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ORIGINAL PAPER

Identification of mine water inrush source based on multiple heterogeneous fusion: a case study in Lilou Coal Mine, China

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Abstract
The occurrence of mine water damage in the process of coal mining and the unknown nature of sudden water source seriously threaten the safety production of coal mine. How to quickly and accurately identify the burst water source has become a hot research topic of mine water damage prevention and control. In order to explore the new identification method of mine water source, taking the working face of 1303 in Shandong Lilou Coal Mine as an example, the main purpose of this study is to accurately identify the source of a large amount of old empty water on the working surface of 1303, point out the direction for water dredging work, and ensure the safety production of coal mine. Fifty-six groups of main aquifer water samples were collected based on groundwater chemical theory and mathematical theory. The contents of water samples Na^+, Mg^{2+}, Ca^{2+}, $CO_3{}^{2-}$, $HCO_3{}^-$, $SO_4{}^{2-}$, and Cl^-; 7 conventional ions; hydrogen ion concentration (PH); total dissolved solids (TDS), electrical conductance (EC); Cu, Mo, Ba, Ni, Zn, As, and D; and ^{18}O 2 isotopes were determined. The water source system is based on conventional hydrochemical characteristics, fuzzy comprehensive evaluation of trace elements, and isotope analysis. The results show that the conventional water chemical analysis shows that the water sample and the top water in the study area and trace element analysis show that the relative membership of the water sample and the top water is up to 67.25%; isotope analysis shows that the water sample has the same supply source and the ash water varies from other aquifers. Finally, it is determined that the old empty water on the working surface of 1303 of Lilou Coal Mine is mainly derived from the roof sandstone aquifer, which contains a small amount of three ash water and no Austrian ash water. The research results are consistent with the actual mining situation of the mine. The research results provide a new and accurate identification method for mine water source identification and provide a theoretical and technical basis for coal mine safety production.

Keywords Mine water inrush · Water source identification. Heterogeneous system · Conventional hydrochemical characteristics · Fuzzy comprehensive evaluation of trace elements · Isotopic analysis

Introduction

Groundwater is closely related to people's lives. Many scholars have conducted a lot of research on the groundwater classification. For example, Langer conducts European groundwater exploitation research (Langer 2020); Hussain conducted a study on removing water chemical pollutants from drinking water (Hussain and Al-Fatlawi 2020); Cadraku performs a quality assessment of groundwater for irrigation (Çadraku 2021). Groundwater brings convenience to people's life but also brings inconvenience to people's production activities. In particular, the safe mining of underground mining resources poses great challenges. China is a country with coal as the main energy source; coal will still be the main energy for a long time, but after long-term mining, shallow coal resources are exhausted; the vast majority of mines into the deep mining and geological and hydrogeological conditions are more complex; mine water damage accidents occur; sudden water sources also tend to be diverse (Meng et al. 2012; Tripathy and Ala 2018). According to statistics, the personnel deaths from 2012 to 2015

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in 2015 were four times that of the major coal mining countries. A total of 278 coal mines occurred in China, causing 1,772 deaths, while the sudden accidents were 267, accounting for 15.1% of the total number, second only to the personnel losses caused by gas accidents. It can be seen that the rapid and accurate identification of mine water burst water source has become a long-term practical problem and needs to be constantly solved in coal mine safety production.

Many scholars and experts have carried out a lot of research on the water source identification of mine water burst, and the water source identification method is mainly divided into several categories: physical analysis method, water chemical analysis method, and mathematical theory analysis method. Physical analysis mainly includes water temperature method and water level method; hydrogeochemical research proves that the water level has different water temperatures, but it is only applicable to mining areas (Shen 1986); hydrochemical analysis mainly includes Shukev classification (Gao et al. 2001), radioactive element method, and isotope method (Ji et al. 2017; Guo et al. 2020). For example, Dinka studied the hydrochemical characteristics of different surface water and groundwater bodies in Matahara to analyze the source of pollutants (Dinka et al. 2015); Huang studied the hydrochemical characteristics of Tangdou, China, and determined the source of underground hot water in the study area using proportional coefficient and factor analysis (Huang et al. 2008). Differences in water chemistry in different aquifers are shown. This method identify the burst water source mainly by comparing the water chemical characteristic ions and identifies it quick and simple but with the ambiguity and the uncertainty. The application of mathematical theoretical analysis method in water source identification mainly includes distance discrimination (Wang et al. 2011), fuzzy comprehensive evaluation (Gao 2012), Bayes (Ju et al. 2018), Fisher (Xu and Wang 2016), cluster analysis, and neural network (Yu et al.2007). In compliance with Qu, he applies factor analysis and distance discrimination theory to mine burst water source identification. Examples verify that if the discriminant indicator selection is appropriate, two couplings can effectively eliminate the mutual influence between the discriminant indicator and increase the discrimination rate (Qu and Shi 2018); Sun uses GIS technology to visually output the fuzzy comprehensive discrimination results. The identification of water source and the division of water space are realized. However, this method has high requirements for raw data (Sun et al. 2007); Zhang used the scalable theory to distinguish the mine water. The numerical index is selected as the discrimination factor and high model recognition rate (Zhang et al. 2009). Wu used for the first time a fuzzy mathematical method in groundwater pollution evaluation. It provides a new identification method for groundwater pollution control (Wu et al.).

However, at present, a complete and effective area water source identification technology method system has not been formed (Wang et al. 2001). Old empty water damage is a disaster caused by water flooding into the pit in the old empty area. It is the main type of major water damage accidents in China's coal mines in recent years (Wu 2014). The occurrence of the old empty water damage is mainly caused by the water-proof coal (rock) column in the old empty area which is not enough to resist the water pressure after the excavation project.

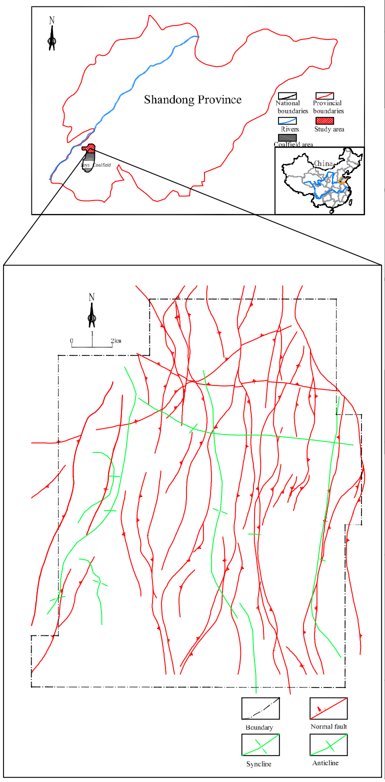
In summary, the method of identifying mine water sources involves multiple disciplines and fields and has developed from the traditional water quality type comparison method to a deep, systematic, and visual direction. In this paper, aiming at the problem that a large number of water inrush phenomena and complex aquifers occur in the old empty area of the 1303 working surface of Shandong Lilou Coal Mine, which makes it difficult to accurately identify the water source, the comprehensive water chemistry analysis method and the mathematical theory analysis method establish a multi-faceted identification system for the water inrush water source of the mine based on conventional ions, trace elements, and isotopes, which provides a new method for the prevention and control of mine water inrush.

Methods and materials

Study area

Lilou Coal Mine is located in the north of Juye coalfield, Heze in Shandong Province, China, and is a fully concealed Carboniferous–Permian coalfield in North China. In general, it is a monoclinic structure with a north–south strike and an eastward dip, and the secondary first-order wide fold is developed with a certain number of faults. At present, Shandong Lilou Coal Mine adopts fully mechanized top coal mining, main mining Permian Shanxi formation No. 3 coal seam, seam thickness 6.70 ~ 7.31 m, and average coal thickness 7.03 m. The coal seam inclination is 4 ~ 16° and average of 13°, seam floor elevation is – 994 ~—– 890 m, and coal seam buried depth is 1035 ~ 933 m. The average strike length of 1303 mine face is 2575 m (Fig. 1); the average tilt length is 243.7 m.

On October 1, 2019, 1303 face propulsion speed 1.6 m/day. In the process of mine face propulsion, large area water gushing occurs in goaf. Up to January 10, 2020, when the mine face advances to 155 m, the water inflow reaches 1600 m^3/h. According to the regional hydrogeological data, the main mine aquifers from top to bottom are Quaternary sandstone aquifer, Neogene sandstone aquifer, Permian Shihezi



Stratum	Histogram	Thickness/m	Water abundance	The way to enter	Remarks
Quaternary sand layer		105.00~139.60 / 122.09	medium	No	No participation
Neogene sand layer		338.20~460.40 / 394.72	low	Balizhuang fault	Less participation
Permian Shihezi Formation sand layer		0~653.50 / 359.35	low~ medium	Water-conducting fracture zone / Balizhuang fault / leading overburden movement fracture	Main participation/ The passage is located on the roof of the coal seam
Permian Shanxi Formation sand layer		0~81.00 / 50.15	low		
Coal seam 3		6.70~7.31 / 7.03			
Carboniferous Taiyuan Formation 3 th limestone layer		1.79~6.30 / 5.20	low~ medium	fault	Less likely to participate
Carboniferous Taiyuan Formation 10 th limestone layer		2.06~7.45 / 4.41	medium	Karst fissure/ Balizhuang fault / leading overburden movement fracture	Studies have shown that only three ash aquifers in Taiyuan formation are recharged and not involved
Ordovician limestone layer		>800	medium~ high		

Fig. 1 Location and stratum of Lilou Coal Mine

formation sandstone aquifer, Permian Shanxi formation sandstone aquifer, Carboniferous Taiyuan formation 3rd and tenth limestone aquifers, and Ordovician limestone aquifer (Fig. 1), among which Shihezi formation sandstone aquifer, Shanxi formation sandstone aquifer, and Taiyuan formation the 3rd limestone aquifer are the main mine inrush aquifer.

Water sample collection and testing

For a collection of 56 groups of water samples (Fig. 2A) of major water inrush aquifers, among them, 9 were key water intake points: 1303 track along channel 17# chamber, 1# hole, ground BSD6 Austrian ash hydrological observation borehole, rail return 3# contact roadway, three ash hydrological observation holes, 1302 mine face, 1301 track along channel 7# drilling chamber roof hole, 1301(upper) mine face, 1303 track along channel 1700# point water silo, 1300 mine face, and 1303 drainage roadway 2# contact roadway. The roof water of 1302 mine face and 1303 mine face is the mixture of Shanxi formation and Shihezi formation sandstone water (9 kinds of water intake points are defined as 1–9 for further study).

The pH, TDS, EC, conductivity, conventional hydrochemical components (Na^+, Mg^{2+}, Ca^{2+}, HCO_3^-, SO_4^{2-}, Cl^-), trace elements (V, Cu, Mo, Ba, Ni, Zn, As), and hydrogen and oxygen isotopes (D, ^{18}O) of the water samples were determined. The sample data with large error caused by the test instrument is eliminated to avoid the influence on the overall effect of the data. The data of the same water intake point are processed by means. The stable isotope mass spectrometer MAT253 (Fig. 2B) was used to determine the isotopic content of the sample. The determination method was according to DZ/T0064-93 standard; ICPS-7000 (Fig. 2C) and ICS-600 (Fig. 2D) were used to determine the content of cations and anions, respectively.

Construction of multiple heterogeneous system for water inrush identification

A heterogeneous system for water source identification consists of three parts (Fig. 3), one is conventional hydrochemical characteristic ion analysis, the other is fuzzy comprehensive evaluation and analysis of trace elements, and the 3rd is isotopic analysis.

Main methods and characteristics of conventional water chemical characteristics analysis There are many groundwater chemical types of classification, which is most widely used in the groundwater chemical classification. The classification is proposed by former Soviet scholar Shukalev (C. A. укапев),

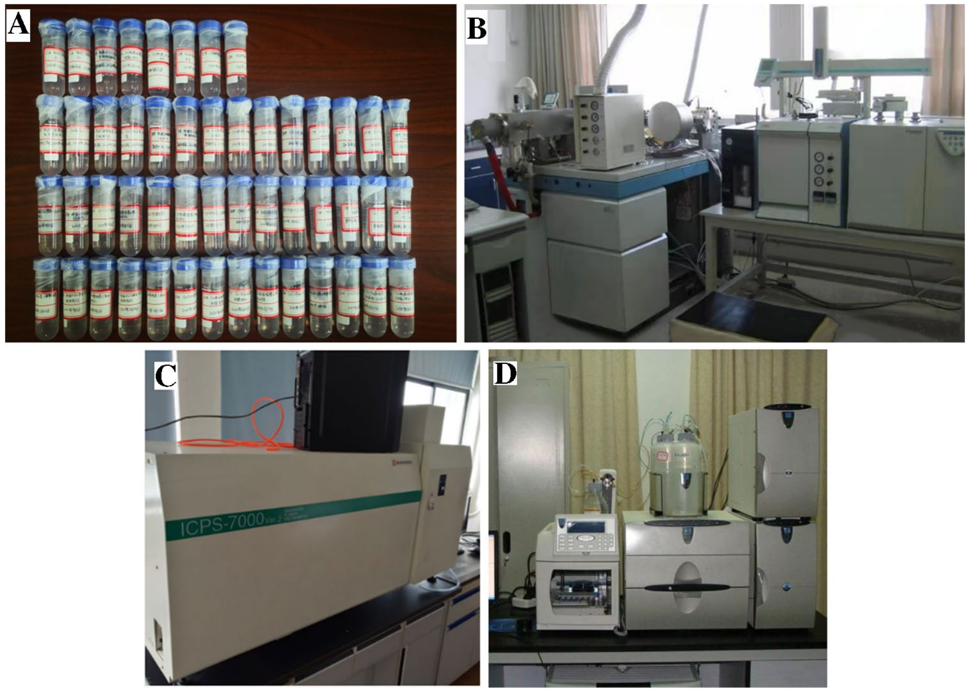


Fig. 2 Test samples and instruments (**A**) 56 groups of water samples (**B**) MAT253 (**C**) ICPS-7000 (**D**) ICS-600

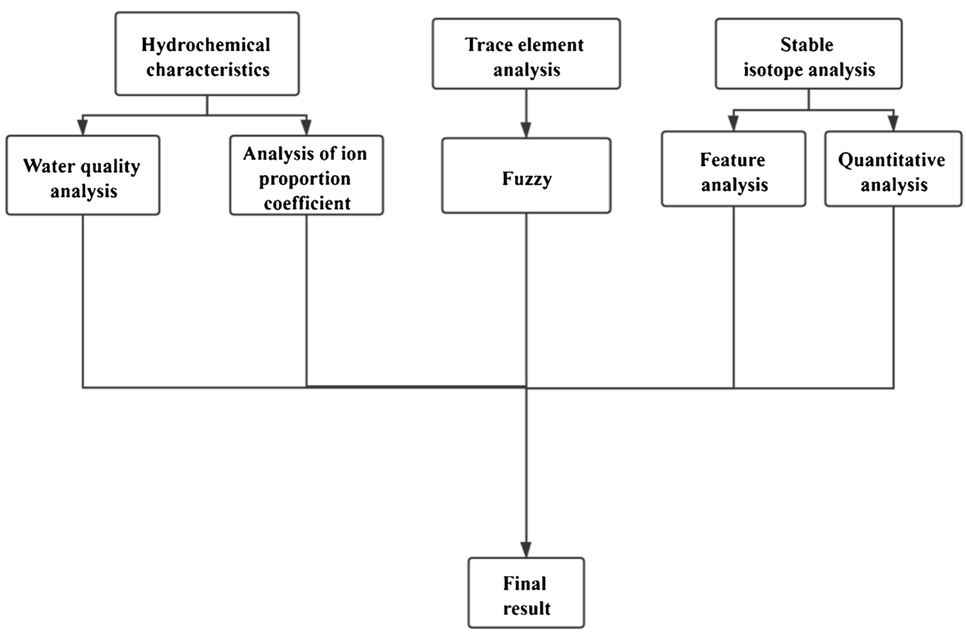


Fig. 3 Flowchart of the methods

which is divided according to the content size and mineralization of Yin and Yang ions. Through a combination of anions and cations with a content greater than 25% mg of equivalent (Table 1), only six kinds of ions can be reached in nature, namely, Na^+, Mg^{2+}, Ca^{2+}, HCO_3^-, SO_4^{2-}, and Cl^-. Although this method is simple and easy to understand, it can be used to organize the water quality analysis data using the table system. However, there are still some defects and are easy to ignore the equivalent percentage of less than 25% trace ions and unable to compare the primary and secondary ions relationship. The characteristic ion ratio coefficient is also introduced here, which in the chemical composition of groundwater is often used to study certain hydrogeochemical problems (Wang et al. 1995). The $\gamma(Na^+)/\gamma(Cl^-)$ coefficient, known as the origin coefficient of groundwater, is a hydrogeochemical parameter characterizing the enrichment of sodium ions in groundwater. A larger proportionality coefficient indicates stronger groundwater mobility, and vice versa, and worse mobility.

Table 1 Shukalev classified groundwater types

>25% (mEq)	HCO_3	HCO_3+SO_4	HCO_3+SO_4+Cl	HCO_3+Cl	SO_4	SO_4+Cl	Cl
Ca	1	8	15	22	29	36	43
Ca+Mg	2	9	16	23	30	37	44
Mg	3	10	17	24	31	38	45
Na+Ca	4	11	18	25	32	39	46
Na+Ca+Mg	5	12	19	26	33	40	47
Na+Mg	6	13	20	27	34	41	48
Na	7	14	21	28	35	42	49

Main methods and characteristics of trace element fuzzy comprehensive evaluation and analysis In order to solve the disadvantages of less than 25% equivalent percentage of trace ions in Schukalev classification method, the fuzzy comprehensive evaluation method is used for groundwater trace element analysis. The fuzzy comprehensive evaluation (FCE) was first proposed in 1965 by Prof. L.A. Zadeh, which has been widely used in engineering technology, economic management, and social life. It is a comprehensive evaluation method based on fuzzy mathematics (Zadeh 1978). The comprehensive evaluation method transforms the qualitative evaluation into a quantitative evaluation according to the membership evaluation theory of the fuzzy mathematics, that is, the fuzzy mathematics is used to make an overall evaluation of the things or objects restricted by various factors. It has the characteristics of clear results and strong system, which can better solve the fuzzy and difficult to quantify problems, and is suitable for the solution of various non-deterministic problems.

Main methods and characteristics of isotope analysis Because isotope does not react with other components, not easy to adsorption, and groundwater has good "mark" and "conservation," the study of groundwater age, the origin of water, trace groundwater movement, measuring hydrogeological parameters, and many other aspects have achieved satisfactory effect, especially stable isotope is not affected by human factors and naturally exists in the environment, and the application effect is better. The hydrogen and oxygen isotopic composition and content of natural water in nature are influenced by complex geophysical, chemical, and biochemical effects. Therefore, the isotopic water molecules have different masses and have different saturated vapor pressures. During evaporation and condensation, heavy isotopic water molecules (D_2O, H_2O^{18}) are preferentially enriched in the liquid phase and impoverished in the gas phase, leading to differences in hydrogen and oxygen isotopic composition between the liquid and gas phase, that is, fractionation of the isotopes occurs. Groundwater is replenished by atmospheric precipitation, and the water in the atmosphere mainly comes from seawater evaporation. As the result of isotopic fractionation, various natural waters have different isotopic characteristics; studying water D and ^{18}O is very effective for determining the source and origin of water (Xue 2019; Ian and Fritz 2006). At the same time, by measuring and comparing natural water, atmospheric precipitation, groundwater, and surface water D and ^{18}O, we can study the supply source of groundwater, determine the hydraulic connection between different aquifers, and calculate the mixed proportion of each source of water, which is very effective in the current mine water control application (Pan et al. 2009).

The three methods complement their advantages, and the main steps to build the sudden water source identification system are as follows:

Step 1: The conventional hydrochemical characteristics of the old empty water and the suspected water source in the 1303 mine face of Li Lou Coal Mine are analyzed by using the Shukalev classification method, and the fuzzy comprehensive evaluation set is determined.

Step 2: Establish a water source identification system with trace elements V, Cu, Mo, Ba, Ni, Zn, and As as the index.$X = \{x_1, x_2, x_3, x_4, x_5, x_6, x_7\}$. Other mines face source water (A), roof water of 1303 (B), the 3rd limestone water of Taiyuan formation (C), Austria ash water (D) four types of suspected water sources as background values, recorded as $V = \{A, B, C, D\}$.

Step 3: Use principal component analysis (PCA) to quantify the relative importance of 7 trace elements (V, Cu, Mo, Ba, Ni, Zn, As) with the help of the SPSS 22.0.

Step 4: Starting from a single evaluation index, the relative membership degree r_{nm} is calculated by "Reduced half trapezoid distribution method," and the relative membership degree of the water sample to the suspected water source A, B, C, and D is determined. Combined with the index weight vector matrix, the membership degree of the evaluation set is solved.

Step 5: Analyzing the stable isotopic composition of hydrogen and oxygen in each water-bearing system, the calculation model of mixed groundwater recharge ratio is constructed, and the composition of old empty water in 1303 mine face is divided.

Results and discussions

Conventional hydrochemical characteristics

Map the piper triple line from the conventional water chemical ion content (Piper 1944), and the water quality types of water intake points 1, 4, 5, 6, 7, 8, and 9 are basically the same (Fig. 4), the anions are mainly SO2 − 4, and the cations are Na^+, and the water type is SO_4-Na; No. 2 water intake point (lime water) anion to Cl^- and SO2 − 4 mainly and cations are Na^+, Ca^{2+}, and Mg^{2+}; and the water type is SO_4·Cl-Na,·Ca,·and Mg; point 3 (the 3rd limestone) anion to SO2 − 4, and Cl^-, cation mainly to Na^+; water type is SO_4·Cl-Na.

Preliminary identification results of conventional water chemical characteristics analysis according to Shukalev classification.

Fifty-six groups of groundwater samples from 9 water intake points were divided into 5 categories: water samples (4, 5, 6, 7, 8) collected from other mine faces were marked as A; roof water of 1303 sample (1) marked as B; (3) water sample of the 3rd limestone aquifer marked as C; Ordovician limestone aquifer water sample (2) marked as D; and the goaf water of 1303 is the water sample to be awarded.

The scale coefficient of relevant examples can determine the hydrodynamic conditions and water yield of water samples, and for the water yield of class C water $\gamma(Cl^-)/\gamma(Ca^{2+})$, the coefficient is 20 ~ 130, and the other type of water system is between 0 and ~ 20 (Fig. 5), indicating that the 3rd

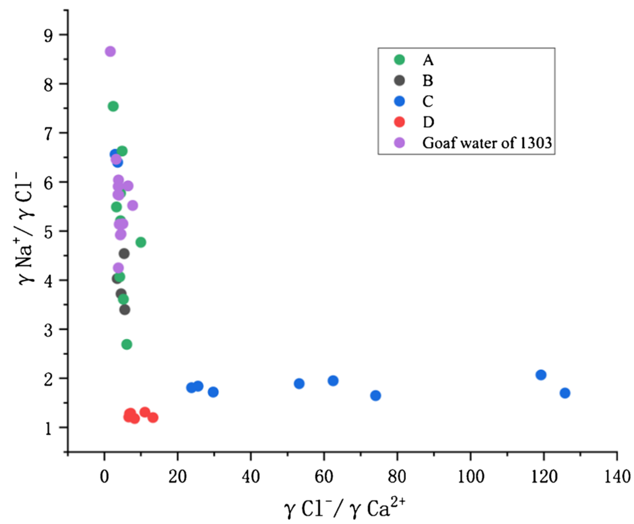


Fig. 5 Ion proportion coefficient of the five types of water

limestone water of the Carboniferous Taiyuan formation has better hydrodynamic conditions, better circulation, better permeability, and water abundance. A, B, and 1303 $\gamma(Na^+)/\gamma(Cl^-)$, the coefficient of water between 2.5 and ~ 9, and C and D are mainly between 1 and ~ 2, indicating that there is strong hydraulic connection between goaf water of 1303 and roof water of 1303 and other working surface sources, and groundwater shows a certain infiltration behavior. For the Ordovician limestone water $\gamma(Na^+)/\gamma(Cl^-)$, the minimum coefficient indicates that its circulation is poor and

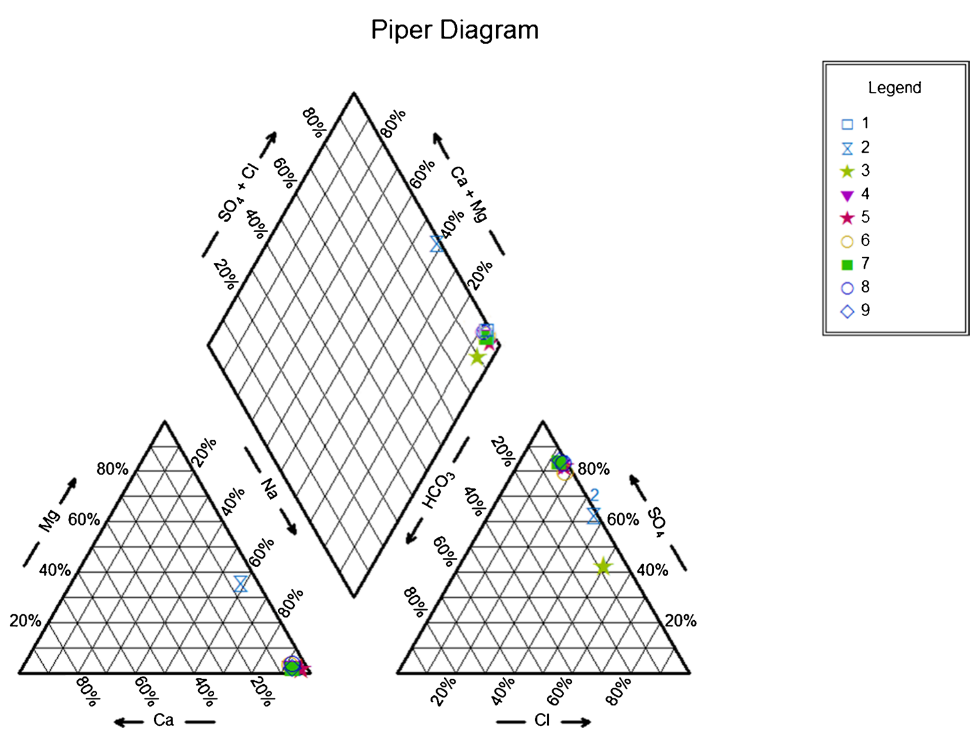


Fig. 4 Characteristic ion analysis Piper three-line of different aquifer superimpositions

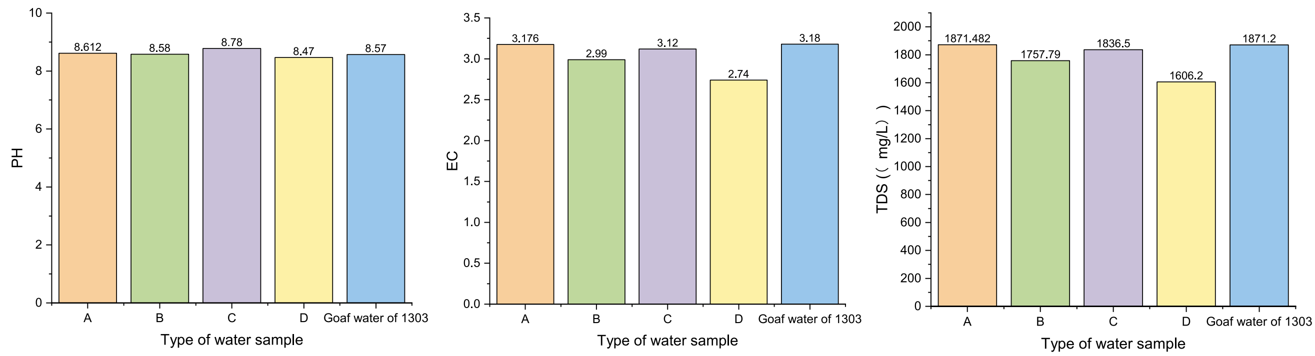


Fig. 6 Basic parameters of water quality

Table 2 Data analysis of the five types of water

Item	A	B	C	D	Goaf water of 1303
Water type	SO_4-Na	SO_4-Na	SO_4·Cl-Na	SO_4·Cl-Na·Ca·Mg	SO_4-Na
$\gamma(Na^+)/\gamma(Cl^-)$	5.09	3.92	2.76	1.25	5.72
$\gamma(Cl^-)/\gamma(Ca^{2+})$	5.62	4.57	23.8	8.33	4.23
pH	8.61	8.58	8.78	8.47	8.57
Total dissolved solids (TDS)	1871.48	1757.79	1836.50	1606.20	1871.20
Electrical conductivity (EC)	3.18	2.99	3.12	2.74	3.18

is less affected by infiltration and has the characteristics of deep karst water. According to Fig. 4, Fig. 5, and Fig. 6, the difference between the water quality type and ion ratio coefficient of Ordovician limestone water and the target water sample goaf water of 1303 is obvious (Table 2).

Routine water chemical characteristic analysis method concluded 1303 old empty water, and the top plate water quality type is consistent and may be mainly the sudden water source. Whether it contains Austrian ash water and three ash water is unclear.

Trace element discrimination

On the basis of the content distribution of trace element V, Cu, Mo, Ba, Ni, Zn, and As in water body, the average content profiles of trace element in main water inrush aquifer A, B, C, and D and water samples 1, 2, and 3 to be examined were drawn, respectively (Fig. 7). As can be seen from the diagram, the overall change trend of V, Cu, Mo, Ba, Ni, Zn, and As in the main water inrush aquifer and the water sample to be examined is similar, but with the difference of water-bearing system, it shows that a trace element is more enriched in a certain kind of water-bearing system.

With the help of SPSS 22.0, this paper establishes a water source identification system based on trace element V, Cu, Mo, Ba, Ni, Zn, and As, using principal component analysis (PCA) to quantify the relative importance of seven trace elements (Table 3). For example, Cu, based on fuzzy comprehensive evaluation theory, the relative membership $(r_1(x), r_2(x), r_3(x))$

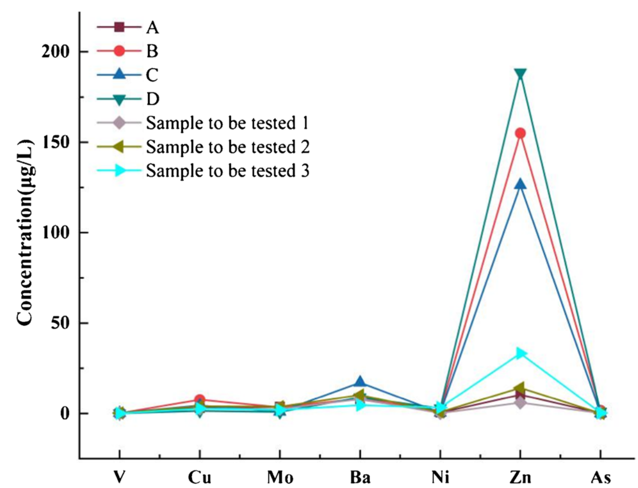


Fig. 7 Profile of the mean content of trace elements

of water samples 1, 2, and 3 for suspected water A, B, C, and D inrush is solved:

$$r_1(x) = \begin{cases} 0 & x \le 0.19 \\ \frac{x-1.39}{4.403-1.39} & x \in (1.39, 4.403] \\ \frac{7.598-x}{7.598-4.403} & x \in (4.403, 7.598] \\ 0 & x > 7.598 \end{cases}$$

Table 3 Weight of indicators

Indicator items	V	Cu	Mo	Ba	Ni	Zn	As
Indicator weights	0.13	0.16	0.13	0.11	0.13	0.17	0.17

Table 4 Membership of water samples to suspected water sources

Suspected water source	Sample pending 1	Sample pending 2	Sample pending 3	Membership
Roof water of 1303	0.5265	0.6725	0.5056	0.5682
Olues	0.1237	0.0246	0.1057	0.0847
III ash water	0.1462	0.1002	0.2869	0.1778
Other mine face source water	0.2036	0.2027	0.1018	0.1694

$$r_2(x) = \begin{cases} 1 & x \le 1.39 \\ \frac{4.403-x}{4.403-1.39} & x \in (1.39, 4.403] \\ 0 & x > 4.403 \end{cases}$$

$$r_3(x) = \begin{cases} 0 & x \le 4.403 \\ \frac{x-4.403}{7.598-4.403} & x \in (4.403, 7.598] \\ 1 & x > 7.598 \end{cases}$$

According to the relative membership degree of the index, the weight judgment matrix is constructed R, and the fuzzy relationship between the evaluation index of trace elements and the evaluation set of water inrush source is defined:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}$$

where r_{nm} : is the relative membership degree of the n factor x_n in the evaluation factor X to the m target v_m in the evaluation set.

On the basis of index weight vector matrix W and weight judgment matrix R, operator $M(\cdot, \oplus)$ is used to calculate the membership degree of water samples 1, 2, and 3 to suspected water source A, B, C, and D:

$$B = W * R = [b_1, b_2, \cdots, b_m]$$

Based on the maximum membership principle (Table 4), the membership of the 3 distinguished water samples and 1303 top plate water samples was the highest, with an average membership of 0.5682 and the lowest for Austrian ash water.

The analysis of fuzzy comprehensive evaluation concluded that the top plate water of 1303 (3 sands and Shihezi sandstone mixed water) is the old empty water source of 1303. In order to further determine the proportion of mixed water in the working area of 1303, the mixed groundwater recharge ratio calculation model was constructed by

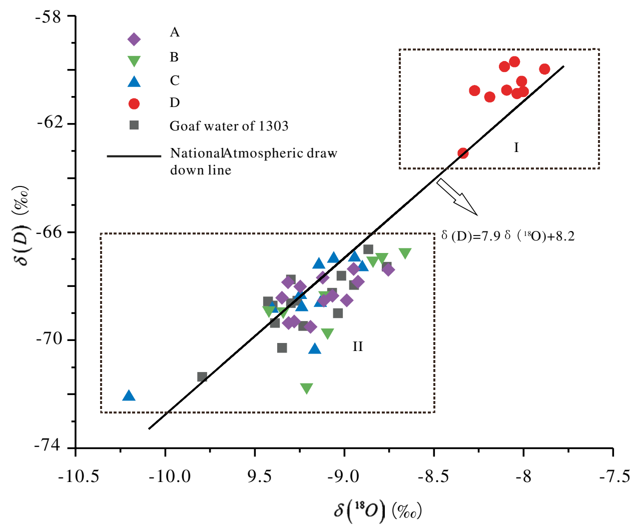


Fig. 8 $\delta(D)$-$\delta\left({}^{18}O\right)$

analyzing the composition characteristics of hydrogen and oxygen stable isotopes in water bodies.

Isotopic analysis

Draw 56 groups of different water-bearing system $\delta(D)$-$\delta\left({}^{18}O\right)$ relationships (Fig. 8). It can be seen from the diagram that most of the water sample points are distributed near the national precipitation line, indicating that the recharge of mine groundwater mainly comes from atmospheric precipitation. However, some water samples deviate from the precipitation line due to isotopic fractionation during the migration of groundwater in aquifers and water diversion channels. The stable isotopic composition of different aquifer water bodies is different, indicating that the migration law is different.

The results show that the area I is the fall point of Ordovician limestone water, $\delta(D)$ is $-59.7 \sim -63.1‰$, and $\delta\left({}^{18}O\right)$ is $-7.88 \sim -8.34$ ‰. The content of $\delta(D)$ and $\delta\left({}^{18}O\right)$ is the largest, which indicates that the area I is well supplied by atmospheric precipitation. The water sample points all fall above the precipitation line, which indicates that the Ordovician limestone aquifer is only recharged by atmospheric precipitation, the recharge time is relatively long, and there is no hydraulic connection with other aquifers.

Area II is located in the lower left of area I, and the water sample points are distributed on both sides of the precipitation line, and more are located below the precipitation line, which indicates that there is a certain hydraulic relationship between the 3rd limestone water of Taiyuan formation, the roof water of 1303, the other mine face goaf water, and the roof water, and the goaf water of 1303.

According to the quantitative study of water sample mixing (Xue 2019; Ian and Fritz 2006), this paper constructs the calculation model of mixed groundwater recharge ratio by using $\delta(D)\,\delta\left(^{18}O\right)$ binary first-order equation solves the proportion of the 3rd limestone water of Taiyuan formation, roof water of 1303, and other mine face water in 1303 mine face and divides the composition of 1303 mine face old empty water:

$$\begin{cases} \delta_1 = \lambda_C\delta_{C1} + \lambda_B\delta_{B1} + \left(1 - \lambda_C - \lambda_B\right)\delta_{A1} \\ \delta_2 = \lambda_C\delta_{C2} + \lambda_B\delta_{B2} + \left(1 - \lambda_C - \lambda_B\right)\delta_{A2} \end{cases}$$

In the formula, δ_1 is the value of old empty water $\delta\left(^{18}O\right)$ of 1303 mine face, taking − 9.08‰; δ_2 is the value of old empty water $\delta(D)$ of 1303 mine face, taking − 68.11 ‰; δ_{C1} is the value of lime fly ash water $\delta\left(^{18}O\right)$, taking − 9.14 ‰; δ_{C2} is the value of lime fly ash water $\delta(D)$, taking − 68.15‰; δ_{B1} is the value of roof water of 1303 $\delta\left(^{18}O\right)$, taking − 9.04 ‰, δ_{B2} is the value of roof water of 1303 $\delta(D)$, taking 68.08‰; δ_{A1} is the value of water $\delta\left(^{18}O\right)$ from other mine faces, taking − 9.12 ‰; and δ_{A2} is the value of water $\delta(D)$ from other mine faces, taking − 68.32 ‰ (Table 5).

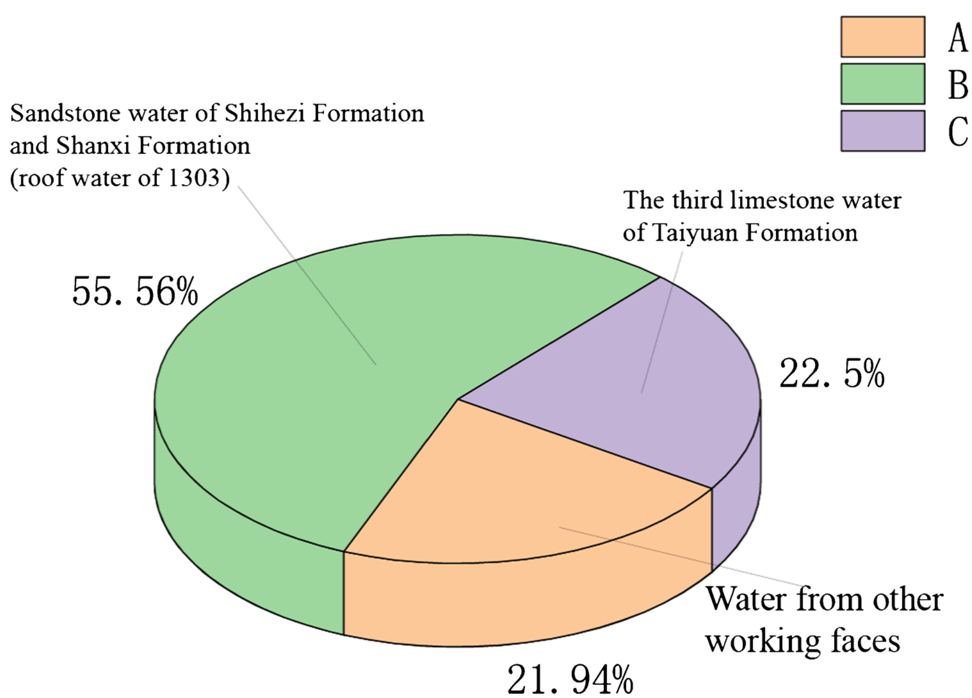
Isotopic analysis concluded to sum up goaf water of 1303 which mainly comes from roof water of 1303, mixed with a small amount of the 3rd limestone water of Taiyuan formation, no Ordovician limestone water, of which roof water of 1303 accounts for 55.56%, the 3rd limestone water of Taiyuan formation accounts for 22.5%, and other mine face water accounts for 21.94%(Fig. 9).

Table 5 Statistical table of hydrogen and oxygen isotope contents of suspected source in mineral area

	1303 face old empty water	The 3rd limestone water of Taiyuan Formation	Roof water of 1303	Other mine face source water
$\delta(^{18}O)$	− 9.08‰	− 9.14‰	− 9.04‰	− 9.12‰
$\delta(D)$	− 68.11‰	− 68.15‰	− 68.08‰	− 68.32‰

λ_A = 21.94%, λ_B = 55.56%, λ_C = 22.5%。

Fig. 9 Source water ratio



Conclusions

(1) Hydrochemical methods were applied to analyze the hydrogeochemial characteristics of the four aquifers and three samples to be tested in Lilou Coal Mine. The goaf water and roof sandstone water were characterized by the SO_4-Na type and could easily be distinguished from other aquifers, while the hydrochemical type of the Ordovician limestone water was SO_4·Cl-Na·Ca·Mg, and the 3rd limestone water was SO_4·Cl-Na.

(2) The water source identification model of fuzzy comprehensive theory of trace elements is constructed and confirmed with the results of mixed groundwater recharge ratio calculation model. The results show that goaf water of 1303 mainly comes from roof water of 1303, mixed with a small amount of Taiyuan formation the 3rd limestone water, and no Ordovician limestone water.

(3) The multi-heterogeneous water source identification system integrates conventional hydrochemical characteristic analysis, trace element fuzzy comprehensive evaluation, and isotope analysis, which complement and verify each other and overcome the independence between multiple attributes, and the discrimination results are in line with the actual mining situation of the mine, providing a new method for effectively identifying the water inrush source of the mine. It provides a theoretical basis for mine water disaster prevention and control.

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Declarations

Conflict of interest The authors declare no competing interests.

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