/L. The cation concentrations in the water overall are the same as Cenozoic aquifers, and the anion concentrations are the highest for SO\(_4\)\(^{2-}\), followed in descending order by HCO\(_3\)\(^{-}\) and Cl\(^{-}\). The mass concentration of K\(^{+}\)Na\(^{+}\) is 40.5 times and 75.5 times of the mass concentration of Ca\(^{2+}\) and Mg\(^{2+}\), respectively. The mass concentration of SO\(_4\)\(^{2-}\) is 3.8 times and 9.7 times of HCO\(_3\)\(^{-}\) and Cl\(^{-}\), respectively.

The average salinity of the Carboniferous aquifers is 2534.47 mg/L. The cation concentrations in the water overall are the same as Cenozoic and Permian aquifers, and the anion concentrations are the same as Permian aquifers. This is consistent with the change of ion concentration in the coal measure sandstone aquifer. The mass concentration of K\(^{+}\)Na\(^{+}\) is 1.9 and 3.3 times of the mass concentrations of Ca\(^{2+}\) and Mg\(^{2+}\), respectively. The mass concentration of SO\(_4\)\(^{2-}\) is 5.8 and 9.8 times of HCO\(_3\)\(^{-}\) and Cl\(^{-}\), respectively. The concentration skewness coefficient of each ionizer in the three aquifers is close to 0 and adheres to a normal stable distribution. This indicates that the distribution of ions in the aquifer is relatively stable and is less disturbed by hydrogeological conditions and other factors.

### Table 1: Sample indexes-descriptive statistics.

| Parameters | The Cenozoic aquifer | The Permian aquifer | The Carboniferous aquifer |
|------------|----------------------|---------------------|--------------------------|
| K\(^{+}\)Na\(^{+}\) (mg/L) | 111 | 202.47 | 1550.27 | 1036.94 | 0.05 | 168.65 | 813.98 | 398.6 | 0.48 |
| Ca\(^{2+}\) (mg/L) | 79.55 | 124.73 | 99.89 | 0.24 | 1.13 | 63.15 | 25.59 | 0.63 | 2.42 | 447.56 | 202.17 | 0.09 |
| Mg\(^{2+}\) (mg/L) | 28.81 | 81.12 | 54.93 | 0.09 | 1.17 | 38.66 | 13.73 | 0.8 | 5.53 | 323.69 | 121.44 | 1.09 |
| Cl\(^{-}\) (mg/L) | 91.98 | 144.67 | 115.43 | 0.15 | 56.46 | 354.16 | 171.91 | 0.82 | 82.98 | 188.91 | 143.39 | -0.37 |
| SO\(_4\)\(^{2-}\) (mg/L) | 207.06 | 417.26 | 283.62 | 1.01 | 833.2 | 2524.69 | 1668.09 | 0.45 | 1001.36 | 1770.6 | 1404.92 | -0.16 |
| HCO\(_3\)\(^{-}\) (mg/L) | 279.83 | 541.86 | 419.79 | -0.35 | 164.21 | 692.17 | 435.72 | -0.14 | 129.91 | 340.89 | 240.28 | 0.29 |
| TDS (mg/L) | 899.23 | 1239.45 | 1058.24 | 0.22 | 2023.48 | 5005.01 | 3371.35 | 0.32 | 2020.85 | 3088.47 | 2534.47 | 0.02 |
| PH | 7.3 | 8.4 | 7.57 | 2.39 | 7.79 | 8.32 | 7.94 | 1.96 | 7.1 | 8.3 | 7.68 | -0.6 |

3. Results and Discussion

3.1. Statistics Analysis. Table 1 shows the results of the hydrochemical statistical analysis for the samples from the Cenozoic aquifers, Permian aquifers, and Carboniferous aquifers. The analysis shows that the pH value of all samples varies from 7.10 to 8.32, making the entire underground aquifer weakly alkaline. In the weakly alkaline environment, the CO\(_3\)\(^{2-}\) levels are less than 5% of the sum of HCO\(_3\)\(^{-}\) and CO\(_3\)\(^{2-}\), making it unimportant to assess CO\(_3\)\(^{2-}\) levels.

The average salinity of the Cenozoic aquifers is 1058.24 mg/L. The cation concentrations in the water overall is highest for K\(^{+}\)Na\(^{+}\), followed in descending order by Ca\(^{2+}\) and Mg\(^{2+}\). The anion concentrations are the highest for HCO\(_3\), followed in descending order by SO\(_4\)\(^{2-}\), and Cl\(^{-}\). The mass concentration of K\(^{+}\)Na\(^{+}\) is 1.5 times and 2.8 times of the mass concentration of Ca\(^{2+}\) and Mg\(^{2+}\), respectively.

The average salinity of Permian aquifers is 3371.35 mg/L. The cation concentrations in the water overall are the same as Cenozoic aquifers, and the anion concentrations are the highest for SO\(_4\)\(^{2-}\), followed in descending order by HCO\(_3\)\(^{-}\) and Cl\(^{-}\). The mass concentration of K\(^{+}\)Na\(^{+}\) is 40.5 times and 75.5 times of the mass concentration of Ca\(^{2+}\) and Mg\(^{2+}\), respectively. The mass concentration of SO\(_4\)\(^{2-}\) is 3.8 times and 9.7 times of HCO\(_3\)\(^{-}\) and Cl\(^{-}\), respectively.

The average salinity of the Carboniferous aquifers is 2534.47 mg/L. The cation concentrations in the water overall are the same as Cenozoic and Permian aquifers, and the anion concentrations are the same as Permian aquifers. This is consistent with the change of ion concentration in the coal measure sandstone aquifer. The mass concentration of K\(^{+}\)Na\(^{+}\) is 1.9 and 3.3 times of the mass concentrations of Ca\(^{2+}\) and Mg\(^{2+}\), respectively. The mass concentration of SO\(_4\)\(^{2-}\) is 5.8 and 9.8 times of HCO\(_3\)\(^{-}\) and Cl\(^{-}\), respectively.

3.2. Analysis of Hydrochemical Components. The hydrochemical types and distribution of all aquifers in the study area are shown in Figure 2. The distribution of water sample drops in the Cenozoic aquifers is relatively concentrated, with alkaline metal ions Ca\(^{2+}\) and Mg\(^{2+}\) present at greater concentrations than alkali metal ions K\(^{+}\). The percentage of SO\(_4\)\(^{2-}\) exceeds 80%, and the percentage of HCO\(_3\)\(^{-}\) equivalent ranges from 40 to 60%. Therefore, the hydrochemical type of the quaternary aquifer is mainly the SO\(_4\)\(^{2-}\)-HCO\(_3\)-Na-Ca(Mg) type. The distribution of water samples in the Permian aquifers is also relatively concentrated. The percentages of Ca\(^{2+}\) and SO\(_4\)\(^{2-}\) equivalents both exceed 80%, and the percentage of Cl\(^{-}\) equivalent is within the range of 40-90%. This indicates that the hydrochemical type is the SO\(_4\)Cl-Ca type. The water samples in the Carboniferous aquifers are relatively dispersed, with hydrochemical types of SO\(_4\)Cl-Ca-Mg or SO\(_4\)Cl-Na-Ca(Mg). This overlaps with the sample drops of the Cenozoic aquifer and the Permian aquifers, indicating that the Carboniferous aquifers have
similar hydrogeochemical characteristics and corresponding hydraulic relations.

The boxplot directly reflects the change of the ion levels in each aquifer [18]. Figures 3(a) and 3(d) show that the K⁺+Na⁺ concentration in Permian aquifers is higher compared to the Carboniferous, due to the strong chloride dissolution effect in Permian aquifers. The levels in the Cenozoic aquifers are the lowest. Cl⁻ in the aquifer is the most stable ion in groundwater, leaving the Cl⁻ concentrations of the same ions in different aquifers. The comparison of changes in ion levels cannot reflect the main hydrogeochemical process and genesis. High K⁺+Na⁺, SO₄²⁻, Ca²⁺ and Mg²⁺ concentration in the Cenozoic is essentially unchanged. Figures 3(b) and 3(c) show that the Ca²⁺ and Mg²⁺ concentration in the Cenozoic and Carboniferous aquifers is significantly higher compared to the Permian aquifers. This is caused by the dissolution of carbonate and sulfate minerals. In Figures 3(e) and 3(f), the SO₄²⁻ concentration in the Cenozoic to Permian aquifers gradually increased overall. In contrast, the HCO₃⁻ concentration in the water from the Permian to Carboniferous aquifers gradually decreased. This was caused by the enhanced sulfate dissolution and weakened desulfurization acid. Therefore, high HCO₃⁻ concentrations and low Mg²⁺ concentrations are characteristics of the three water-bearing strata. High K⁺+Na⁺, SO₄²⁻, and HCO₃⁻ concentrations and low Ca²⁺ and Mg²⁺ concentrations are the characteristics of the Permian aquifers. However, the Carboniferous aquifers are characterized by high Ca²⁺, Mg²⁺, and SO₄²⁻ concentrations and low HCO₃⁻ concentrations. Because there are equivalent concentrations of the same ions in different aquifers, the simple comparison of changes in ion levels cannot reflect the main hydrogeochemical process and genesis.

3.3. Ion Source Analysis. There are differences in the ion combination ratio among groundwater components. As such, the source of groundwater chemical components can be determined using the ion proportion coefficient method [23]. The bubble diagram of the ion combination ratio of each aquifer is shown in Figure 4. The bubble size indicates the change in the TDS concentrations of the samples.

Cl⁻ is the most stable ion in groundwater, and the source of Na⁺ can be characterized by analysing γ(K⁺ + Na⁺)/γ(Cl⁻) [24–27]. Figure 4(a) shows that γ(K⁺ + Na⁺)/γ(Cl⁻) > 1 in all water samples from the three aquifers, and the Na⁺ concentration increases with as the TDS value increases. This shows that in addition to the Na⁺ produced by the dissolution of salt rock, cation exchange is also a source of Na⁺. The value of γ(K⁺ + Na⁺)/γ(Cl⁻) significantly exceeds 1 in the Permian aquifer, and the TDS value also exceeds the value in other aquifers. As such, cation exchange is stronger than in other aquifers, supporting the enrichment of Na⁺.

The source of Ca²⁺ and Mg²⁺ can be characterized by analysing γ(Ca²⁺ + Mg²⁺)/γ(SO₄²⁻) [28–30]. Figure 4(b) shows that only a small number of the Cenozoic aquifer water samples fall above the γ = x line, and the rest of the samples fall below that line. In particular, the values of γ(Ca²⁺ + Mg²⁺)/γ(SO₄²⁻) + 0.5γ(HCO₃⁻) in the Permian aquifer is far less than 1. In addition, the TDS values in the Permian aquifer are significantly higher compared to other aquifers. It shows that cation exchange has occurred. Therefore, the dissolution of sulfate and carbonate is not the only source of Ca²⁺ and Mg²⁺, further confirming that alternate cation adsorption is reasonable.
When $\gamma(Ca^{2+} + Mg^{2+})/0.5\gamma(HCO_3^-) = 1$, it means that the Ca$^{2+}$, Mg$^{2+}$, and HCO$_3^-$ in the groundwater are derived from carbonate dissolution [31]. The Cenozoic and Carboniferous aquifer samples fall above the $y=x$ line. The TDS values in the Carboniferous aquifer are significantly greater than in the Cenozoic aquifer. This indicates that Ca$^{2+}$, Mg$^{2+}$, and HCO$_3^-$ are mainly derived from dissolution occurring in the Cenozoic and Carboniferous aquifer. A small number of the Permian aquifer samples are located above the line; however, the TDS values remain still higher compared to other aquifers. This indicates that the carbonate dissolution is not the only source of Ca$^{2+}$ and Mg$^{2+}$ and may also be caused by cation exchange in the Permian aquifer.

Most Permian aquifer samples align with the conditions of $\gamma(Ca^{2+} + Mg^{2+})/0.5\gamma(HCO_3^-) < 1$. This indicates that there are other sources of HCO$_3^-$, such as desulfurization.

Based on $\gamma(Ca^{2+} + Mg^{2+})/\gamma(SO_4^{2-}) = 1$, it appears that Ca$^{2+}$, Mg$^{2+}$, and SO$_4^{2-}$ are mainly derived from the sulfate dissolution in Figure 4(d) [32]. The Ca$^{2+}$ and Mg$^{2+}$ concentrations are low in the Permian aquifer; however, the TDS values are higher compared to other aquifers. This is due to the cation exchange, which facilitates the enrichment of Na$^+$. In the Permian and Carboniferous aquifers, the ratio of $\gamma(Ca^{2+} + Mg^{2+})/\gamma(SO_4^{2-})$ in some samples is less than 1, indicating that sulfate dissolution is not the only source of Ca$^{2+}$, Mg$^{2+}$, and SO$_4^{2-}$; pyrite oxidation may be another source.

**Figure 3:** Ion box diagram.
The expression \( \gamma(\text{Na}^+ - \text{Cl}^-)/\gamma(\text{Ca}^{2+} + \text{Mg}^{2+} - \text{SO}_4^{2-} - \text{HCO}_3^-) \) is used commonly to reveal the cation exchange rate [33]. Figure 4(e) shows that the Cenozoic and Permian aquifer samples are infinitely close to \( y = -x \), and the TDS values are larger, confirming there is cation exchange. Part of the Permian aquifer is above \( y = -x \), indicating there may be strong cation exchange. In Figure 4(f), each water sample is close to the \( y = x \) line, which shows the mass concentration balance of the anions and cations.

The analytical results of each ion combination ratio show that \( \text{Na}^+ \) is mainly derived from salt rock dissolution and cation exchange. \( \text{Ca}^{2+} \) and \( \text{Mg}^{2+} \) are derived from sulfate or carbonate dissolution and cation exchange, as shown in Eq. (1). \( \text{HCO}_3^- \) and \( \text{SO}_4^{2-} \) are derived from sulfate and carbonate dissolution. Because the Permian aquifer in the study area is -350-800 m below ground surface, it is an overall reducing environment. This means that desulfurization is one of the important sources of \( \text{HCO}_3^- \) in the Permian aquifer, as shown in Eq. (2). Further, there are low sulfate levels and high pyrite levels in the Permian and Carboniferous aquifers. This indicates that the \( \text{SO}_4^{2-} \) may be derived from pyrite oxidation, as the deep aquifer is in an overall reducing environment. However, some areas are affected by coal mining activities. This leads to the area becoming a semiopen oxidizing environment.

Figure 4: Bubble chart of ion combination of different aquifers.
allowing CO$_2$ and O$_2$ to enter the aquifer and react with pyrite, as shown in Eq. (3).

$$\text{Na}^+ (\text{Rock}) + \text{Ca}^{2+}/\text{Mg}^{2+} (\text{Water}) \rightarrow \text{Na}^+ (\text{Water}) + \text{Ca}^{2+}/\text{Mg}^{2+} (\text{Rock})$$

$$\text{SO}_4^{2-} + 2\text{C} + 2\text{H}_2\text{O} \rightarrow \text{H}_2\text{S} \downarrow + 2\text{HCO}_3^-,$$

$$\text{FeS}_2 + 15/4\text{O}_2 + 7/2\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 \downarrow + 2\text{SO}_4^{2-} + 4\text{H}^+.$$  

3.4. Factor Analysis. Both the $R$-type factor analysis and principal component analysis provide approximations of the covariance matrix and dimension reduction interpretation of the data set, specifically for the positive index and standardization index automatically executed by the SPSS software [34]. The correlation between variables is determined using a correlation coefficient matrix, and the eigenvalues and eigenvectors of phase relation number matrix are generated. Principal components and factors are linearly independent, and the cumulative contribution rate, index standardization, and index standardization are used. The number of principal components and factors is determined without a loss of variables. The naming basis is the correlation coefficient of principal components, factors, and variables. The difference is that principal component analysis and factor analysis are separate from the initial factor load matrix. The principal component analysis generates the principal component coefficient matrix, principal component, and its value through the unit of the initial factor load array vector or by dividing the corresponding eigenvalue root. The factor analysis generates the factor load matrix by rotating the initial factor load matrix and then obtaining the factor score and its value through regression. The $R$-type factor analysis has the advantage of clearly naming the main factors and enables a clear comprehensive evaluation of the causes [35–37]. The factor analysis method generally includes the following steps [38].

1. Firstly normalize the indicators, and then standardize the data to eliminate errors caused by large differences in values between variables.

2. Use the SPSS software to obtain total variance explained and rotated component matrix. Total variance explained meets the contribution rate requirement, and the variables in the rotated component matrix are not lost, thereby comprehensively determining $m$ principal factors.

3. Calculate the factor load matrix $B_m$ and classify the corresponding variable with the largest absolute value of the $i$th column of $B_m$ into $Z_i$ category, and then name $Z_i$ for hydrogeochemical effects, which has high clarity.

4. According to the factor score coefficient matrix obtained by the SPSS software, find the expression of the main factor score function: $S_{Z_i} = \omega_i X$

The correlation coefficient thermograph (Figure 5) directly describes the degree of correlation degree among
the variables. The K\(^+\)+Na\(^+\) value is positively correlated with Cl\(^-\), SO\(_4\)\(^2-\), and HCO\(_3\)\(^-\). This is due to the existence of rock salt dissolution. The K\(^+\)+Na\(^+\) is negatively correlated with Ca\(^{2+}\) and Mg\(^{2+}\); and TDS is strongly positively correlated with K\(^+\)+Na\(^+\) and is negatively related to Ca\(^{2+}\) and Mg\(^{2+}\). This is caused by cation exchange. There is a weak negative correlation between SO\(_4\)\(^2-\) and HCO\(_3\)\(^-\), indicating that desulfurization has occurred in the aquifers.

The factor analysis method uses the principal component extraction method to generate the total variance explanation shown in Table 2. The cumulative variance contribution rate is 69.078%, and there is no variable loss. Then, two factors (Z1, Z2) are determined by the rotated component matrix in Table 3. The variance contribution rate of Z1 is 35.056%, which is characterized by a high positive loading of SO\(_4\)\(^2-\) and Na\(^+\), and a weak loading of HCO\(_3\)\(^-\), Ca\(^{2+}\), and Mg\(^{2+}\). This indicates the dissolution of sulfate minerals, pyrite oxidation, and cation exchange. The variance contribution rate of Z2 is 34.021%, in which Ca\(^{2+}\) and Mg\(^{2+}\) are strongly loaded. HCO\(_3\)\(^-\) is strongly positively loaded, and SO\(_4\)\(^2-\) is weakly loaded, indicating the dissolution and desulfurization of calcite and dolomite, respectively. Therefore, Z1 represents the dissolution of sulfate minerals, pyrite oxidation, and cation exchange, and Z2 represents the dissolution and desulfurization of calcite and dolomite. These are displayed using Figure 6.

Table 4 shows the factor score coefficients for the six ions of K\(^+\)+Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), Cl\(^-\), SO\(_4\)\(^2-\), and HCO\(_3\)\(^-\) in groundwater samples from the Hengyuan coal mine. These were used as the variables for analysis, yielding the following factor score functions:

\[
S_{Z1} = 0.323x_1 - 0.081x_2 + 0.075x_3 + 0.342x_4 + 0.514x_5 - 0.208x_6, \quad (4)
\]

\[
S_{Z2} = 0.160x_1 - 0.278x_3 - 0.379x_3 - 0.059x_4 - 0.215x_5 + 0.511x_6. \quad (5)
\]

Substituting the collected data from the 74 water samples into \(S_{Z1}\) (Eq. (4) and Eq. (5)) yields the dispersion point diagram illustrating the groundwater factors Z1-Z2 for the Hengyuan mine (Figure 7). The Cenozoic aquifers are mainly distributed in the second quadrant, indicating that calcite and dolomite experience significant dissolution with desulfuration. The Permian aquifers are mainly distributed in the first quadrant, with a partial distribution in the second quadrant. It indicates that the Permian aquifers experience the desulfuration and dissolution of calcite and dolomite and is accompanied by the dissolution of sulfate minerals, pyrite oxidation, and cation exchange. The Carboniferous aquifer samples are mainly located in the third and fourth quadrants, indicating they are mainly affected by sulfate mineral dissolution, pyrite oxidation, and cation exchange. The two Permian aquifer samples in the figure are in the range of Carboniferous aquifers, and a Carboniferous aquifer sample in the range of Permian aquifers. It indicates there may be a hydraulic connection between Permian and Carboniferous aquifers.

### 3.5. Hydrogeochemical Spatial Evolution Characteristics

The K\(^+\)+Na\(^+\), Ca\(^{2+}\), Mg\(^{2+}\), Cl\(^-\), SO\(_4\)\(^2-\), and HCO\(_3\)\(^-\) values of 74 groundwater samples from the Hengyuan Coal Mine were substituted into the factor score function expression (Eq. (4), Eq. (5)). A Surfer Kriging interpolation was used to draw the load score contour map (Figures 8–10) of the principal factors Z1 and Z2. This was used to describe the water chemistry control factors of the multi-aquifer system, as follows.

### 3.6. The Cenozoic Aquifer

Figure 8 shows that the \(S_{Z1}\) values are negative in the study area, with a uniform distribution. The \(S_{Z1}\) values range from -2.04 to -1.56. In contrast, the \(S_{Z2}\) values are positive, with a relatively uniform distribution, and the \(S_{Z2}\) values vary between 0.25 and 1. The \(S_{Z1}\) values gradually increase from west to east, and the \(S_{Z2}\) values gradually decrease. Due to the control of mining activities in the east, the Cenozoic aquifer is discharged, and the groundwater flow accelerates from west to east. This increases the dissolution and contact time of minerals and groundwater. At the same time, the aquifers are in a semioxidized environment during mining activities. In addition, the west area is controlled by structures such as the Wenzhuang syncline and the Mengkou fault, resulting in a relatively closed groundwater environment. From west to east, the sulfate dissolution and cation exchange are enhanced, while the desulfurization effect is weakened.

### 3.7. The Permian Aquifer

Figure 9 shows that \(S_{Z1}\) values are positive in most of the study area, with an uneven distribution. In the north, the \(S_{Z1}\) values vary from 0.2 to 2.0; in the south, they vary from 0.2 to 1.6; and in the east, they vary from -0.8 to 0.2. \(S_{Z2}\) values are positive and unevenly distributed in the study area, increasing gradually from the north and south sides to the middle. A high \(S_{Z1}\) value and a low \(S_{Z2}\) value appear near the Wenzhuang syncline. Under the action of syncline, this area is a closed
Figure 6: Load distribution of each parameter on the principal factor Z1–Z2.

Table 4: Principal factor score coefficients.

| Parameters | 1   | 2   |
|------------|-----|-----|
| Na⁺        | 0.323 | 0.16 |
| Ca²⁺       | -0.081 | -0.278 |
| Mg²⁺       | 0.075 | -0.379 |
| Cl⁻        | 0.342 | -0.059 |
| SO₄²⁻      | 0.514 | -0.215 |
| HCO₃⁻      | -0.208 | 0.511 |

Figure 7: Scatter diagram with load scores from aquifer samples.
recharge area environment with a strong water yield. There is a long interaction time between groundwater and minerals, enhancing cation exchange and sulfate dissolution. In the area surrounded by the Lvlou fault, the BF4 fault, and the Xiaocheng anticline, the $S_{Z1}$ value is high and the $S_{Z2}$ value is low. The aquifers are well sealed, benefiting cation exchange and desulfurization. The $S_{Z1}$ and $S_{Z2}$ values are higher from the middle to east. Due to the long-term mining activities, the Permian aquifer has become a semioxidized environment in some areas. This benefits the carbonate and sulfate dissolution and the pyrite oxidation.

3.8. The Carboniferous Aquifer. Figure 10 shows that the $S_{Z1}$ values in the study area are unevenly distributed; the values gradually decrease to the north between the Xiaocheng anticline and the Lvlou anticline and gradually increase to the south of the Xiaocheng anticline. The $S_{Z2}$ values are all negative. The values are low near the Mengkou fault; the highest value appears to the west of the Mengkou fault. The $S_{Z2}$ values in the south are lower than other areas overall and are higher at the Lvlou anticline in the east. The mining activities are mainly located in the north wing of the Xiaocheng anticline and the west wing of the Lvlou anticline. The groundwater circulation conditions at the axis of the anticline are good, enhancing the pyrite oxidation, the carbonate dissolution, sulfate dissolution, and cation exchange in the mining area. The groundwater flow near the Wenzhuang syncline is affected by the Mengkou fault, which leads to pyrite oxidation, carbonate and sulfate dissolution, and cation exchange. In contrast, the aquifers at the syncline are deeply buried, leading to increased desulfurization.

4. Conclusions

This study investigated the hydrogeochemical evolution characteristics of the complex underground multiaquifer system in Hengyuan Coal Mine in China. Traditional hydrochemical analysis methods and Q-factor analysis methods were used to analyse the collected water samples, leading to the following conclusions.
The cation levels in the three aquifers were the highest for K$^+$+Na$^+$, followed in descending order by Ca$^{2+}$ and Mg$^{2+}$. In the Permian and Carboniferous aquifers, SO$_4^{2-}$ was present at the highest levels, followed by HCO$_3^-$ and Cl$^-$. In the Cenozoic aquifers, HCO$_3^-$ was the highest, followed by SO$_4^{2-}$ and Cl$^-$. The overall TDS values of each aquifer were the highest for the coal, followed by the Taihui and Cenozoic. The TDS values successively decreased in the Permian, Carboniferous, and Cenozoic aquifers. The difference in ion skewness in different aquifers is due to the comprehensive reflection of different hydrogeochemical processes.

The hydrogeological conditions and mining activities impact the hydrogeochemical processes of the Hengyuan coal mine. These processes mainly include carbonate and sulfate dissolution, cation exchange, desulfurization, and pyrite oxidation. Carbonate dissolution and desulfurization are significant in the Cenozoic aquifer, and the cation exchange and pyrite oxidation in the Permian aquifers are the most significant. There is significant sulfate dissolution, cation exchange, and pyrite oxidation in the Carboniferous aquifers.

The hydrogeochemical evolution process in underground aquifers is mainly controlled by mining activities, faults, and folds, and the hydrogeochemical evolution process of aquifers in the study area shows obvious zonation. Studying the chemical changes of groundwater can provide a geological basis for the accurate identification of potential water inrush sources and protection of water resources and has certain guiding significance for coal mine safety production. The chemical evolution of groundwater is a dynamic process, and water chemistry data should be collected regularly to find out the changes of groundwater in...
coal mine areas. In the future, we can study the evolution process of ground hydrology and geochemistry from the perspective of time and space.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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