



An assessment of water yield properties for weathered bedrock zone in Northern Shaanxi Jurassic coalfield: a case study in Jinjitan coal mine, Western China

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Abstract

Jurassic weathered bedrock is widely distributed in the Jurassic coalfield of Northern Shaanxi Province. Its fracture network is connected with each other well, which provides a good space foundation for groundwater storage. It makes bedrock weathered zone become one of the important aquifers that endanger coal mine safe production. It is quite necessary to predict bedrock weathered zone aquifer water yield property scientifically to provide a technical guarantee for mine water inrush hazard prevention and control. In order to find out the characteristics of bedrock weathered zone aquifer water yield property, the 5 main control factors affecting weathered bedrock aquifer water yield property, characteristics of overlying aquifer, weathered bedrock strata age, lithologic composition feature, weathering intensity of bedrock, and bedrock weathered zone thickness, are selected to establish a water yield property index mathematical model on weathered bedrock aquifer by the fuzzy Delphi analytic hierarchy process (FDAHP) method and protracted water yield property partition map with the help of ArcGIS. Through analysis and comparison, established water yield property index model and partition map are feasible with a relative high accuracy. Meanwhile, it has some good directive significance to predict weathered bedrock aquifer water yield property type for surrounding mines with similar conditions.

Keywords Weathered bedrock · Aquifer · Water yield property evaluation · FDAHP method

Introduction

With the large-scale exploitation of coal resources in China, mine water hazard caused by mines is becoming more and more serious. Especially in the arid and semi-arid areas of

Northwest China, coal reserves are huge but there is a huge contradiction between mine drainage and ecological environment, industry, agriculture, and living water for residents. Quaternary phreatic aquifer water is not only a huge threat to safe mining but also typical of water supply significance and important ecological value (Zhang et al. 2010). Jurassic bedrock weathered zone is widespread in the Jurassic coalfield of Northern Shaanxi. Some scholars have studied that weathered bedrock can be used as an aquifuge, which has a good water separation ability (Xu et al. 2016). It is beneficial to prevent and control water damage of Quaternary phreatic aquifer. The occurrence of water inrush in some fully mechanized stope shows that weathered bedrock zone can also be an important source of water bursting in mine, which leads to a serious threat to mine production (Xu and Gong 2011; Yin et al. 2016). However, there is poor research data relatively about weathered bedrock zone water yield property, water retention, and spatial variation characteristics. Wu et al. studied bedrock weathered belt engineering geological features (Li et al. 2011; Li et al. 2014). Li et al. (2016) studied support

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technology of weathered bedrock in mines. Some scholars summarized gushing water law of Jurassic Zhiluo Formation weathered bedrock aquifer in the Jinjie coal mine (Zhou et al. 2013; Wang et al. 2014a, b). Therefore, it is an urgent problem for mine water control work to master bedrock weathered zone water yield property and its spatial variation characteristics.

Weathering is that hard rock or mineral of the Earth's crust in the surface or near the surface environment, where it is usually considered to be a geomorphic process, is decomposed and destroyed in situ due to temperature, atmospheric, water, and biological effects, which contains physical weathering, chemical weathering, and biological weathering (Rassam 2013; Wang et al. 2018). However, bedrock is more complicated, which is composed of minerals that are affected more easily by weathering than quartz and clay minerals (Berner and Berner 2012). Once bedrock is weathered, pores and fissures become more widespread and more fractured (Neuman 2005). Witty et al. (2003) studied contributions of water supply from the weathered bedrock zone to forest soil quality. Rushton and Silva studied sustainable yields from large-diameter wells in shallow weathered aquifers. Stephen studied bedrock permeability by weathering (Worthington et al. 2016). Extensively developed pores and fissures provide abundant occurrence space for groundwater. Groundwater makes pore and fissure scale further developed and rock mass further broken (Wu et al. 2018), which is conducive to further weathering and denudation. Therefore, weathering can also be a vital hydrogeologic procedure because it can occur at greater depths and enhance the permeability of bedrock aquifers, which can improve weathered bedrock aquifer water yield property. Weathered bedrock aquifer water yield property can be quantitatively evaluated by pumping test specific yield q of hydrological holes. However, it is impossible to partition weathered bedrock water yield property spatial variation accurately because of the limited number of hydrological observation holes.

The paper takes the Jinjitan coal mine in the Jurassic coalfield of Northern Shaanxi Province as an example; the development characteristics and water yield property of bedrock weathered zone are summarized based on the analysis of borehole data. A mathematical model is established to predict weathered bedrock aquifer water yield property by borehole data without pumping test, which provides a new feasible method.

General situations of the study area

The Jinjitan coal mine is located in the southeast margin of Mu Us Desert geographically, which belongs to Yuyang district of

Yulin City, Shaanxi Province, China, on the level of administrative regions. It is convenient in the traffic of highway, railway, and air transportation with surrounding areas as shown in Fig. 1.

The terrain is relatively flat on a regional scale, which has a natural ground elevation range from + 1181 to + 1275 m. Most of the area is covered by Aeolian sand, which is a typical Aeolian dune and beach wetland landform. Aeolian sand is dominated by sand fixation with high vegetation coverage. Beach wetlands are distributed discontinuously with closed irregular shapes; its water level is shallow, generally about 2.0 m. The surface water system contains two rivers, Erdaohe and Sandaohe, mainly in the well field; the two rivers are short, so there is no obvious watershed (Fig. 2). Temperature ranges from $- 32.7$ to $+ 39.0$ °C with an annual average temperature of 9.3 °C over the years. Annual average precipitation is 406.2 mm, which is unequally distributed and mainly concentrated from July to September.

Geological survey

Stratigraphic division of the study area belongs to North China stratigraphic region Ordos Basin subregion. Most of the surface is covered by Quaternary sediments. There are small pieces of bedrock scattered around the Wanji Xiaotan and Sandaohe. After drilling exposure, strata from top to bottom consist of Holocene Aeolian Sand (Q_4^{col}), Upper Pleistocene Salawusu Formation (Q_{3s}), Quaternary Middle Pleistocene Lishi Formation (Q_{21}), Neocene Upper Miocene Baode Formation (N_{2b}), Middle Jurassic Anding Formation (J_{2a}), Zhiluo Formation (J_{2z}), and Yanan Formation (J_{2y}) (Fig. 3a, b). Characteristics of each aquifer are presented in Table 1.

Key aquifers of Lishi loess (Q_{21}) and Baode laterite (N_{2b}) develop widely above unweathered bedrock of the Jinjitan coal mine. It is very important to protect surface phreatic water which plays a key role in surface vegetation coverage (Yang et al. 2018), and it is also an important barrier to ensure coal mine safe production at the same time. While within the Jinjitan minefield, since Baode laterite (N_{2b}) has been weathered and pinched out and disappeared under the influence of nature and geology, Baode laterite (N_{2b}) distributes discontinuously and mainly develops in the west and southeast of the minefield. N_{2b} distributed in most areas of the minefield is absent or thin, which is in the range from 0 to 49.45 m with an average value of 13.20 m (Fig. 4). Therefore, the exploitation of coal seam causes a lack of an important aquifer which is a typical sand base engineering geologic condition. Baode laterite (N_{2b}) generally consists of light red, brown-red clay and mild clay, and irregular calcareous concretion layer. Because of its compact structure and undeveloped fissures, Baode laterite (N_{2b}) aquifer has poor water yield property, which has weak hydraulic conductivity in the range from

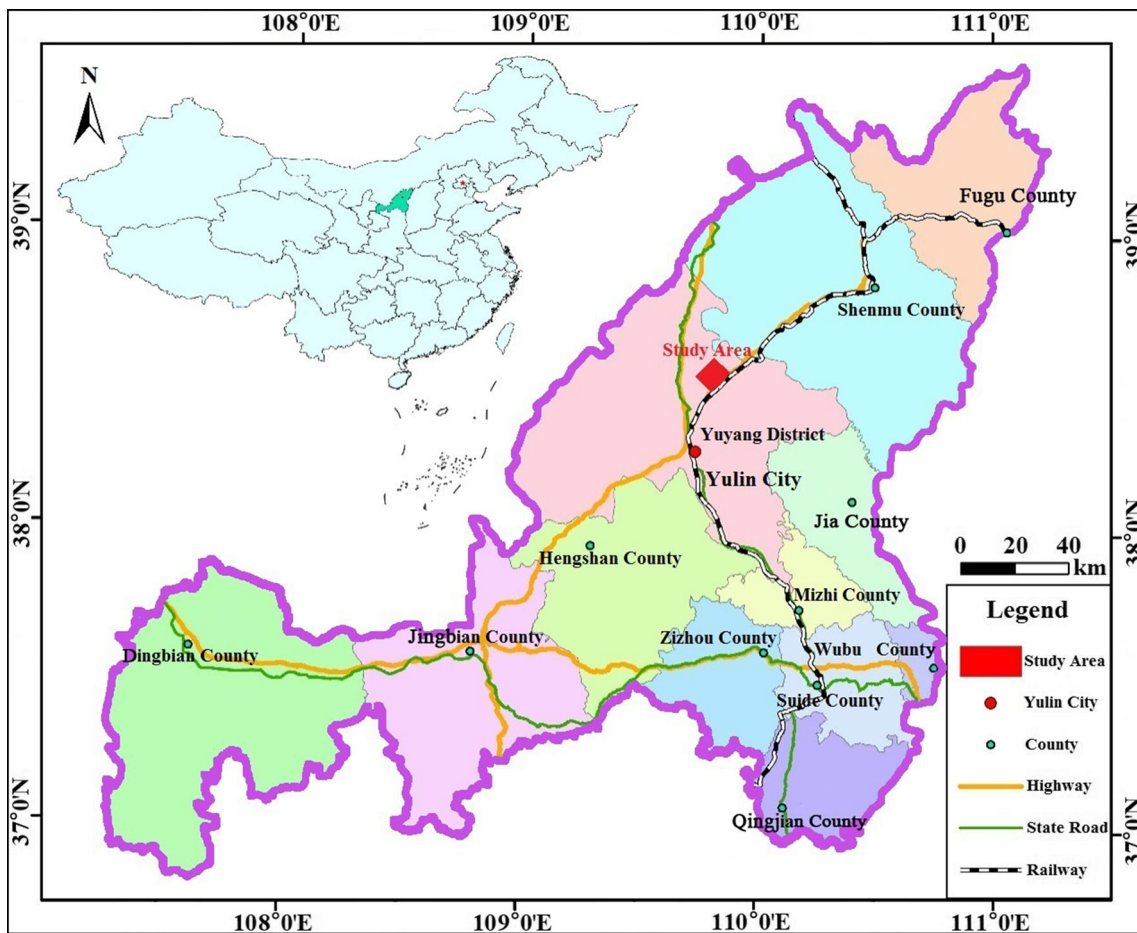


Fig. 1 Position and transportation map of the study area

0.0016 to 0.00248 m/day with an average value of 0.00203 m/day. Lishi loess(Q₂₁) generally consists of light brown-yellow and brown-yellow mild clay, mild sandy soil, thin brown paleosol, calcareous concretions layer, and gravel beds at the bottom. The loess (Q₂₁) of the minefield is complex and diverse with obviously varied thickness and punctuated or discontinuous sheet distributions (Fig.5); the thickness is relatively large in the west and southeast of the minefield; the central part is relatively thin, which is in range from 0 to 50.54 m with an average value of 20.02 m. In the loess layer, vertical fractures are more developed and vertical permeability is better; its hydraulic conductivity is in the range from 0.0137 to 0.0613 m/day with an average value of 0.0386 m/d, which has some water-resisting ability. Due to the lack of Baode laterite(N_{2b}) in some areas, Quaternary phreatic water connects with water in bedrock weathered zone closely, which is an important factor of coal mine water hazard in coal production. Therefore, weathered bedrock fissure confined aquifer is treated as a major source of mine water hazard.

The Jinjitan minefield has the advantages of simple structure, flat stratum, an angle less than 1° trend overall and the NW dipping monocline structure only with some small wide, gentle undulations, and a high angle normal fault F1, Q which

is located in the Ordos syncline east wing, North Shaanxi slope (Fig. 6).

Bedrock weathered zone characteristics

Lithologic characteristics and mineral composition

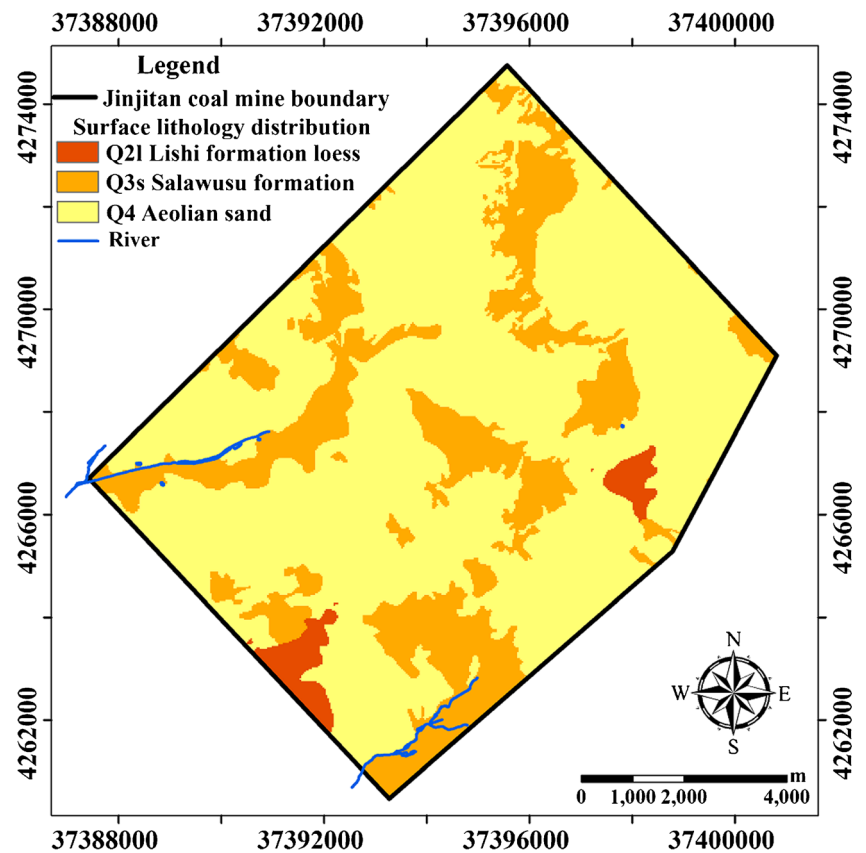
Jinjitan minefield weathered strata is Middle Jurassic. Weathered bedrock lithology contains mottled siltstone, mudstone, and sandstone mainly and its lithologic characteristics are described as follows.

Siltstone, its color is grayish green mainly and partly brownish red. Mineral composition is mainly quartz and feldspar containing a small amount of mica and dark mineral.

Mudstone, its color is grayish green, reseda mainly and partly tan. The main types of its clay minerals are kaolinite and illite.

Sandstone, its color is grayish green, grayish yellow mainly, and partly fuchsia, brownish red. The main types of its minerals are feldspar and quartz mainly containing dark minerals and mica fragments.

Fig. 2 Surface lithology distribution map of the study area



Weathered bedrock development characteristics

Jinjitan mine field bedrock weathered zone is developed at the top of Jurassic Formation, under Neocene Upper Miocene Baode Formation (N_{2b}) laterite aquifuge. By analyzing the data of 61 boreholes, weathered bedrock has the following development distribution characteristics:

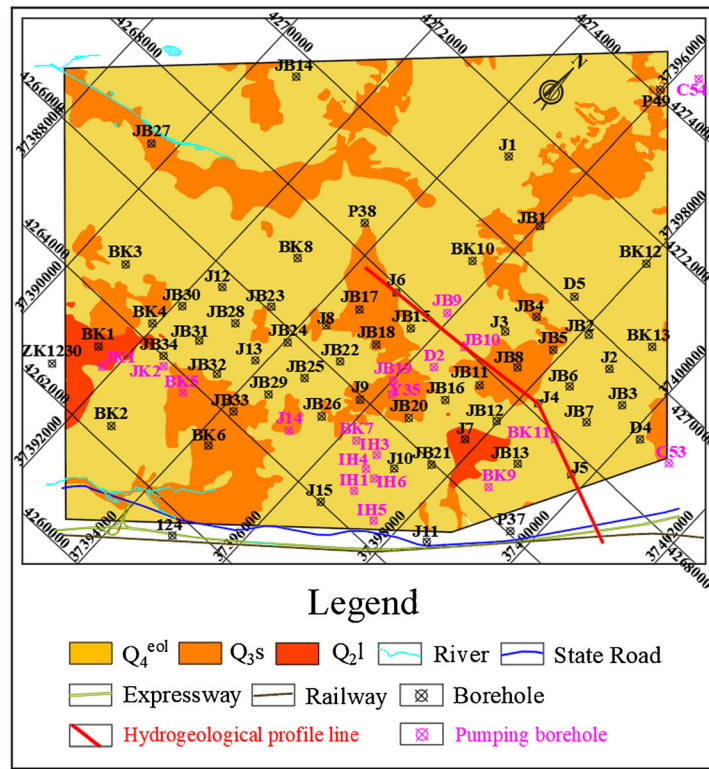
1. According to macroscopic rock features, bedrock weathered zone can be divided into 3 types: strongly weathered zone, moderately weathered zone, and weakly weathered zone (Table 2).
2. Weathered bedrock formation is different, which shows a trend of a new stratum to an old one from northwest to southeast. In the northwest of the minefield, weathered strata are mainly Middle Jurassic Anding Formation (J_{2a}). In the central region, Middle Jurassic Anding Formation (J_{2a}) and Zhiluo Formation (J_{2z}) are both weathered. Continuing to extend to the southeast, Anding Formation is worn away so that there is a lack of Anding Formation with only sandstone and mudstone weathered products of Zhiluo Formation remaining (Fig. 7).
3. Weathered bedrock zone is generally developed in the whole minefield (Fig. 8). Thickness of bedrock weathered zone is in the range from 5.68 to 81.6 m, which is

relatively large in central part of the minefield. The thickness of bedrock weathered zone in northwestern region develops worse than that in the southeastern region. The rock structures of the weathered zone are with features of disordered, soft, friable, increased porosity, enhanced rock permeability, and obvious joint fissures.

Compared with Fig. 9, because undulating paleotopography seriously affects the thickness of the weathered zone, there is a certain correlation between thickness and paleotopography that the higher the paleotopography, the higher the thickness of bedrock weathered zone broadly (Chai and Li 2014; Chapela Lara et al. 2017).

Formation mechanism

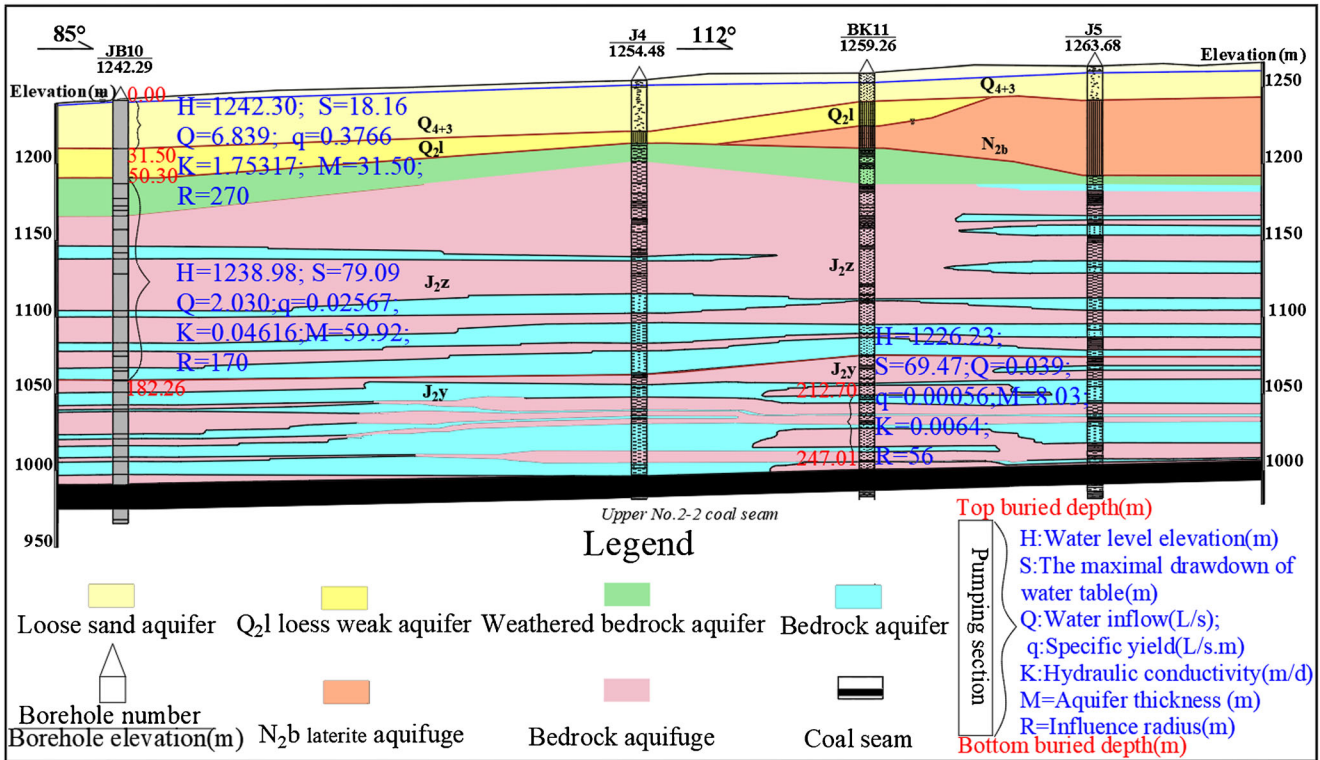
The location of Jinjitan coal mine is in the northeastern edge of the Ordos basin. Since the late Cretaceous, it has entered a period of late reformation; the basin is lifted upward as a whole; eastern edge formations of basin is tilted upwards so that the bedrock formed during the Jurassic and Cretaceous periods was exposed to the surface of the Earth for a long time (Wang et al. 2005; Liu et al. 2006). The upper Jurassic was subjected to weathering and denudation gravely so that Anding Formation and Zhiluo Formation were missed in



Legend

- Q_4^{eol}
- Q_3s
- Q_2l
- River
- State Road
- Expressway
- Railway
- Borehole
- Pumping borehole
- Hydrogeological profile line

(a)



Legend

- Loose sand aquifer
- Q_2l loess weak aquifer
- Weathered bedrock aquifer
- Bedrock aquifer
- N_2b laterite aquifuge
- Bedrock aquifuge
- Coal seam
- Borehole number
- Borehole elevation(m)

- Top buried depth(m)
- H: Water level elevation(m)
- S: The maximal drawdown of water table(m)
- Q: Water inflow(L/s);
- q: Specific yield(L/s.m)
- K: Hydraulic conductivity(m/d)
- M= Aquifer thickness (m)
- R= Influence radius(m)
- Bottom buried depth(m)

(b)

Fig. 3 Hydrogeological profile map of Jinjitan minefield (a)Hydrogeological profile line location of Jinjitan minefield (b)Hydrogeological profile and aquifer correlated parameters

Table 1 Feature list of all the aquifers

Aquifer group	Quaternary aquifer group	The No.2-2 and upper the No.2-2 coal seam roof sandstone aquifers group		
Aquifer	Salawusu Formation pore-phreatic aquifer	Weathered bedrock fissure confined aquifer	Zhiluo Formation pore fissure confined aquifer	Yanan Formation pore fissure confined aquifer
Average thickness (m)	19.88	25	46.54	35.74
Water level elevation (m)	1194.18–1260.6	1227.20–1231.91	1231.05–1267.64	1169.85–1229.29
Specific yield (L/s m)	0.104–1.112	0.0439–0.381	0.0204–0.0232	0.00056–0.00884
Average hydraulic conductivity (m/day)	2.78293	0.3506	0.0537	0.0072
Hydraulic property	Phreatic water	Confined water		
Pumping borehole	Y35,D2,C53,C54,JB10,J14, IH1,IH4	BK7,IH6, JKY1,JKY2	JB10,BK9,IH5	JB19,BK5,IH3, BK11

some areas; until late Miocene, the whole region accepted Baode Formation (N_{2b}) sediments. During this period, paleotopography was generally low in the east and high in the west. Anding Formation in the northwest was strongly weathered, the eastern Anding Formation was denuded absolutely, and Zhiluo Formation was weathered strongly.

Main control factors

Because of the long-term weathering and denudation, a large number of fractures are developed in the bedrock weathered

zone, which provides a good space for groundwater storage. Bedrock weathered zone pore fissure confined aquifer continuously distributed in the minefield, its average thickness is about 25 m. According to pumping test data, its water depth is 2.58~12.27 m, specific yield $q = 0.0439\sim 0.381$ L/(s m), hydraulic conductivity $K = 0.0253\sim 1.259$ m/day. However, Zhiluo Formation pore fissure confined aquifer, underlying freshly unweathered bedrock of Jurassic, has a q value range of 0.0176~0.0232 L/(s m) in specific yield and $K = 0.0388\sim 0.0762$ m/day in hydraulic conductivity, which are lower than specific yield of bedrock weathered zone. It is shown that there is little hydraulic connection between

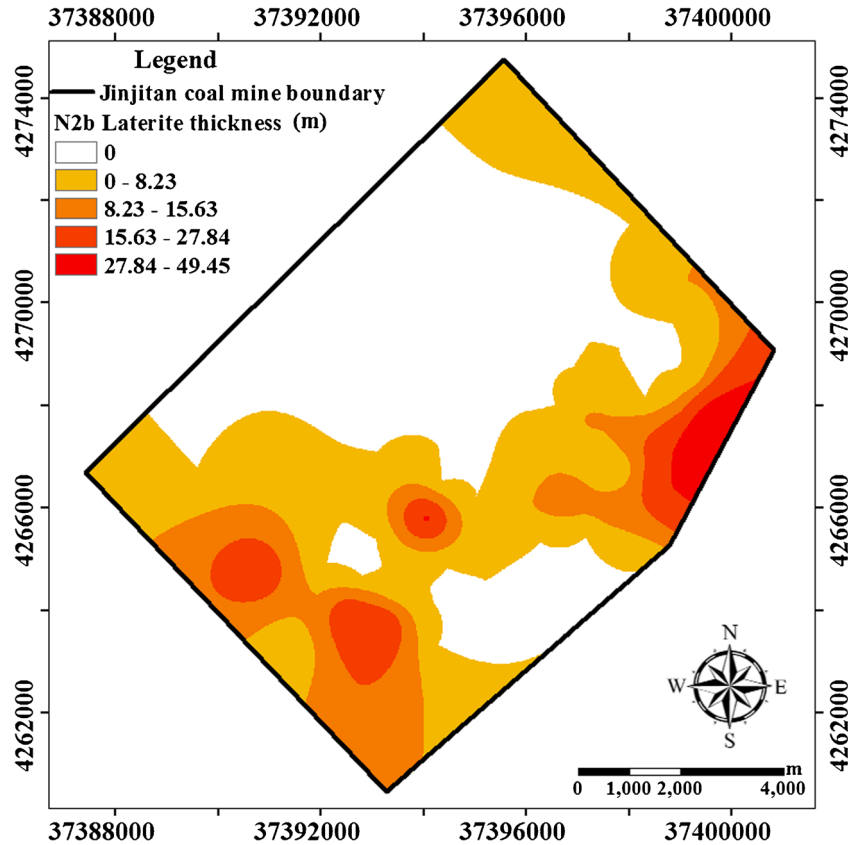
Fig. 4 N_{2b} laterite thickness

Fig. 5 Q₂₁ loess thickness

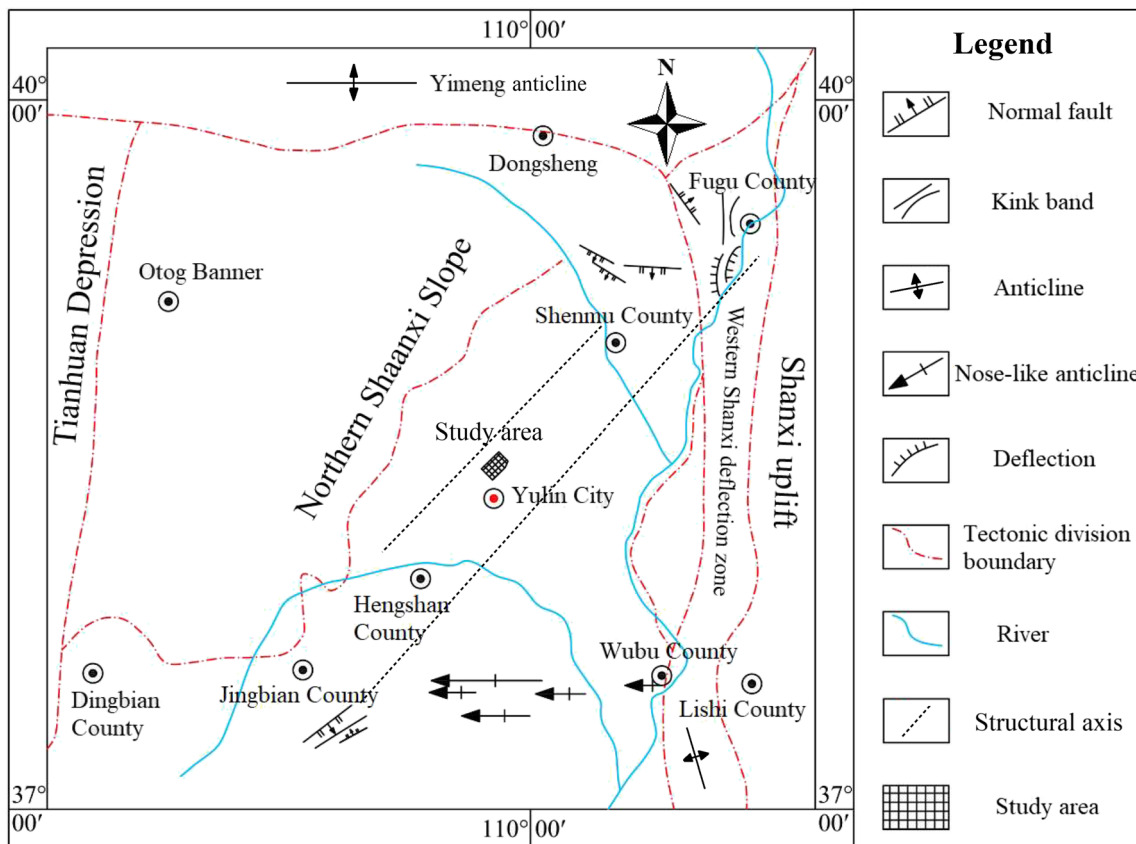
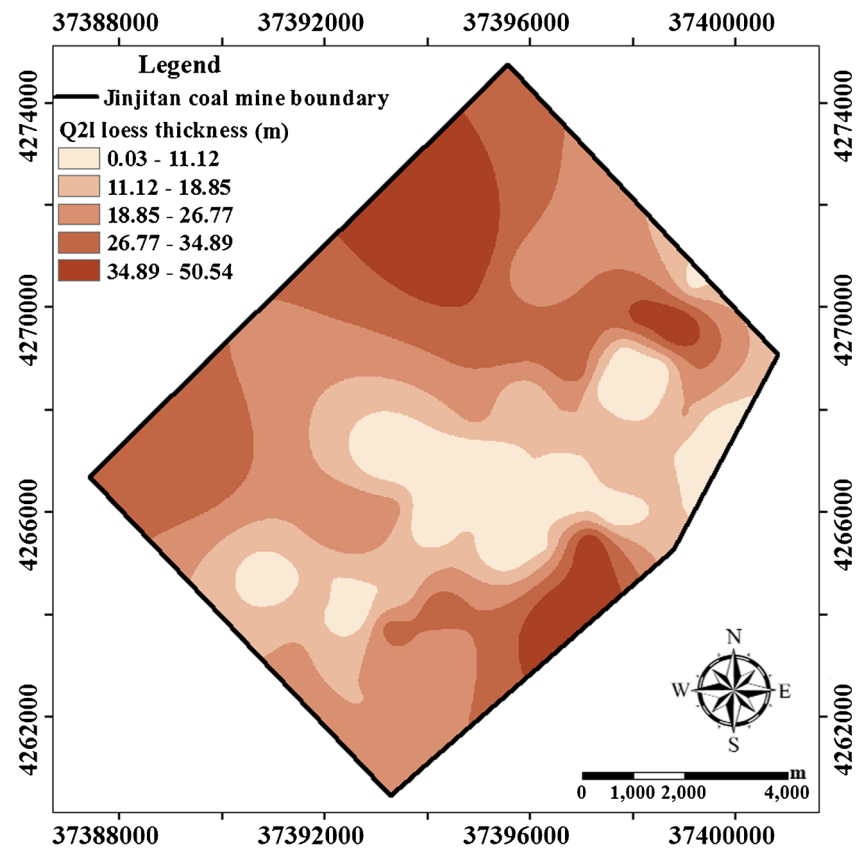


Fig. 6 Structure compendium sketch map of the study area

Table 2 Jinjitan mine field bedrock weathered zone properties

Type	Color	Structure condition
Strongly weathered zone	Mainly grayish green	Badly damaged, loose, and fractured well developed
Moderately weathered zone	Mainly grayish yellow and kelly containing partly reddish brown	Moderately damaged, medium fractured developed with obvious calcareous and pelitic cementation
Weakly weathered zone	Mainly gray and grayish white containing some grayish green and reddish brown	Weakly damaged, a small amount weathered fissures, relatively unabridged rock structure containing some thin beds of layered

bedrock weathered zone and underlying freshly unweathered bedrock. Therefore, after analysis and comparison of weathered bedrock pumping data, bedrock weathered zone pore fissure confined aquifer water yield property is affected by characteristics of overlying aquifer, weathered bedrock formation age, lithologic composition feature, weathering degree, and thickness, 5 factors.

Characteristics of overlying aquifer

Quaternary Upper Pleistocene Salawusu Formation pore phreatic aquifer is above bedrock weathered zone pore-fissure confined aquifer. According to borehole data, the accumulated thickness of Quaternary Upper Pleistocene Salawusu Formation pore phreatic aquifer is generally 10 to 30 m, and

the maximum thickness is 62.82 m. The structure is loose, and the topography and geomorphology are easy to accept atmospheric precipitation recharge. Because of hydraulic connection with bedrock weathered zone, it will affect bedrock weathered zone water yield property. In Fig. 10, the Salawusu Formation pore phreatic aquifer water level shows a gradual decrease trend from the northeast to the southwest; it means pore phreatic water runoff from the northeast to the Southwest, which has the same trend as topographical change in the Jinjitan minefield (Fig 11).

The traditional hydrogeological analysis method is used to describe aquifer water yield property feature by using borehole specific yield (Gao et al. 2018). Specific yield refers to a single borehole water yield that water level draw-down is converted to 1 m when the borehole is pumped

Fig. 7 Lithologic distribution map of weathered bedrock zone

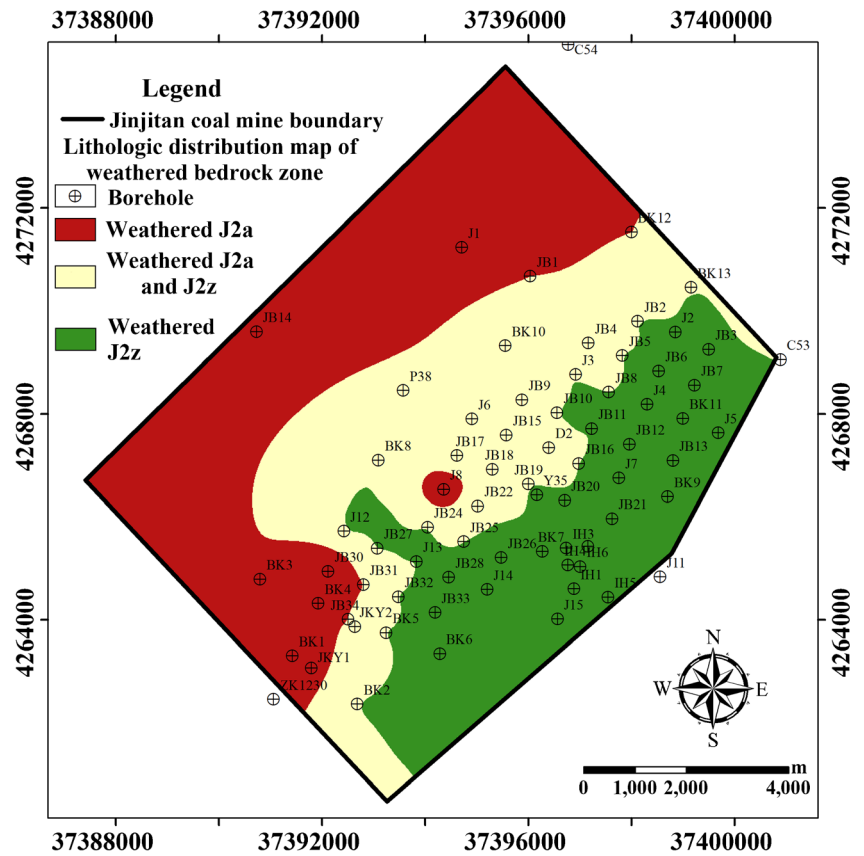


Fig. 8 Thickness of bedrock weathered zone

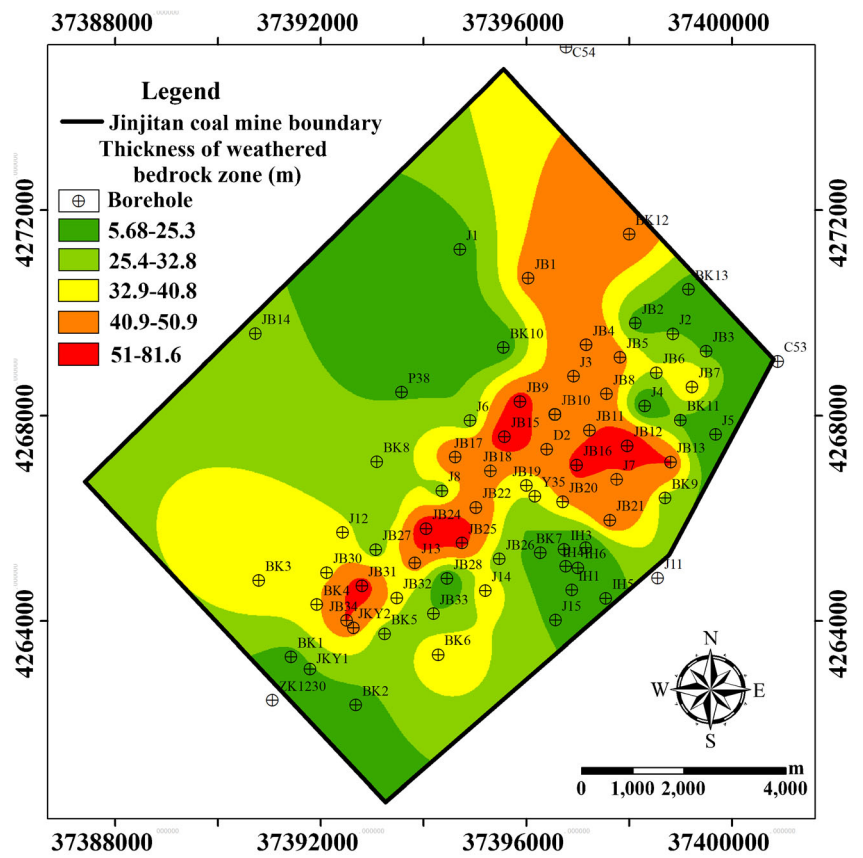
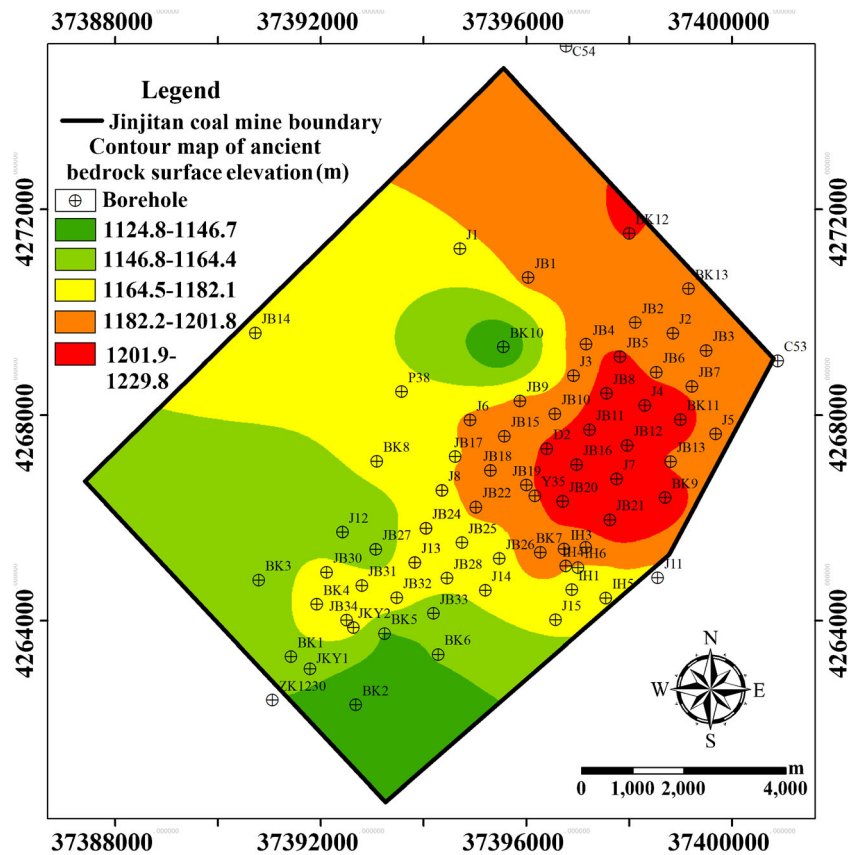


Fig. 9 Contour map of ancient bedrock surface elevation

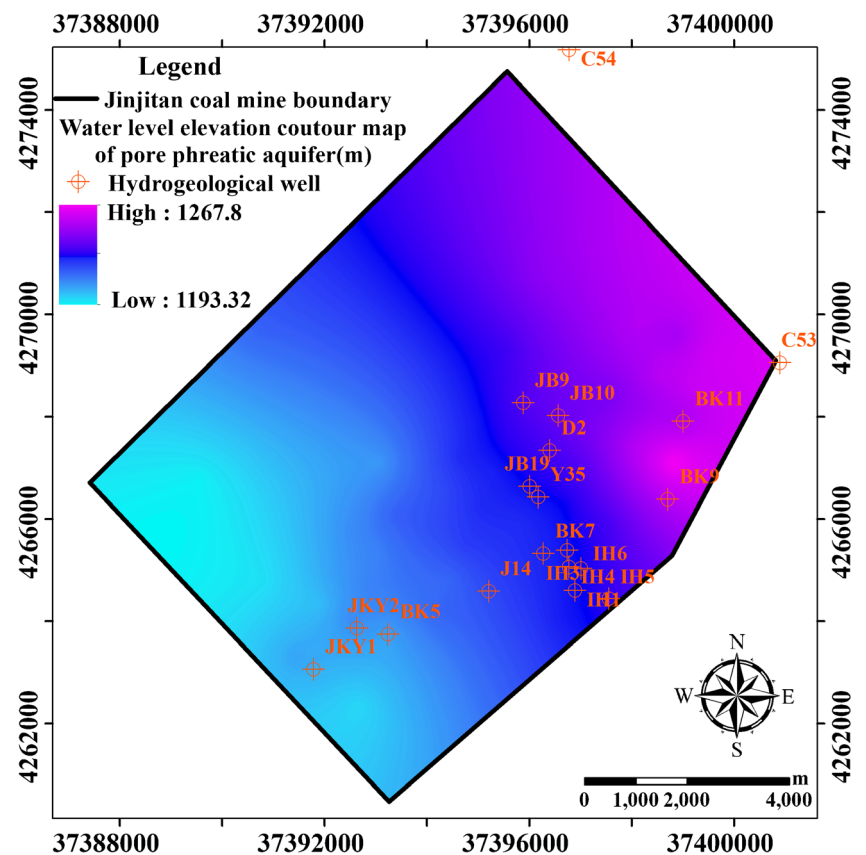


water, which is a parameter reflecting aquifer water yield property. The greater its value means the stronger aquifer water yield property. The structure of the hydrogeological borehole is shown in Fig. 12. Drilling into the bottom of the Salawusu Formation, the borehole diameter was expanded to 450 mm; a screenpipe with a diameter of 273 mm is installed in the borehole. Pumping test borehole was washed to make water clean in pumping test borehole with a deep water pump. Then, the pumping test was carried out. Hydrotasimeter was used to observe water level; a triangle weir was used for flow observation. Therefore, the pumping test result is shown in Fig. 13 and Table 3; specific yield of Quaternary Upper Pleistocene Salawusu Formation pore phreatic aquifer is relatively larger in the central area of the coal mine, which shows relative stronger water yield property (He et al. 2018).

Weathered bedrock strata age

Anding Formation and Zhiluo Formation of the minefield are weathered in varying degrees. The weathering state of weathered rock is generally strong, medium, and weak and changing to freshly unweathered bedrock from shallow to deep strata. Distribution characteristics of weathered rock formations are shown in Fig. 7.

Fig. 10 Water level elevation of pore phreatic aquifer



Lithologic composition feature

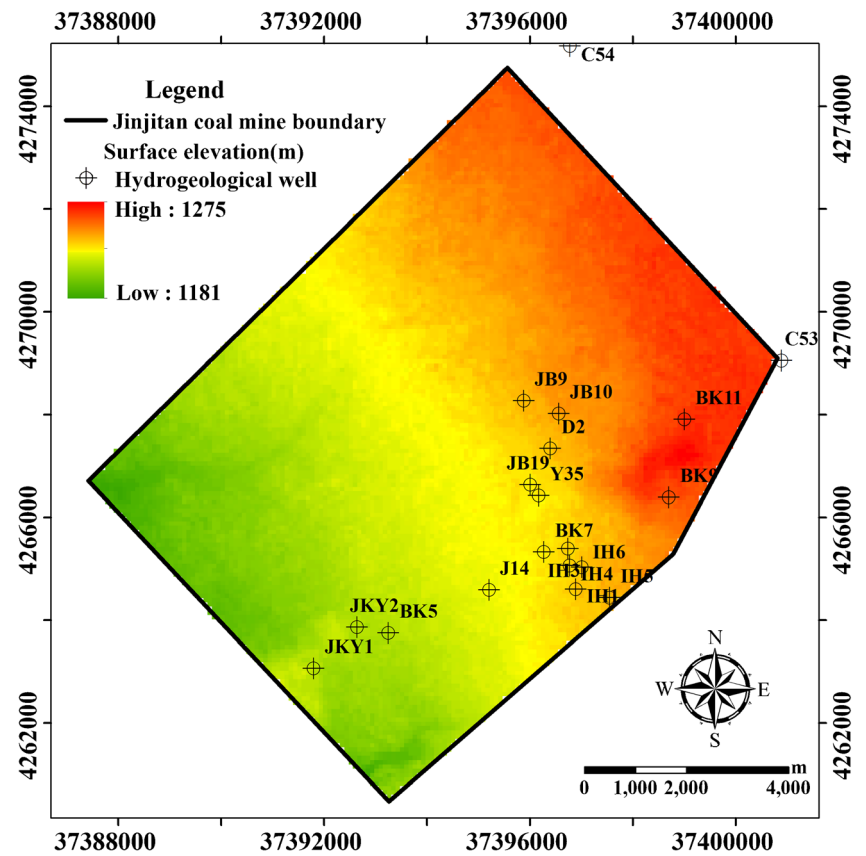
There are obvious differences in the water yield property characteristics of bedrock weathered zone due to different lithology of aquifer media. Because of different mineral and lithological composition in different rock strata, the development of pore and fissure in rock strata is different; the rock particles are thicker; the development of pore and fissure is better in rock (Moyé et al. 2017). Therefore, the water yield property is different in rock strata with different particle composition. Bedrock weathered zone is composed of mudstone and sandstone with different particle sizes. Firstly, different lithologic properties are assigned to different values according to the relation between lithology and water yield property or contribution of lithology to water yield property (Table 4). Secondly, establishment of lithologic composition coefficient r is used to describe water yield property of different lithological composition, the greater r means stronger water yield property (Li et al. 2018).

$$r = \frac{\sum r_i h_i}{\sum h_i} \quad (1)$$

where r_i is each lithologic assignment; h_i is each lithologic thickness.

After calculating the lithological composition coefficient, a thematic map is established according to calculations (Fig.

Fig. 11 Surface elevation



14). It shows that the largest lithological combination coefficient area lies in the northeast part of the minefield and distributes unevenly. It shows an increasing trend of lithological composition coefficient gradually from northwest to southeast.

Weathering intensity of bedrock

Bedrock structure suffered weathering strongly and is destroyed, loose, broken, and with large porosity and high water content ratio. The stronger weathered bedrock means the more fractured rock mass structure and the better developed fissure. The fissures are mainly developed in the vertical direction (Zeng et al. 2018). Because of the paleoclimate of arid, low rainfall, and large temperature difference in the Ordos basin, it is very beneficial for the vertical development of fractures in weathered bedrock. It provides a good spatial foundation for groundwater storage. Therefore, different weathering degrees imply differences in water yield property. For lithological composition, weathering intensity of different lithology is not the same necessarily. Weathering coefficient w is used to describe weathering intensity of bedrock. The greater w means stronger weathering intensity (Hou et al. 2016).

$$w = \sum w_i h_i / \sum h_i \tag{2}$$

where w_i is weathering intensity of lithology; h_i is each lithologic thickness.

According to borehole lithology description, weathering intensity is divided into three categories: strong, medium, and weak and assigned respectively (Table 5).

As the thematic map in Fig. 15 shows, in the western and northeastern part of the minefield, weathering intensity of

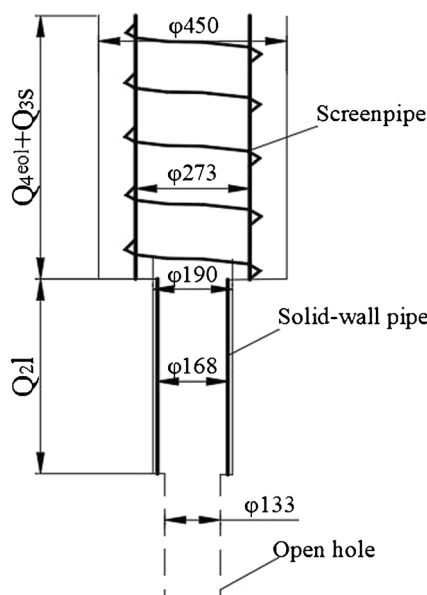
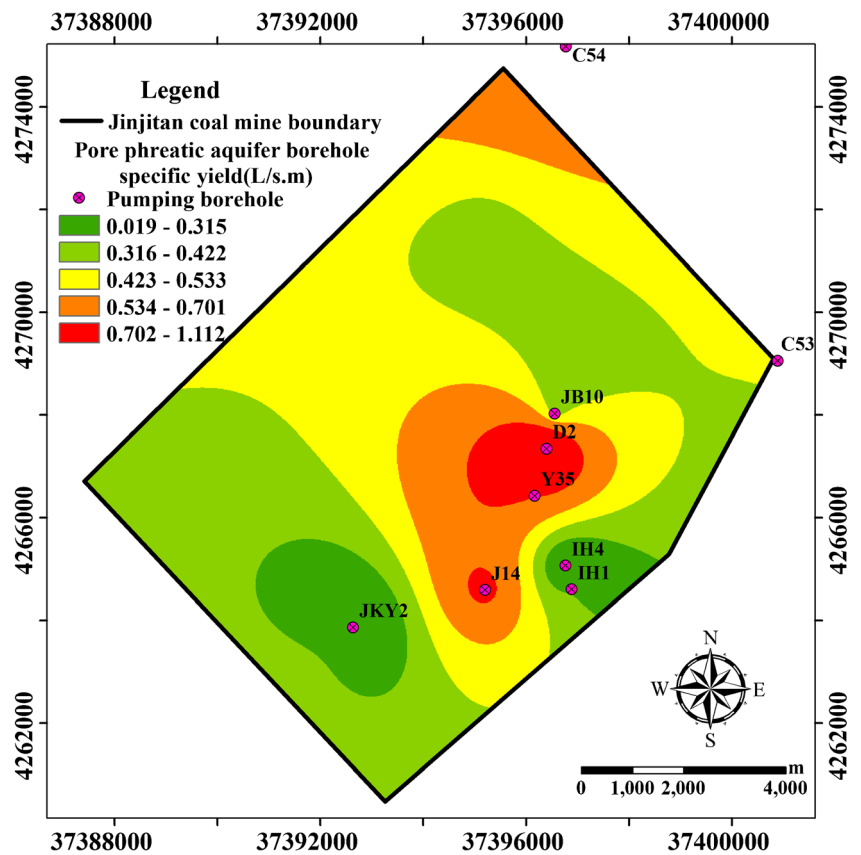


Fig. 12 Structure of the hydrogeological borehole

Fig. 13 Specific yield of pore phreatic aquifer



bedrock is relatively strong, and weathering intensity of bedrock is relatively weak in the central and southeast.

Weathered bedrock zone thickness

Bedrock experiences weathering, weathering fractures are often further developed on the basis of diagenetic fissures and structural fractures to generate fracture network which is dense, uniform, without obvious direction, and good connectivity. The larger the bedrock weathered zone thickness, the more development of the fracture network. A well-developed

fracture network provides abundant storage space for groundwater occurrence. Therefore, it is one of the important control factors that affect the water yield property of bedrock weathered zone. Bedrock weathered zone thickness thematic map is established (Fig. 8).

Evaluation process

Because several boreholes, including BK7, IH6, JKY1, and JKY2, have been subjected to weathered zone

Table 3 Pumping test results of Salawusu Formation pore phreatic aquifer

Borehole	Aquifer	Groundwater level depth (m)	Aquifer thickness (m)	Average specific yield (L/s m)	Average hydraulic conductivity (m/day)	Average influence radius (m)
Y35	Q _{3s}	0.8	29.5	0.70822	2.64617	112.73
D2	Q _{3s}	0.9	15.5	1.11251	8.3274	151.1
J14	Q _{3s}	2.06	31.85	0.77756	2.63818	151.31
IH1	Q _{3s}	3.7	10.9	0.30432	3.44363	88.22
IH4	Q _{3s}	3.29	5.26	0.10378	3.2017	45.63
JB10	Q _{3s}	0.64	31.5	0.43684	1.66439	177.33
C53	Q _{3s}	0.51	71.55	0.43468	0.70852	178.31
C54	Q _{3s}	0.43	39.44	0.81345	2.1977	145.81
JKY2	Q _{3s}	3.98	8.37	0.016303	0.357412	26.91

Table 4 Assignment on lithology of weathered bedrock

Lithology	Assignment	Lithology	Assignment
Mudstone	1	Fine-grained sandstone	3
Sandy mudstone	1.5	Medium-grained sandstone	4
Siltstone	2	Coarse-grained sandstone	5

pumping test, the specific yield q obtained from the pumping test is very scarce and it is not sufficient to describe bedrock weathered zone water yield property as a whole, which makes it difficult to prevent and control water hazard of bedrock weathered zone. It is necessary to explore a method to evaluate water yield property of weathered bedrock under the condition of lacking specific yield.

Fuzzy Delphi analytic hierarchy process method

The fuzzy Delphi analytic hierarchy process method is a kind of fuzzy group decision-making method which integrates fuzzy mathematics appraisal, analytic hierarchy process, and the Delphi group decision method together (Feng 2006; Hoseinie et al. 2009; Cai and Cheng 2012; Wu et al. 2017). Its basic steps are as follows:

Establishing a hierarchical structure model based on the analytic hierarchy process method

Assuming that there are m evaluation indicators to be considered, the purpose is to determine the weight of these m indicators on the decision criteria.

Constructing comparison judgment matrixes

Identify the relative importance degree judgment value $B_{ij,k}$ between i and j factors which is determined by expert k under a certain rule based on traditional Delphi method. Setting up the judgment matrix $B(k) = [B_{ij,k}]$.

Group fuzzy judgment matrix

The advice of experts is integrated by using triangular fuzzy numbers to establish a relatively objective fuzzy group

Fig. 14 Contour map of lithological composition coefficient

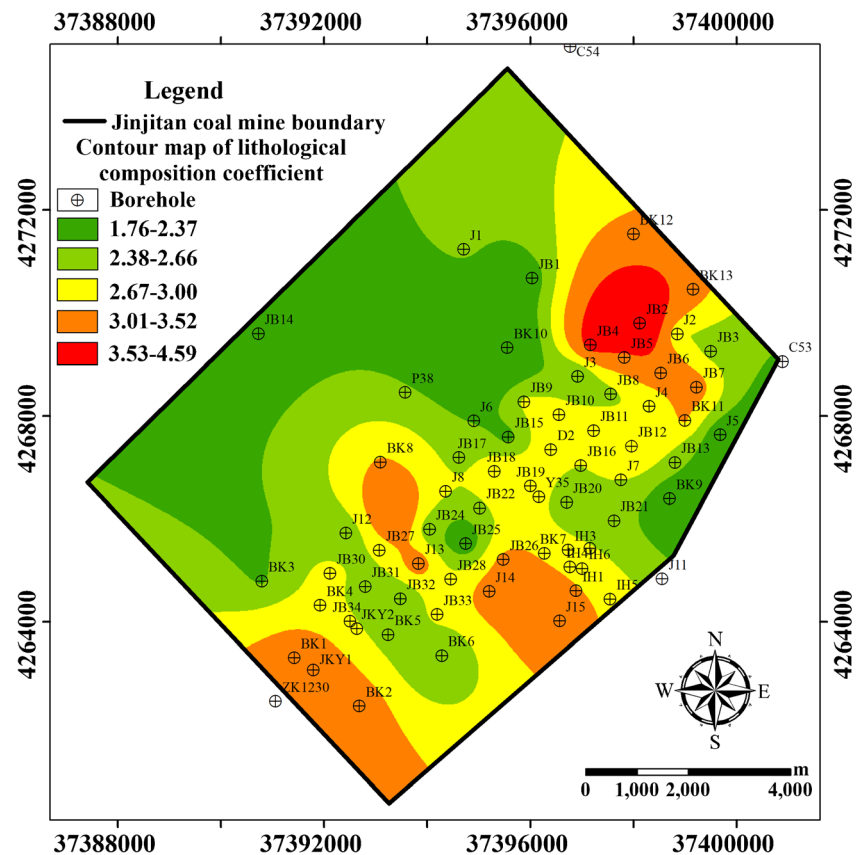


Table 5 Assignment on bedrock weathering intensity

Weathering intensity	Strong weathering	Medium weathering	Weak weathering
Assignment	3	2	1

judgment matrix on the basis of the decision-maker’s subjective opinion. The fuzzy group judgment matrix is expressed as follows:

$$B_{ij} = [\alpha_{ij}, \beta_{ij}, \gamma_{ij}] \tag{3}$$

where B_{ij} are triangular fuzzy numbers, which consists of 3 elements, α_{ij} , β_{ij} , and γ_{ij} , and $\alpha_{ij} \leq \beta_{ij} \leq \gamma_{ij}$; in addition, $\alpha_{ij}, \beta_{ij}, \gamma_{ij} \in [1/9, 1] \cup [1, 9]$.

$$\alpha_{ij} = \min(B_{ij.k}), k = 1, 2, \dots, n \tag{4}$$

$$\beta_{ij} = \text{geomean}(B_{ij.k}), k = 1, 2, \dots, n \tag{5}$$

$$\gamma_{ij} = \max(B_{ij.k}), k = 1, 2, \dots, n \tag{6}$$

where n is the number of score experts and cases in total; $B_{ij.k}$ indicates the relative intensity of importance degree judgment value between factors i and j of expert k ; $\min(B_{ij.k})$ is the minimum value of all expert scoring results; $\max(B_{ij.k})$ is maximum value of all expert scoring results; $\text{geomean}(B_{ij.k})$ is geometric mean of all expert scoring results.

The geometric mean is calculated as follows:

$$\text{geomean}(a_1, a_2, \dots, a_n) = (a_1 \times a_2 \times \dots \times a_n)^{\frac{1}{n}} \tag{7}$$

Determine group fuzzy weight vector

Calculating vector for any evaluation index i ($i = 1, 2, \dots, n$):

$$r_i = (B_{i1} \otimes B_{i2} \otimes \dots \otimes B_{im})^{\frac{1}{m}} \tag{8}$$

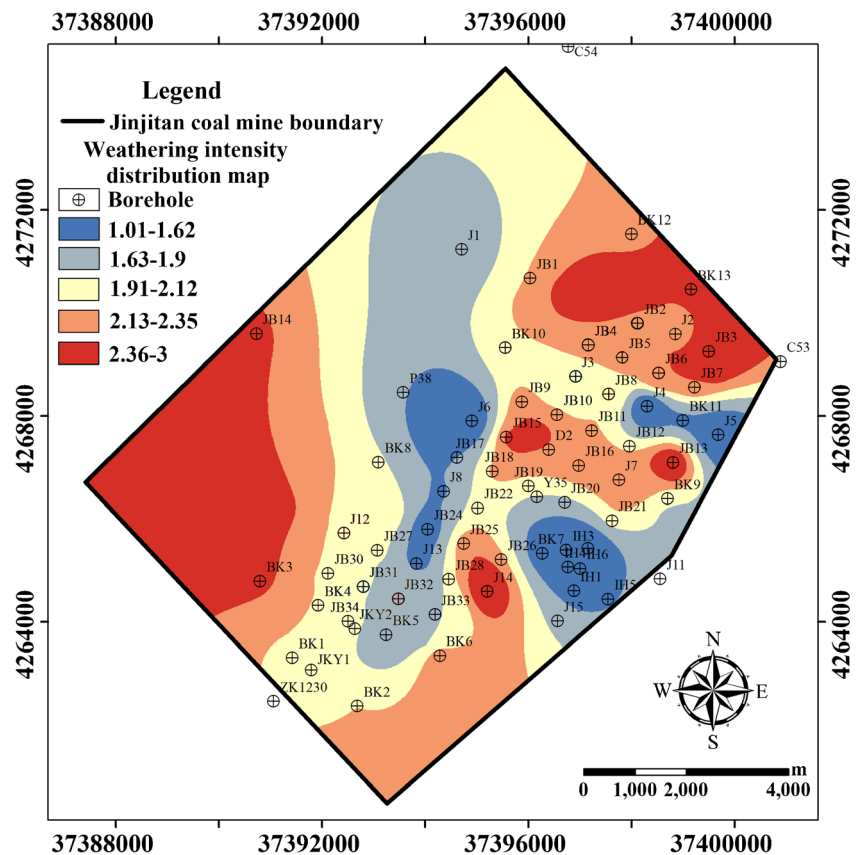
where r_i is the multiplication relation of triangular fuzzy numbers. Furthermore, calculating group fuzzy weight vector:

$$w_i = r_i \otimes (r_1 \oplus r_2 \oplus \dots \oplus r_m)^{-1} \tag{9}$$

where w_i is the addition operation of triangular fuzzy numbers.

Triangular fuzzy numbers that are mentioned above are calculated as follows: let $a = [a_1, a_2, a_3]$ and $b = [b_1, b_2, b_3]$ are

Fig. 15 Weathering intensity distribution map



two positive triangular fuzzy numbers. According to triangular fuzzy number theory:

$$a \oplus b = [a_1 + b_1, a_2 + b_2, a_3 + b_3] \tag{10}$$

$$a \otimes b = [a_1 \times b_1, a_2 \times b_2, a_3 \times b_3] \tag{11}$$

$$a^{-1} = \left[\frac{1}{a_3}, \frac{1}{a_2}, \frac{1}{a_1} \right] \tag{12}$$

Weight decision analysis

For fuzzy weight vector of each index obtained by calculation:

$$w_i = (w_i^L, w_i^M, w_i^U) \tag{13}$$

Where w_i^L , w_i^M and w_i^U are the minimum, intermediate and maximum of fuzzy weight vector three components.

The relative weights of each evaluation index are calculated by the geometric average method, and then normalized. It is obtained normalized decision weight as follow:

$$W_i = \frac{\sqrt[3]{w_i^L \times w_i^M \times w_i^U}}{\sum_i \sqrt[3]{w_i^L \times w_i^M \times w_i^U}} \tag{14}$$

Because the FDAHP method allows the decision-maker to make irrational judgment, the judgment matrix does not need consistency checking.

Hierarchical model

According to analysis of bedrock weathered zone water yield property main control factors mentioned above, the target layer studied in this paper is weathered zone aquifer water yield property index; the indicator layer includes phreatic aquifer specific yield (F1), weathered bedrock formation age (F2),

Table 6 Rating of main control factors

Expert	F1	F2	F3	F4	F5
Expert1(P1)	4	1	6	8	7
Expert2(P2)	3	2	7	8	8
Expert3(P3)	4	1	7	9	7
Expert4(P4)	3	2	6	7	7
Expert5(P5)	3	2	8	8	8

lithologic composition coefficient(F3), weathering intensity (F4), and bedrock weathered zone thickness (F5), 5 indicators. The weathered bedrock aquifer water yield property evaluation hierarchical model is presented in Fig.16.

Delphi expert survey subjective scoring method

Based on analysis of bedrock weathered zone aquifer main control geological factors, opinions were solicited and consulted from experts and researchers in related fields by the Delphi expert survey method, the relative importance of one element to bedrock weathered zone aquifer water yield property is evaluated according to 1~9 scale method(Golden 2011; Ishizaka and Labib 2011) as Table 6.

Comparison judgment matrix

According to subjective and objective evaluation, the impact degree of assessment indicator is evaluated to compare their relative importance. 5 comparison judgment matrixes combined subjective evaluation with objective evaluation are established based on formula 15.

$$A = [a_{ij}] = \begin{bmatrix} 1 & a_{12} & a_{13} & a_{14} & a_{15} \\ 1/a_{12} & 1 & a_{23} & a_{24} & a_{25} \\ 1/a_{13} & 1/a_{23} & 1 & a_{34} & a_{35} \\ 1/a_{14} & 1/a_{24} & 1/a_{34} & 1 & a_{45} \\ 1/a_{15} & 1/a_{25} & 1/a_{35} & 1/a_{45} & 1 \end{bmatrix} \tag{15}$$

Where $a_{ij} = C_i/C_j$, a_{ij} is the relative importance of factors Fi to Fj; C_i and C_j are scores of Fi and Fj of an expert.

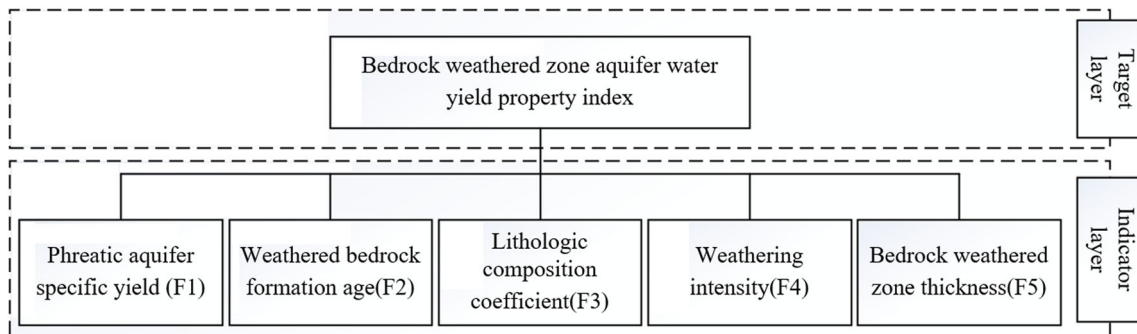


Fig. 16 Hierarchy structure of water yield property evaluation

Group fuzzy judgment matrix

FDAHP method mainly solves the problem of uncertainty and fuzziness that traditional analytic hierarchy process method cannot overcome, which uses triangular fuzzy number to eliminate the fuzziness in decision-making(Hayaty et al. 2014). Group fuzzy judgment matrix of experts is represented based on formula (16).

$$B = [B_1 \ B_2 \ B_3 \ B_4 \ B_5] \tag{16}$$

$$B_1 = \begin{bmatrix} 1 & 1 & 1 \\ 1/\gamma_{12} & 1/\beta_{12} & 1/\alpha_{12} \\ 1/\gamma_{13} & 1/\beta_{13} & 1/\alpha_{13} \\ 1/\gamma_{14} & 1/\beta_{14} & 1/\alpha_{14} \\ 1/\gamma_{15} & 1/\beta_{15} & 1/\alpha_{15} \end{bmatrix} = \begin{bmatrix} 1.000 & 1.000 & 1.000 \\ 0.250 & 0.450 & 0.667 \\ 1.500 & 1.896 & 2.333 \\ 2.000 & 2.369 & 2.667 \\ 1.750 & 2.194 & 2.667 \end{bmatrix} \tag{17}$$

$$B_2 = \begin{bmatrix} \alpha_{12} & \beta_{12} & \gamma_{12} \\ 1 & 1 & 1 \\ 1/\gamma_{23} & 1/\beta_{23} & 1/\alpha_{23} \\ 1/\gamma_{24} & 1/\beta_{24} & 1/\alpha_{24} \\ 1/\gamma_{25} & 1/\beta_{25} & 1/\alpha_{25} \end{bmatrix} = \begin{bmatrix} 1.500 & 2.221 & 4.000 \\ 1.000 & 1.000 & 1.000 \\ 3.000 & 4.210 & 6.000 \\ 4.000 & 5.261 & 8.000 \\ 3.500 & 4.872 & 7.000 \end{bmatrix} \tag{18}$$

$$B_3 = \begin{bmatrix} \alpha_{13} & \beta_{13} & \gamma_{13} \\ \alpha_{23} & \beta_{23} & \gamma_{23} \\ 1 & 1 & 1 \\ 1/\gamma_{34} & 1/\beta_{34} & 1/\alpha_{34} \\ 1/\gamma_{35} & 1/\beta_{35} & 1/\alpha_{35} \end{bmatrix} = \begin{bmatrix} 0.429 & 0.527 & 0.667 \\ 0.375 & 0.422 & 0.500 \\ 1.000 & 1.000 & 1.000 \\ 1.143 & 1.250 & 1.333 \\ 1.000 & 1.157 & 1.333 \end{bmatrix} \tag{19}$$

$$B_4 = \begin{bmatrix} \alpha_{14} & \beta_{14} & \gamma_{14} \\ \alpha_{24} & \beta_{24} & \gamma_{24} \\ \alpha_{34} & \beta_{34} & \gamma_{34} \\ 1 & 1 & 1 \\ 1/\gamma_{45} & 1/\beta_{45} & 1/\alpha_{45} \end{bmatrix} = \begin{bmatrix} 0.375 & 0.456 & 0.571 \\ 0.167 & 0.238 & 0.333 \\ 0.1625 & 0.190 & 0.250 \\ 1.000 & 1.000 & 1.000 \\ 0.778 & 0.926 & 1.000 \end{bmatrix} \tag{20}$$

$$B_5 = \begin{bmatrix} \alpha_{15} & \beta_{15} & \gamma_{15} \\ \alpha_{25} & \beta_{25} & \gamma_{25} \\ \alpha_{35} & \beta_{35} & \gamma_{35} \\ \alpha_{45} & \beta_{45} & \gamma_{45} \\ 1 & 1 & 1 \end{bmatrix} = \begin{bmatrix} 0.143 & 0.205 & 0.286 \\ 0.750 & 0.800 & 0.875 \\ 0.750 & 0.864 & 1.000 \\ 1.000 & 1.080 & 1.286 \\ 1.000 & 1.000 & 1.000 \end{bmatrix} \tag{21}$$

Group fuzzy weight vector

Based on established group fuzzy judgment matrix B, group fuzzy weight vector is obtained through the geometric average method:

$r_1 = [0.510 \ 0.643 \ 0.847]$	$w_1 = [0.109 \ 0.167 \ 0.271]$
$r_2 = [0.411 \ 0.555 \ 0.627]$	$w_2 = [0.088 \ 0.134 \ 0.201]$
$r_3 = [0.841 \ 1.056 \ 1.285]$	$w_3 = [0.181 \ 0.275 \ 0.411]$
$r_4 = [1.557 \ 1.759 \ 2.054]$	$w_4 = [0.334 \ 0.458 \ 0.657]$
$r_5 = [1.366 \ 1.628 \ 1.902]$	$w_5 = [0.293 \ 0.424 \ 0.608]$

Weight determination

The relative weight of each assessment indicator is calculated by the geometric average method, and then normalized weights are obtained: $W_1 = 0.116$, $W_2 = 0.091$, $W_3 = 0.187$, $W_4 = 0.317$, $W_5 = 0.289$.

Data normalization

Because physical meaning of each index is different, the difference in dimension affects evaluation result. In order to eliminate the influence of different geological factor data dimension, it is necessary to normalize the data to make data comparable and statistically significant for system analysis(Jain et al. 2018).

$$A_i = a + (b-a) \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)} \tag{22}$$

Where A_i is normalized data; a, b are lower and upper bounds for normalized range, $a = 0$, $b = 1$; x_i is original data before normalization; $\min(x_i)$ and $\max(x_i)$ are minimum and maximum values of each main control factor.

Fig. 17 Weathered bedrock aquifer water yield property index frequency diagram

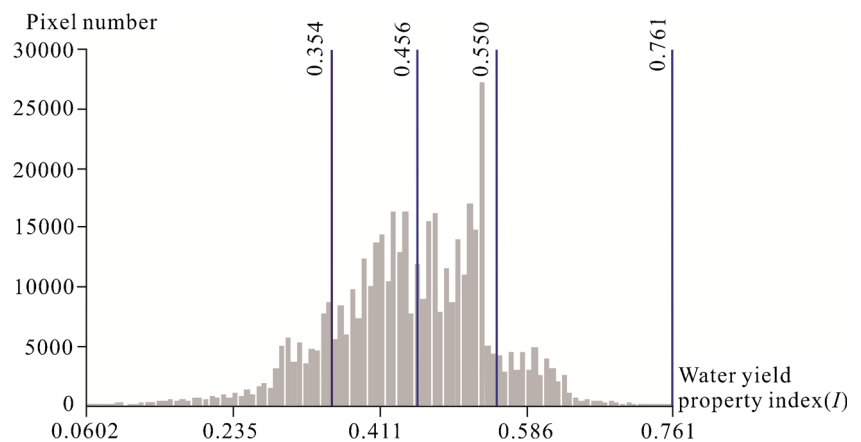


Table 7 Grade standard for aquifer water yield property

Specific yield $q(L/(s\ m))$	Water yield property
$q \leq 0.1$	Weak
$0.1 < q \leq 1$	Medium
$1 < q \leq 5$	Strong
$q > 5$	Extremely strong

Prediction and evaluation of aquifer water yield property

Because water yield property law and distribution of aquifer are controlled by many factors, complexed control mechanism, and various aquifers composed type, it is difficult to describe aquifer water yield property and the relationship among multiple main control factors to determine quantitative mathematical equation and model in time-space domain. However, the influence degree of aquifer water yield property main control factors is different at different coordinate points and under different hydrogeological conditions. Therefore, the control degree of various factors on aquifer water yield property law is different (Wu et al. 2011). In view of the above characteristics, ArcGIS with powerful spatial information analysis and processing function is selected to describe the changing characteristics of main control factors with the spatial domain. And modern information fusion method is selected to quantitatively determine the weight ratio of different main control factor to aquifer water yield property based on some certain known samples. Then the quantitative evaluation model of aquifer water yield property index is obtained by using ArcGIS spatial analysis function by coupling method. According to the analysis of water yield property index distribution frequency histogram, the aquifer water yield property is quantitatively zoned after determining partition threshold.

Normalized thematic maps of main control factors are fused together combining with weight values determined by FDAHP method in ArcGIS. The bedrock weathered zone aquifer water yield property index mathematical model and relative partition map are obtained.

Water yield property index mathematical model is built according to formula (23):

$$I = \sum_{k=1}^m w_k \cdot f_k(x, y) \tag{23}$$

where I is water yield property index; w_k is a main control factor weight; $f_k(x, y)$ is a single factor influence function. Bedrock weathered zone aquifer water yield property index mathematical model in Jinjitan coal mine is shown as follows:

$$I = \sum_{i=1}^5 w_k \cdot f_k(x, y) = 0.116f_1(x, y) + 0.091f_2(x, y) + 0.187f_3(x, y) + 0.317f_4(x, y) + 0.289f_5(x, y)$$

According to weathered bedrock aquifer water yield property index evaluation model, the frequency statistics of water yield property index in Jinjitan coal mine is carried out (Fig. 17).

Therefore, the partition thresholds of water yield property index evaluation model in the Jinjitan coal mine is divided into four grades by using the natural breakpoint classification method.

Zone I	$0.061 \leq I \leq 0.355$	Extremely weak water yield property
Zone II	$0.355 \leq I \leq 0.456$	Weak water yield property
Zone III	$0.456 \leq I \leq 0.550$	Medium water yield property
Zone IV	$0.551 \leq I \leq 0.761$	Strong water yield property

Exploration specification of hydrogeology and engineering geology in mining areas (Qian et al. 2016) stipulates that aquifer water yield property should be classified into 4 levels which are weak, medium, strong, and extremely strong, according to borehole specific yield (Table 7). Specific yield values obtained from only four pumping test holes of bedrock weathered zone in the mine field are shown in Table 8.

Weathered bedrock aquifer water yield property is unevenly distributed; water yield property is stronger with the larger value of water yield property evaluation index. Weathered bedrock aquifer water yield property is weak to medium in the whole, which is mainly related to bedrock weathering intensity. Water yield property is relatively stronger in areas with stronger weathering intensity. Strong water yield

Table 8 Bedrock weathered zone specific yield

Boreholes	X	Y	Specific yield (L/(s m))	Water yield property evaluation index	Water yield property
BK7	37396276.36	4265324.491	0.00417	0.2407	Extremely weak
IH6	37397012.02	4265027.638	0.0439	0.1701	Weak
JKY1	37391797.37	4263058.061	0.381	0.4805	Medium
JKY2	37392641.52	4263858.54	0.032	0.4413	Weak

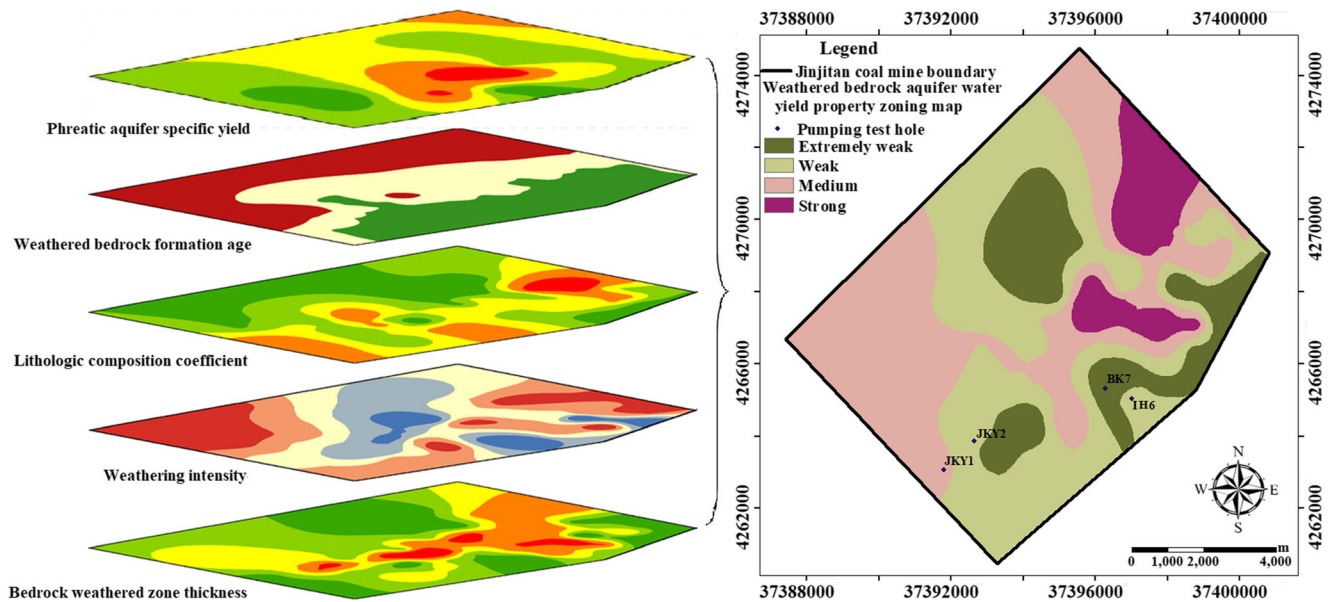


Fig. 18 Relative partition for water yield property evaluation index

property is in the northeastern minefield, and medium water yield property is in the west. The water yield property in the northwest and southeast is relative weak generally.

The position distribution of four boreholes is shown in Fig. 18. Comparing water yield property situation of borehole with the zoning map, the results are consistent. It shows that the threshold of water yield property index is reasonable, which has high accuracy. The partition map can be used as an important basis for preventing and controlling mine water geohazard.

The method which combines the FDAHP method with ArcGIS not only makes full use of a lot of complicated spatial information, uses qualitative and quantitative ways to study geosciences, and analyzes the question nature, but also the evaluation result is more intuitive and accurate than single text description.

Conclusions and Suggestions

- (1) The bedrock weathered zone of the Jurassic coalfield in Northern Shaanxi was formed between the early Cretaceous and the Pliocene epoch, and its water yield property characteristics are generally weak to strong, with great spatial variation. Weathered bedrock aquifer is the main discharge aquifer of coal seam roof in Jinjitan coal mine. On the basis of studying its developmental characteristics, Weathering coefficient w is selected to describe the effect of weathering on water yield property. At the same time, water yield property of overlying aquifer, weathered bedrock strata age, lithologic composition feature, weathering intensity of bedrock, and bedrock

weathered zone thickness are identified as main control factors of affecting bedrock weathered zone aquifer.

- (2) A bedrock weathered zone aquifer water yield property index model and partition map established by the FDAHP weight analysis method and ArcGIS software are used to predict water yield property type, which is feasible in the absence of data on weathered bedrock aquifer pumping test.
- (3) A bedrock weathered zone aquifer water yield property index model is established based on geological exploration data. It has a good directive significance to predict weathered bedrock aquifer water yield property type for surrounding mines with similar conditions. However, adopted geological exploration data comes from the southeastern part of the minefield mostly; exploration of the northwest region should be strengthened to improve the model in the future.

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