

Article

Prediction of the Water-Bearing Capacity of Coal Strata by Using the Macro and Micro Pore Structure Parameters of Aquifers

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Abstract: Accurate prediction of the water-bearing capacity of aquifers is crucial for protecting the surface ecological environment and ensuring safety during coal mining. In this study, a macro–micro combination was used to investigate the water-bearing capacity of bedrock aquifers. At the micro-level, the micro pore parameters of various sandstones were determined through cast sheeting. At the macro-level, the porosity and water absorption rate of various sandstones were determined experimentally. After that, a new index weighting method was proposed to comprehensively evaluate the water-bearing capacity index of sandstone. According to this method, the water-bearing capacity of aquifers in the Guojiahe coalmine were evaluated. The research results revealed that the water-bearing capacity of sandstone was mainly related to its pore connectivity, and the water-bearing capacity of sandstone in the Luo'he and Zhi'luo formation was considerably greater than that in the Yan'an formation. The water bearing capacity of strata in the eastern part of the mining area is lower than that in the western part of the mining area. The research results can provide considerable money savings for coal mining and protect the ecological environment and groundwater resources in the region.

Keywords: pore structure parameters; index weighting method; water-bearing capacity index; coal mining



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1. Introduction

The increase in energy demand is mainly due to the increase in the population and industrialization [1–3]. The large-scale development of energy will lead to a violent conflict between man and nature [4–7]. Mining activities will inevitably cause surface subsidence, water waste and pollution, air pollution and a series of related problems, especially for the fragile ecological environment in some areas; moreover, mining easily causes injury and even death [8–11]. Water inrush is the main disaster of coal mining. Mastering the water content of strata is helpful to protect the groundwater from waste and pollution, and also to help the safe production of coal mining [8,12–14]. The water-bearing capacity of the strata is crucial for predicting sudden roof water rush accidents. Therefore, accurate and reliable evaluation of aquifer water distribution is critical. Many studies have focused on the water distribution evaluation of aquifers. Wei performed classification and partition clustering analysis on roof sandstone aquifers [15]. Wu used the graphic information system (GIS) information joint function to establish an aquifer water-rich evaluation model [5]. Chen used fuzzy clustering method combined with analytic hierarchy process (AHP) to divide the formation water abundance [16,17]. In fact, the water capacity of sandstone aquifer is closely related to its own pore structure. At present, there are many researches on the pore morphology and size of sandstone in the field of oil and gas [18,19]. The application

of various technologies, including low field nuclear magnetic resonance (LF-NMR) [20], nuclear magnetic resonance (NMR) and mercury intrusion porosimetry (MIP) [21], X-ray diffraction (XRD) analysis, thin section, scanning electron microscopy (SEM) [22], small Angle neutron scattering (SANS) [23], X-ray computed tomography (XCT) [24,25], low temperature nitrogen adsorption (LTNA), rate-controlled mercury intrusion (RCMI) and high pressure mercury intrusion (HPMI) [26,27]. These experiments provide advanced methods for the study of the microscopic pore structure of sandstone. However, few scholars pay attention to the effect of pore structure on the water-bearing capacity of sandstone in the field of water control in coal mining.

Therefore, based on previous studies, this study considered the Guojiahe coal mine as an example. Sandstone-type water-bearing capacity has been comprehensively analyzed from the micro and macro perspectives. On the micro level, the plane porosity (PP), average pore diameter (APD), average specific surface (ASS), pore sorting coefficient (PSC), and throat homogenization coefficient (THC) of sandstone with various lithologies are determined through cast sheeting. On the macro level, the porosity and natural water absorption of various sandstone types are obtained by measuring pressure porosity and rock natural water absorption (NWA).

Through exploratory data analysis (EDA) of the indexes, it was found that there is a strong correlation between the indicators. Therefore, this paper proposes a new index weighting method that may well identify factors affecting the water-bearing capacity of sandstone formations. Grey relational analysis (GRA) method may be effective for evaluating the correlation between indicators and ranking different indicators according to their importance, but it cannot accurately provide quantitative weight assignment [28–30]. The new method considers the basis of the grey correlation coefficient, quantitatively estimates the change trend between sequences, considers the analysis of the nonlinear relation between multiple variables which is used to determine the grey correlation coefficient, and then establishes an objective evaluation based on the grey correlation coefficient matrix and computing feature vector according to different characteristics of the matrix vector value of sensitivity calculation [31–34]. On this basis, the model of sandstone water capacity is established. Then, the water-bearing capacity of groundwater was evaluated, and it was found that the water-bearing capacity of bedrock aquifer in the second mining area is weak, so large-scale geophysical exploration and water exploration and release work may not be conducted. The purpose of this study is to evaluate the water-bearing capacity of the bedrock strata in the study area through experiments on the water-bearing capacity of the strata, so as to ensure the safety of coal mining while protecting the groundwater resources from being wasted.

2. Background and Method

2.1. Background of the Study Area

The Guojiahe coal mine is located in Shanxi Province, China. Many folds and faults occur in the mining area and the groundwater resources are rich. In August 2020, during the mining of the 1309 working face in the first mining area, a serious water inrush accident occurred, with the maximum water inrush reaching 1200 m³/h. The maximum water depth of approximately 1 m and the cumulative water inflow was approximately 12.6 × 10⁴ m³. The collapse of the hydraulic support for coal seam protection in mining reduced the transportation efficiency of the belt conveyor and caused an economic loss of nearly 10 million US dollars [35,36]. The second mining area to be mined in the future is located west of the Guojiahe coal mine. The thickness of the aquifer in part of the second mining area is similar to that of the 1309 working face. Therefore, to ensure coal mining safety, large-scale geophysical exploration was planned to be carried out in the second mining area, covering nearly 11 km². Then, 80 boreholes were designed in the second mining area to extract water from the aquifer. The plan would cost a lot of time and money and cause irreparable damage to groundwater (Figure 1).

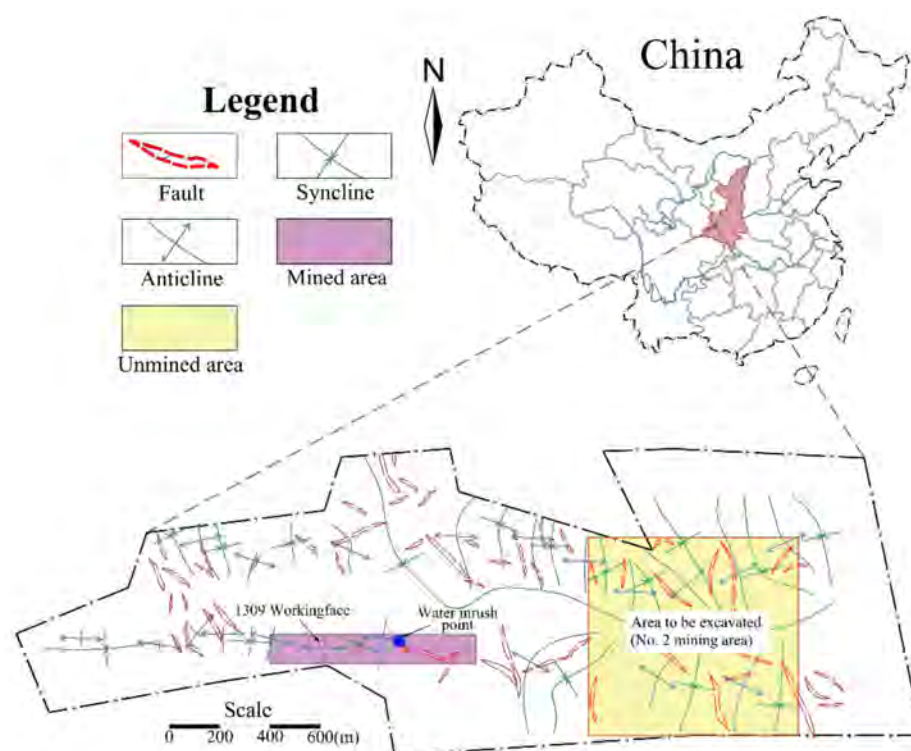


Figure 1. Location of the study area in Shaanxi Province, China and the geological structure of the Guojiahe coal mine.

The main mining coal seam is the Jurassic 3[#] coal seam, and the main roof aquifers are the Cretaceous Luo'he Formation and Jurassic Zhi'luo and Yan'an formations. The average thickness of the Luo'he Formation is 191 m, and its main lithology is brown-red sandstone with weak cementation. The average thickness of the Zhi'luo Formation is 42.5 m, and its main lithology is greyish green sandstone with medium sorting, secondary calcareous cementation and high hardness. The average thickness of the Yan'an Formation is 27.6 m and its main lithology is greyish black sandstone, which is poorly sorted and contains fine quartz gravel. In general, sandstone aquifers have large pores and locally developed fractures in water-rich heterogeneous layers (Figure 2).

In this experiment, sandstone samples were obtained from the Luo'he, Zhi'luo and Yan'an formations to conduct porosity and water absorption measurement experiments to predict the water-bearing capacity of aquifers with various lithologies.

2.2. Experiment on the Pore Structure Characteristics

The water storage space of sandstone aquifer contains various pores of different origins. The primary pores are gradually compacted and filled during deposition, burial, and diagenesis [37–39]. Simultaneously, the particles are destroyed by dissolution, resulting in secondary pores and a change in the primary pore structure. The number, size, and connectivity between primary and secondary pores are critical factors affecting strata aquifers.

The microscopic observations of casting sheets can be used to effectively study the size, distribution, type, connectivity, characteristics, and geometric morphology of rock pores; average pore throat ratio; average pore radius; throat; coordination number; fracture length and width; and fracture rate [40,41]. These parameters determine the pore structure characteristics of the rock. Therefore, after the collection of the rock samples from the coal mine, cast thin sections were made with a rock pore casting instrument, and microscopic analyses were performed using an Axio Scope A1 Pol optical microscope. The microscopic pore characteristics of rocks were studied using the fractal theory [42].

Sys-tem	Form-ation	Thick-ness	Colum	Stratigraphic description	Sample
Quaternary		153m		Loess, loose texture, containing calcium nodules.	
Neogene		58m		Clay, pale brown-red, relatively dense.	
Cretaceous	Luohe	191m		Coarse sandstone, dominated by quartz and feldspar, with a small amount of mica, subangular grains, poorly sorted, and gravel size 2-4cm.	
	Yijun	15m		Granite quartzite, gravel diameter is generally 2-9cm.	
Jurassic	Anding	158m		Mudstone, purplish red, argillaceous structure, fragile, easy to disintegrate in water.	
	Zhiluo	42.5m		Medium-Coarse sandstone, with subangular grains.	
	Yanan	27.6m		Sandstone, with rounded, hard and well sorted grains.	
	Fuxian	20m		Dark gray mudstone.	

Figure 2. Stratigraphic column of Guojiahe coalmine.

The macro pore characteristics of sandstone can be investigated using porosity and NWA. Sandstone aquifer is a rock mass formed during geological evolution and is formed through the diagenesis of clastic materials. The water-bearing capacity of sandstone aquifer is closely related to porosity and NWA [43]. The Poropdp-200 porosity measuring instrument was used to measure the porosity of the samples (Figure 3) [44,45]. The equipment constitutes a data control and analysis module, pulse attenuation control module, pressure pump, porosity measurement module, and high-precision pressure sensors with a pressure range of 0–200 psi, and the accuracy of $\pm 0.1\%$ of the full range was used in the study. Helium was used as the test medium. According to Boyle's law, the sample's pore volume was calculated using the helium pressure difference before and after the test to calculate its porosity.

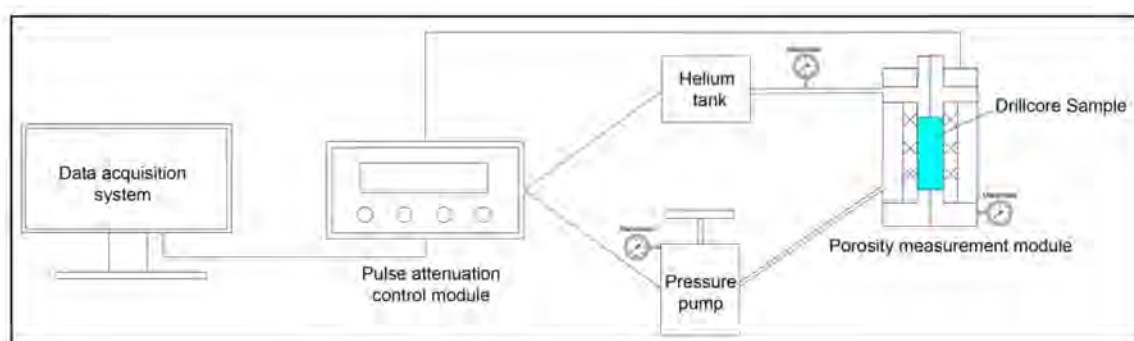


Figure 3. Poropdp-200 porosity measuring instrument.

The NWA of rock is a critical physical and mechanical property and refers to the ratio between the maximum weight of water absorbed by a rock sample under atmospheric pressure and the specimen's drying weight (Equation (1)). The NWA size mainly depends on the number, size and opening degree of pores and fissures in the rock, which can effectively reflect the water-holding capacity of rock and the connectivity between rock pores.

$$W_m = \frac{m_0 - m_s}{m_s} * 100\% \quad (1)$$

W_m – Nature water absorption(%); m_0 – Mass of rock saturated with water(g);
 m_s – Quality of rock after drying(%)

Before measurement, the rock samples to be tested were placed in a vacuum oven and dried at 110 °C for 24 h. Next, the samples were weighed to the accuracy of 0.1 g after cooling to room temperature. The weighed test pieces were then placed in the water tank. Subsequently, water was injected to 1/4 of the test pieces' height and filled to 1/2 and 3/4 places every 2 h. After 8 h, all the core samples were immersed. Next, the sample quality was measured every 8 h until no change was observed in the sample quality. Finally, Equation (1) was used to calculate the NWA of the sample.

2.3. Weighting Method of Eigenvector Based on the GRA

The structure and properties of sandstone determine its water-bearing capacity. The evaluation of the water-bearing capacity of sandstone essentially refers to the coupling of all the influencing indexes. Therefore, the determination of the index weight is the key to solving the multi-attribute decision-making problem. As an objective analysis method, GRA can be used to compare various influencing factors pairwise, observe the grey relational grade (GRG) between the reference and comparison sequences, evaluate the correlation between various indexes from the data level, and sort the correlation. However, combining all indexes and obtaining quantitative evaluation is difficult in GRG [31].

Therefore, based on GRA, an improved index weighting algorithm was proposed in which the index importance can be ranked by estimating the similarity between the data, and the evaluation matrix was established based on this. Then, the eigenvector of the matrix was calculated, and the evaluation model was finally established. The detailed steps of the algorithm are as follows.

First, the evaluation object and evaluation criteria are determined. The reference sequence is recorded as $x_j = \{x_j(1), x_j(2) \cdots x_j(n)\}$. The comparison sequence is recorded as $x_i = \{x_i(1), x_i(2) \cdots x_i(n)\}$. After standardizing the comparison sequence, according to Equation (2), the following evaluation matrix (2) is established:

$$y_i = \frac{x_i - \frac{1}{n} \sum_{i=1}^n x_i}{\sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \frac{1}{n} \sum_{i=1}^n x_i)^2}} \quad (2)$$

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1n} \\ y_{21} & y_{22} & \cdots & y_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ y_{n1} & y_{n2} & \cdots & y_{nn} \end{bmatrix} \quad (3)$$

Second, using Equation (3), the grave correlation coefficient (GCC) was calculated as follows:

$$\xi_i(k) = \frac{\min_i \min_k |y_i(k) - x_j(k)| + \rho \max_i \max_k |y_i(k) - x_j(k)|}{|y_i(k) - x_j(k)| + \rho \max_i \max_k |y_i(k) - x_j(k)|} \quad (4)$$

$\xi_i(k)$ – The GCC of the K in the i ; ρ – Resolution coefficient, the value is 0.54.
 $k = 1, 2, 3, \dots, n$; $i = 1, 2, 3, \dots, m$;

Then, using Equation (4), we calculated the GRG of each evaluation index.

$$G(n, i) = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \quad (5)$$

$G(n, i)$ – The Grey Relational Grade (GRG); $k = 1, 2, 3, \dots, n$; $i = 1, 2, 3, \dots, m$;

The relational degree sequence of the evaluation object is established through GRG, and the relational degree is sorted. The larger the GRG is, the better the correlation is.

Next, the evaluation matrix containing all the indexes was established. The relation degree of the level set, a_{ij} , is closely related to the judgement index and is determined using $G(n, i)$.

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1j} \\ a_{21} & a_{22} & \cdots & a_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} \dots \end{pmatrix} \quad (6)$$

Next, using Equation (7), the eigenvector corresponding to each matrix is calculated as follows:

$$W_i = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \bigg/ \sum_{j=1}^m \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad i = 1, 2, \dots, n; \quad j = 1, 2, \dots, m \quad (7)$$

where W_i is the influence intensity of a comparison sequence on the reference sequence as well as the weight value of the factors in the comparison sequence. To ensure the validity of Equation (7), the matrix completed through calculation is tested for consistency (Equation (8)).

$$CI = \left(\frac{1}{n} \sum_{i=1}^n [(A_w)_i / W_i] - n \right) / (n - 1), \quad CR = CI / RI \quad (8)$$

$$RI = \frac{CI_1 + CI_2 + \dots + CI_n}{n}$$

The consistency test refers to determining the allowable range for judgement matrix A. The unique nonzero characteristic root of the $n \times n$ consistency matrix is n . The largest characteristic root of the $n \times n$ positive matrix, λ , is greater than or equal to n , if and only if $\lambda = n$, then matrix A is consistent.

When $CR < 0.1$, the judgement matrix passes the consistency test. Thus, the weight distribution is reasonable.

3. Results

3.1. Measurement of Pore Structure Parameters

In this case, 18 sandstone slices with various physical properties were selected for analysis. The pore size and connectivity of the samples were determined by measuring the PP, APD, ASS, PSC and THC of the samples. The PP refers to the percentage of pore and throat area in the total area of the slice. The equivalent area circle diameter represents the APD. The ASS relates to the ratio of pore surface area to volume or the ratio of equal circle surface area to volume. The THC is the average pore diameter divided by the maximum pore diameter.

Figure 4 displays the microscopic structures of the samples. Figure 5 shows an SEM image of the samples.

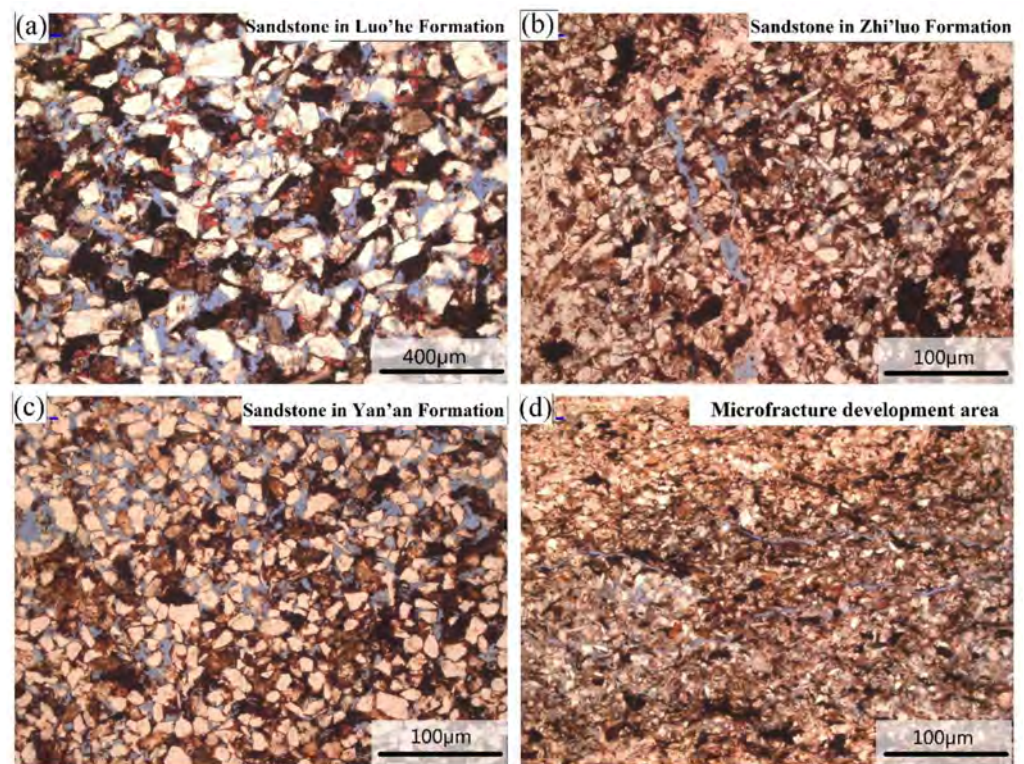


Figure 4. Microscopic observation of sandstone samples. (a) Sandstone in the Luo'he formation; (b) Sandstone in the Zhi'luo formation; (c) Sandstone in the Yan'an formation; (d) Microfracture.

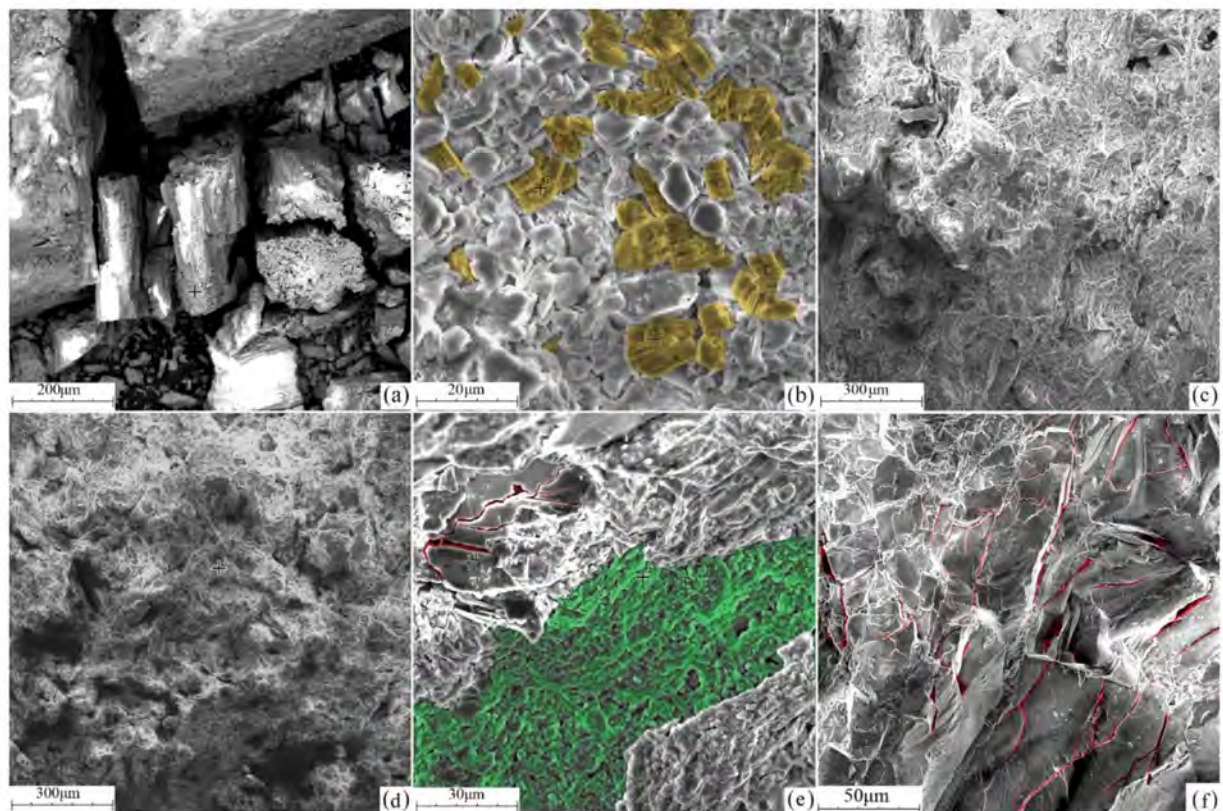


Figure 5. SEM observation of samples. (a) Sandstone pores of the Luo'he formation; (b) Kaolinite; (c) Sandstone in the Zhi'luo formation; (d) Sandstone in the Yan'an formation; (e) Calcareous cementation; (f) Microfracture.

The minerals of the sandstone in the Luo'he formation are dominated by quartz and feldspar, with a particle size of 500–1000 μm . These are subangular, with poor roundness, poor sorting and pore cementation (Figure 4a). Intergranular pores are developed, and pore throat is large (Figure 5a). Feldspar dissolution occurs, and a large amount of kaolinite is formed (Figure 5b).

The porosity of the sandstone in Zhi'luo and Yan'an formations is less than that in the Luo'he formation, indicating their poor packing pattern and intergranular space (Figure 4b,c). Mineral composition mainly constitutes quartz and feldspar. The particle size is mostly between 250 and 500 μm , with pore type cementation and particle support, and some pores are filled with organic matter (Figure 5c,d). The quartz grains are granular aggregate, with calcite cementation (Figure 5e).

The development of micro-cracks in the rock enhances pore connectivity and improves the rocks' water-bearing capacity under certain conditions (Figures 4d and 5f).

As listed in Table 1, the PP of sandstone is 4.57%–20.15%. The APD ranges from 20.3 to 51.9 μm . The ASS ranges from 0.51 μm^{-1} to 1.18 μm^{-1} . The PSC is between 0.44 and 0.63, and the THC is between 13.59 and 28.74. Obvious differences occurred in pore structure parameters among various samples. The average PP, APD, ASS, PSC and THC of Luo'he sandstone were 19.17%, 47.94 μm , 1.125 μm^{-1} , 0.6116 and 27.515, respectively; those of Zhi'luo sandstone were 14.015%, 28.2 μm , 1.02 μm^{-1} , 0.5517 and 20.133, respectively; and those of Yan'an sandstone were 5.89%, 11.83 μm , 0.58 μm^{-1} , 0.473 and 14.81, respectively.

Table 1. Characteristic parameters of pore structure test.

Sample ID	Type	PP (%)	APD (μm)	ASS (μm^{-1})	PSC	THC
XY-1	Sandstone in Luo'he Formation	20.15	51.9	1.18	0.63	28.74
XY-2		19.57	47.7	1.17	0.61	26.74
XY-3		18.71	48.22	1.14	0.6	26.82
XY-4		19.25	45.33	1.11	0.61	27.52
XY-5		18.32	44.79	1.06	0.62	28.14
XY-6		18.99	49.75	1.09	0.6	27.13
XY-7	Sandstone in Zhi'luo Formation	13.74	28.4	0.98	0.53	19.26
XY-8		14.24	32.3	1.07	0.54	21.56
XY-9		14.57	27.2	1.03	0.57	18.69
XY-10		13.32	26.75	0.97	0.56	20.88
XY-11		14.55	27.64	1.01	0.54	19.76
XY-12		13.67	26.88	1.04	0.57	20.65
XY-13	Sandstone in Yan'an Formation	7.07	13.7	0.62	0.5	15.47
XY-14		6.31	12.4	0.61	0.48	16.44
XY-15		5.54	11.1	0.55	0.46	14.41
XY-16		6.62	12.7	0.64	0.49	14.74
XY-17		4.57	10.3	0.51	0.44	13.59
XY-18		5.21	10.8	0.53	0.47	14.21

3.2. Macro Pore Characteristics of the Aquifer

In this experiment, 18 groups of core samples were selected to measure the porosity and NWA. The sampling depth of sandstone in the Luo'he formation was 460–570 m; that in the Zhi'luo formation was 750–810 m, and that in the Yan'an formation was 810–890 m. According to the differences in depth, the overburden pressure gradient was approximately 328.08 psi/m.

Table 2 presents the porosity measurement data of the sandstone core samples from various formations. The average porosities of the Yan'an, Zhi'luo and Luo'he formations were 8.48%, 14.50% and 21.89%, respectively.

Table 2. Test values of overburden porosity of samples.

Sample ID	Type	Depth/m	Porosity/%	Overburden Pressure/Mpa
XY-1	Coarse sandstone	100	22.4	1.04
XY-2		150	22.25	1.56
XY-3		200	21.93	2.08
XY-4		250	21.76	2.60
XY-5		300	21.62	3.12
XY-6		350	21.4	3.64
XY-7	Medium sandstone	500	15.21	5.19
XY-8		530	14.8	5.51
XY-9		550	14.51	5.71
XY-10		570	14.31	5.92
XY-11		600	14.12	6.23
XY-12		620	14.03	6.44
XY-13	Fine sandstone	630	8.60	6.54
XY-14		640	8.55	6.65
XY-15		650	8.48	6.75
XY-16		660	8.45	6.86
XY-17		670	8.40	6.96
XY-18		680	8.38	7.06

The experimental results of NWA are presented in Table 3. The NWA rates of sandstone in the Luo'he, Zhi'luo and Yan'an formations were 7.42–7.63%, 5.2–5.4% and 4.54–4.68%, respectively, with average values of 7.53%, 5.31% and 4.6%, respectively.

Table 3. Test values of the NWA of samples.

Sample ID	Type	Natural/g	Drying/g	Water-Saturated/g	NWA/%	Average NWA/%
XY-1	Sandstone in Luo'he Formation	399.4	374.6	402.7	7.5	7.53
XY-2		373.7	356	382.4	7.42	
XY-3		390.4	365.6	393.4	7.6	
XY-4		394.4	366.9	394.2	7.44	
XY-5		383.2	357.2	384.2	7.56	
XY-6		401.4	390.5	420.3	7.63	
XY-7	Sandstone in Zhi'luo Formation	392.5	385.6	406.4	5.4	5.31
XY-8		416.8	410.2	431.5	5.2	
XY-9		416.6	408.9	430.4	5.25	
XY-10		415	408.8	430.8	5.37	
XY-11		412.3	404.1	425.6	5.33	
XY-12		408.6	391.2	411.9	5.3	
XY-13	Sandstone in Yan'an Formation	437	432.3	452.1	4.57	4.6
XY-14		461.2	447.3	467.6	4.53	
XY-15		442.8	433.2	452.9	4.55	
XY-16		460.6	451.7	472.7	4.65	
XY-17		416.6	408.9	427.7	4.6	
XY-18		450.8	444.2	465	4.68	

3.3. Information Fusion of Micro Pore Parameters

Seven factors, namely NWA, porosity, PP, APD, ASS, PSC and THC, were used to establish the calculation model for sandstone water-carrying capacity.

Considering PP, APD, ASS, PSC, THC, porosity and NWA as reference sequences, the GCC of each index was calculated based on Equation (4). The GRG calculation of the

evaluation index, the GCC of each index and the relationship between the comparison and reference sequences are illustrated in Figure 6.

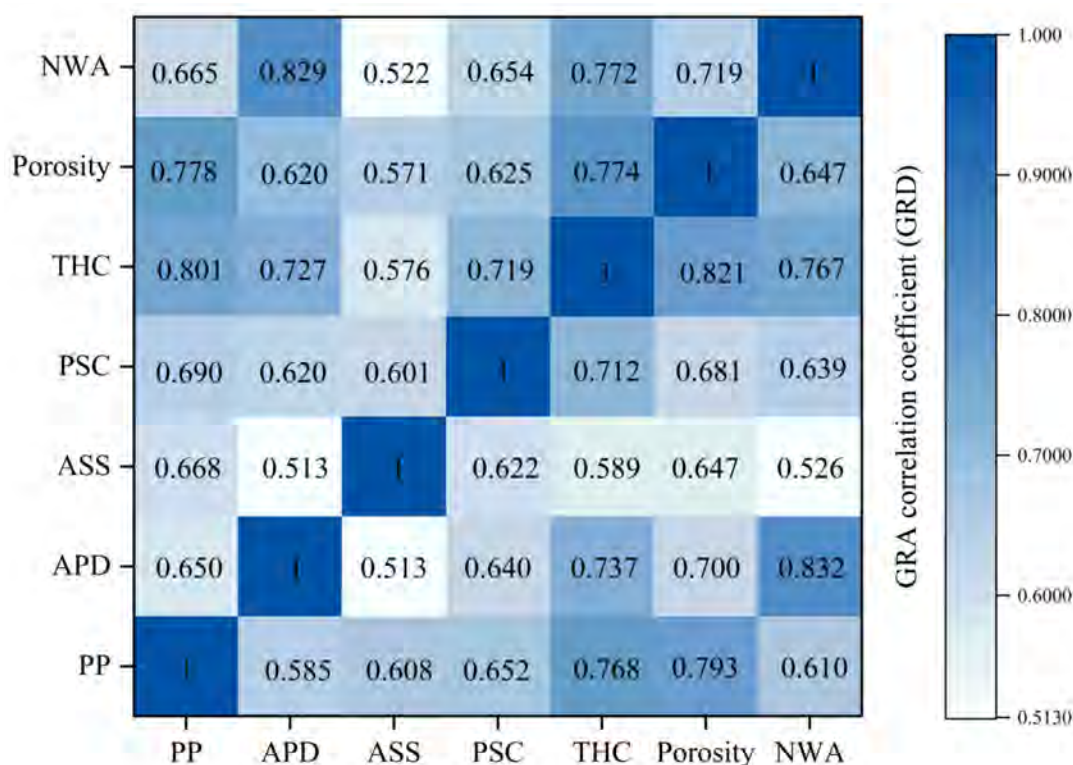


Figure 6. Heat degree of the GCC.

Considering PP as the comparison sequence, the sensitivity of each factor to PP is as follows:

$$\text{Porosity} > \text{THC} > \text{PSC} > \text{NWA} > \text{ASS} > \text{APD}$$

Assuming APD as the comparison sequence, the sensitivity of each factor to APD is as follows:

$$\text{NWA} > \text{Porosity} > \text{THC} > \text{PP} > \text{PSC} > \text{ASS}$$

Considering ASS as the comparison sequence, the sensitivity of each factor to ASS is as follows:

$$\text{PP} > \text{Porosity} > \text{PSC} > \text{THC} > \text{NWA} > \text{APD}$$

With the PSC comparison sequence, the sensitivity of each factor to PSC is as follows:

$$\text{THC} > \text{PP} > \text{Porosity} > \text{NWA} > \text{APD} > \text{ASS}$$

Assuming THC as the comparison sequence, the sensitivity of each factor to THC is as follows:

$$\text{Porosity} > \text{PP} > \text{NWA} > \text{APD} > \text{PSC} > \text{ASS}$$

Assuming porosity as the comparison sequence, the sensitivity of each factor to porosity is as follows:

$$\text{PP} > \text{THC} > \text{NWA} > \text{PSC} > \text{APD} > \text{ASS}$$

With NWA as the comparison sequence, the sensitivity of each factor to NWA is as follows:

$$\text{APD} > \text{THC} > \text{Porosity} > \text{PP} > \text{PSC} > \text{ASS}$$

According to Equation (5), the GRG of each evaluation index is as follows:

$$G(PP) = 0.6692; G(APD) = 0.6786; G(ASS) = 0.5941; \\ G(PSC) = 0.657; G(THC) = 0.735; G(Porosity) = 0.669; G(NWA) = 0.6935$$

According to differences between the GRG values of each index, a nine-level scaling method was established (Table 4), and a judgement matrix A was established based on Table 4. The judgement matrix A is presented in Table 5.

Table 4. Five-level scale method improved using the GRG.

Scale	Meaning	Expression of the GRG
1	The two factors have the same importance	$0 < G(n,i) - G(n,j) < 0.01$
2	One factor was slightly important than the other	$0.01 < G(n,i) - G(n,j) < 0.3$
3	One factor is important to other factors	$0.03 < G(n,i) - G(n,j) < 0.06$
4	One factor is more important than other factors	$0.06 < G(n,i) - G(n,j) < 0.09$
5	One factor is much more important than the other factors	$G(n,i) - G(n,j) > 0.09$

Table 5. Judgement matrix.

	PP	APD	ASS	PSC	THC	Porosity	NWA	Wi
PP	0	−0.009	0.075	0.012	−0.066	0.000	−0.024	0.1139
APD	0.009	0	0.084	0.022	−0.057	0.010	−0.015	0.1187
ASS	−0.075	−0.084	0	−0.063	−0.141	−0.075	−0.099	0.0326
PSC	−0.012	−0.022	0.063	0	−0.078	−0.012	−0.037	0.0724
THC	0.066	0.057	0.141	0.078	0	0.066	0.042	0.3555
Porosity	0.000	−0.010	0.075	0.012	−0.066	0	−0.025	0.1139
NWA	0.024	0.015	0.099	0.037	−0.042	0.025	0	0.1930

Based on Equation (7), the eigenvector W is calculated as follows:

$$W_{PP} = 0.1139, W_{APD} = 0.1187, W_{ASS} = 0.0326, \\ W_{PSC} = 0.0724, W_{THC} = 0.3555, W_{Porosity} = 0.1139, W_{NWA} = 0.1930$$

Table 4 is checked for consistency according to Equation (8), $\lambda_{\max} = 7.2499$ CR = 0.0306 < 0.1.

By comparing the eigenvector coefficient of each index, the indexes difference is as follows:

$$W_{THC} > W_{NWA} > W_{APD} > W_{Porosity} = W_{PP} > W_{PSC} > W_{ASS}$$

The sandstone water-bearing capacity index calculation model was established in line with each index's eigenvector, and the equation is as follows:

$$L = 0.1139 * a_{PP} + 0.1187 * a_{APD} + 0.0326 a_{ASS} + 0.0724 * a_{PSC} + 0.3555 * a_{THC} + 0.1139 * a_{Porosity} + 0.193 * a_{NWA} \quad (9)$$

L—The Sandstone water bearing capacity index

Equation (9) is the evaluation model of the water-bearing capacity of sandstone. The water-bearing capacity of three sandstone types in the study area was calculated and evaluated using this expression (Table 6). According to Table 6, the average water-bearing capacity index of sandstone in the Luo'he, Zhi'luo and Yan'an formations is 0.917, 0.423 and 0.076, respectively. The comparison index revealed that the water-bearing capacity of sandstone in the Luo'he and Zhi'luo formations was higher than that in the Yan'an formation.

$$M_{Equ} = 0.917 * M_{Luohe} + 0.423 * M_{Zhiluo} + 0.076 * M_{Yanan} \quad (10)$$

M_{Equ} – Equivalent thickness of sandstone

Table 6. Statistics of the calculation results of the sandstone water-bearing capacity index.

Sandstone in Luo'he Formation			Sandstone in Zhi'luo Formation			Sandstone in Yan'an Formation		
ID	L	Average	ID	L	Average	ID	L	Average
1	0.986	0.917	7	0.407	0.423	13	0.097	0.076
2	0.895		8	0.467		14	0.131	
3	0.895		9	0.397		15	0.055	
4	0.909		10	0.436		16	0.110	
5	0.904		11	0.408		17	0.011	
6	0.915		12	0.425		18	0.052	

4. Discussion

4.1. Micro Pore Structure Parameters of Various Types of Sandstone

The microscopic pore parameters of various groups of sandstone differ considerably due to the differences in their sedimentary environment, tectonic stress and burial depth. Figure 7 displays the diagram of the pore structure of the sample. The graph provides an intuitive comparison of the differences and trends of the same pore structure parameters of various samples.

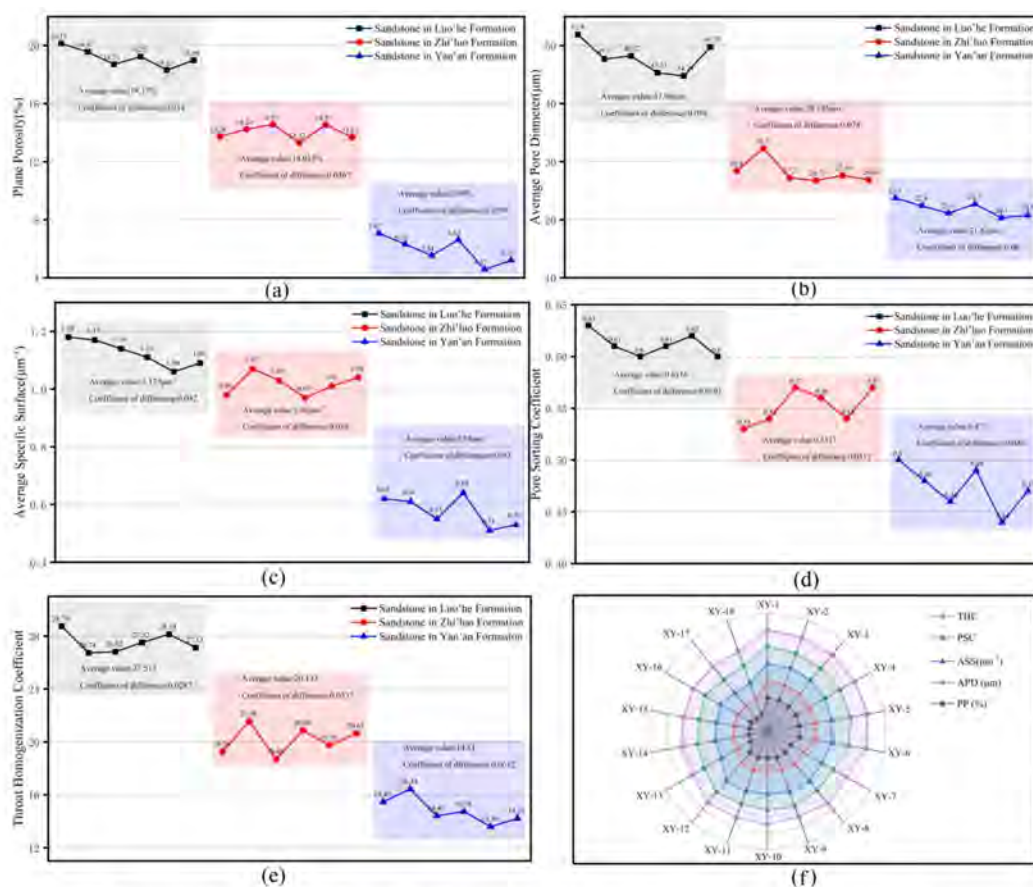


Figure 7. Point-line plot and radar chart of characteristic parameters of the pore structure test. (a) Pore structure parameters of PP; (b) Pore structure parameters of APD; (c) Pore structure parameters of ASS; (d) Pore structure parameters of ASC; (e) Pore structure parameters of THC; (f) The radar chart of pore structure characteristic parameters.

Figure 7a reveals that the PP of various formation samples exhibits obvious step changes, which indicates that the sedimentary environments of the Luo'he, Zhi'luo and Yan'an formations differ considerably, and their pore content is different. In all the formations, the coefficient of variation of PP of different samples is 0.1599 at most, indicating that PP of different samples is stable in the same stratum.

As described in Figure 7b, the APD of Luo'he sandstone is considerably larger than that of the Zhi'luo and Yan'an sandstone, whereas the APD of Zhi'luo and Yan'an sandstone is similar. Thus, the pore connectivity of the Luo'he formation is considerably superior to that of the Zhi'luo and Yan'an formations. In all the formations, the coefficient of variation of APD of different samples is 0.074 at most; APD fluctuations in the same formation do not exceed 8 μm .

Figure 7c illustrates that the ASS of the sandstone in the Luo'he formation differs less from that of the sandstone in the Zhi'luo formation, whereas the ASS of Yan'an sandstone is considerably smaller than Luo'he and Zhi'luo sandstone. The particles of the Luo'he and Zhi'luo formations are rough, with poor roundness and strong adsorption capacity. In all formations, the coefficient of variation of ASS of different samples is 0.093 at most; ASS fluctuations in the same formation do not exceed $0.13 \mu\text{m}^{-1}$.

As displayed in Figure 7d, the PSC of the sandstone in the Luo'he formation is large. The PSC between Zhi'luo and Yan'an sandstone has a few differences. The sandstone of the Luo'he formation exhibits superior seepage capacity compared with that of the Zhi'luo and Yan'an formations. In the same formation, the coefficient of variation of PSC of different samples is no more than 0.0456, indicating that the PSC of the same layer is similar.

Figure 7e displays the variation trend of the THC, which is similar to the variation trend of Figure 7a. The THC of various formation samples exhibits considerable step change. In the same formation, the coefficient of variation of THC of different samples is no more than 0.0682, indicating that the THC of the same layer is similar.

The microscopic pore structure parameters of different samples in the same formation are similar, and the microscopic pore parameters of the samples in different formations show large differences. Therefore, sandstone in the same formation can be considered to belong to the same category when calculating the water-bearing capacity.

Figure 7f displays the radar chart of characteristic parameters of the pore structure test. The variation trends of various structural parameters among all the samples are generally similar, which indicates that PP, APD, AAS, THC and PSC are closely related. A strong correlation exists between the parameters. Therefore, the advantages and disadvantages of the reservoir space can be evaluated through comprehensive information fusion according to the similarity of the five parameters.

4.2. Macro Pore Structure Parameters of Various Types of Sandstone

Figure 8 illustrates a linear plot of porosity variation. First, obvious differences existed in the porosity of the samples of the Luo'he, Zhi'luo and Yan'an formations, indicating that the water-bearing capacity of various horizons differs considerably. Second, with an increase in pressure, the porosity of the samples of the Luo'he and Zhi'luo formations decreases, whereas the porosity of the samples of the Yan'an formations fluctuates relatively less, indicating that the pores of the Luo'he and Zhi'luo formations are large in diameter and suffer from weak original tectonic stress, which is a high-quality water reservoir.

Figure 9 displays the time-varying fitting curves of NWA of the three types of sandstone. The blue, green and red curves represent sandstones in the Luo'he, Zhi'luo and Yan'an formations, respectively. The points in Figure 9 represent the experimental data, and the curve represents the relevant results. The fitting effect is excellent, indicating that the experimental results are accurate. The NWA rate of the sample increased rapidly in the initial 48 h and remained stable during the next 48 h. After 64 h, the NWA rate did not change. Therefore, the experimental time was set for 72 h.

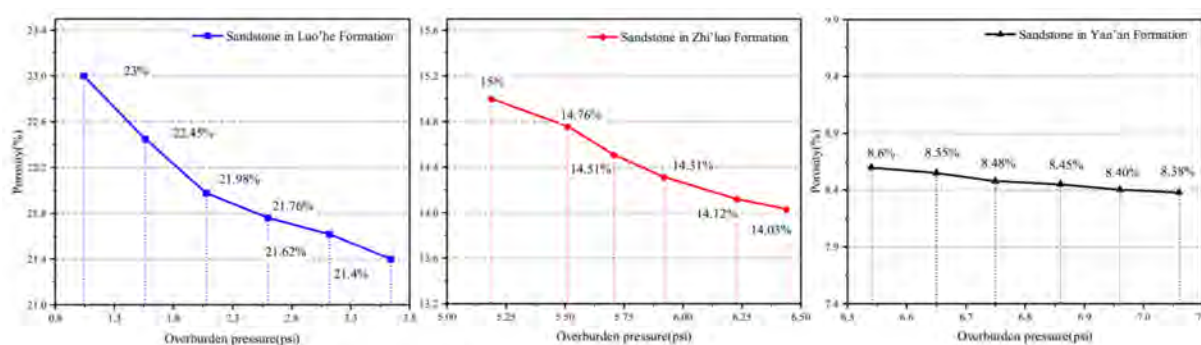


Figure 8. Linear chart of porosity of sandstone core samples.

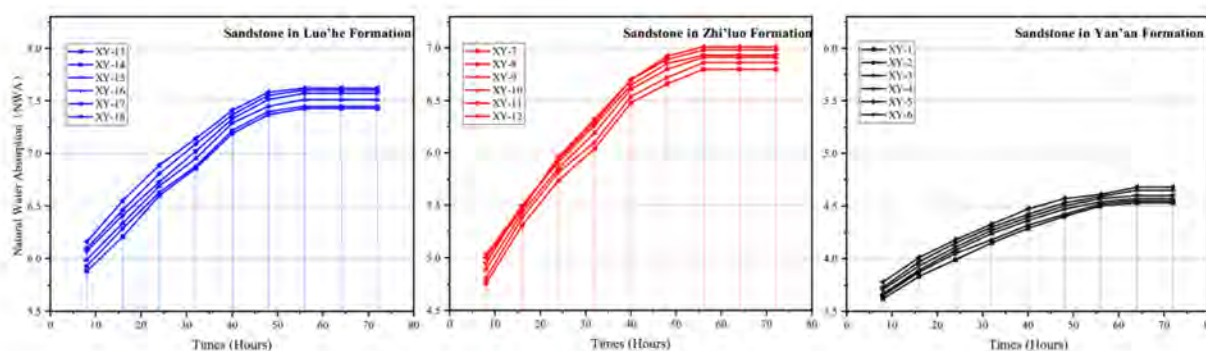


Figure 9. Time-varying fitting curves of the NWA of samples.

The final experimental results revealed limited difference in the samples from Luo'he and Zhi'luo formations, both of which are high-quality aquifers. The NWA rate of the samples from Yan'an formation was inferior; therefore, it was not considered the main aquifer.

4.3. Evaluation Model of Formation Water-Bearing Capacity in the Guojiahe Coal Mine

The established water-bearing capacity model was used to measure the water-bearing capacity. The thickness statistics and calculation results of various types of sandstone in the study area are displayed in Table 7. Next, the contour map (Figure 10) was drawn to comprehensively evaluate the water-bearing capacity of 3[#] coal roof.

Table 7. Statistics table of sandstone thickness in the study area.

Borehole	M_{Luohe}	M_{Zhiluo}	M_{Yanan}	M_{Equ}	Borehole	M_{Luohe}	M_{Zhiluo}	M_{Yanan}	M_{Equ}
G36-1	160	30	26	161	G19-1	265	32	12	257
G36-2	217	54	32	225	G19-2	333	17	4	313
G36-3	241	36	27	238	G31-1	200	53	9	206
G36-4	200	28	30	198	G32-5	191	45	48	198
G37-1	198	40	27	201	G32-7	152	57	15	165
G37-2	234	22	43	227	G33-1	128	28	0	129
G37-3	294	42	19	288	G33-2	136	17	20	133
G38-1	248	54	41	253	G33-3	151	42	12	157
G14-1	220	33	25	217	G33-4	152	55	9	163
G14-2	162	46	17	169	G33-5	146	39	12	151
G15-2	131	33	24	136	G33-6	159	20	1	154
G15-3	42	39	43	59	G33-7	198	26	25	194
G15-4	135	36	53	143	G33-8	217	44	34	220
G15-5	206	48	43	213	G34-1	151	34	30	155
15-6	181	69	32	198	G34-2	139	68	29	159
G16-1	180	31	25	180	G34-3	134	77	43	158
G16-2	154	46	28	162	G34-4	190	51	43	198

Table 7. Cont.

Borehole	M_{Luohe}	M_{Zhiluo}	M_{Yanan}	M_{Equ}	Borehole	M_{Luohe}	M_{Zhiluo}	M_{Yanan}	M_{Equ}
G16-3	167	54	57	180	G34-5	268	70	39	278
G16-4	280	56	32	283	G34-6	309	43	40	305
G16-5	316	53	38	315	G34-7	205	40	10	206
G16-6	114	40	0	121	G35-1	146	50	8	156
G16-7	244	56	24	250	G35-2	147	52	24	159
G17-1	143	61	22	159	G35-3	159	48	36	169
G17-2	237	53	20	242	G35-4	319	42	23	312
G17-3	324	33	26	313	G3	193	151	35	244
G17-4	357	33	22	343	G5-2	211	185	24	273
G17-5	170	32	30	171	G5-3	224	124	79	264
bk-1	308	32	4	296	G6-1	145	31	20	147
bk-2	292	24	34	281	G6-2	139	27	16	140
bk-3	308	41	10	300	G6-3	142	29	12	143
bk-4	348	165	77	395	G6-4	153	55	45	167
c1	365	53	11	358	G6-5	240	51	29	243
C9	190	31	22	189	G6-6	294	41	20	289
c10	237	47	17	238	G7-2	143	50	37	155
c11	281	46	18	279	G7-3	360	46	18	351
C14	200	24	20	195	G7-5	159	34	10	161
C15	180	42	6	183	G8-3	201	42	28	204
C17	228	33	14	224	G8-4	329	30	4	315
C21	171	36	22	174					

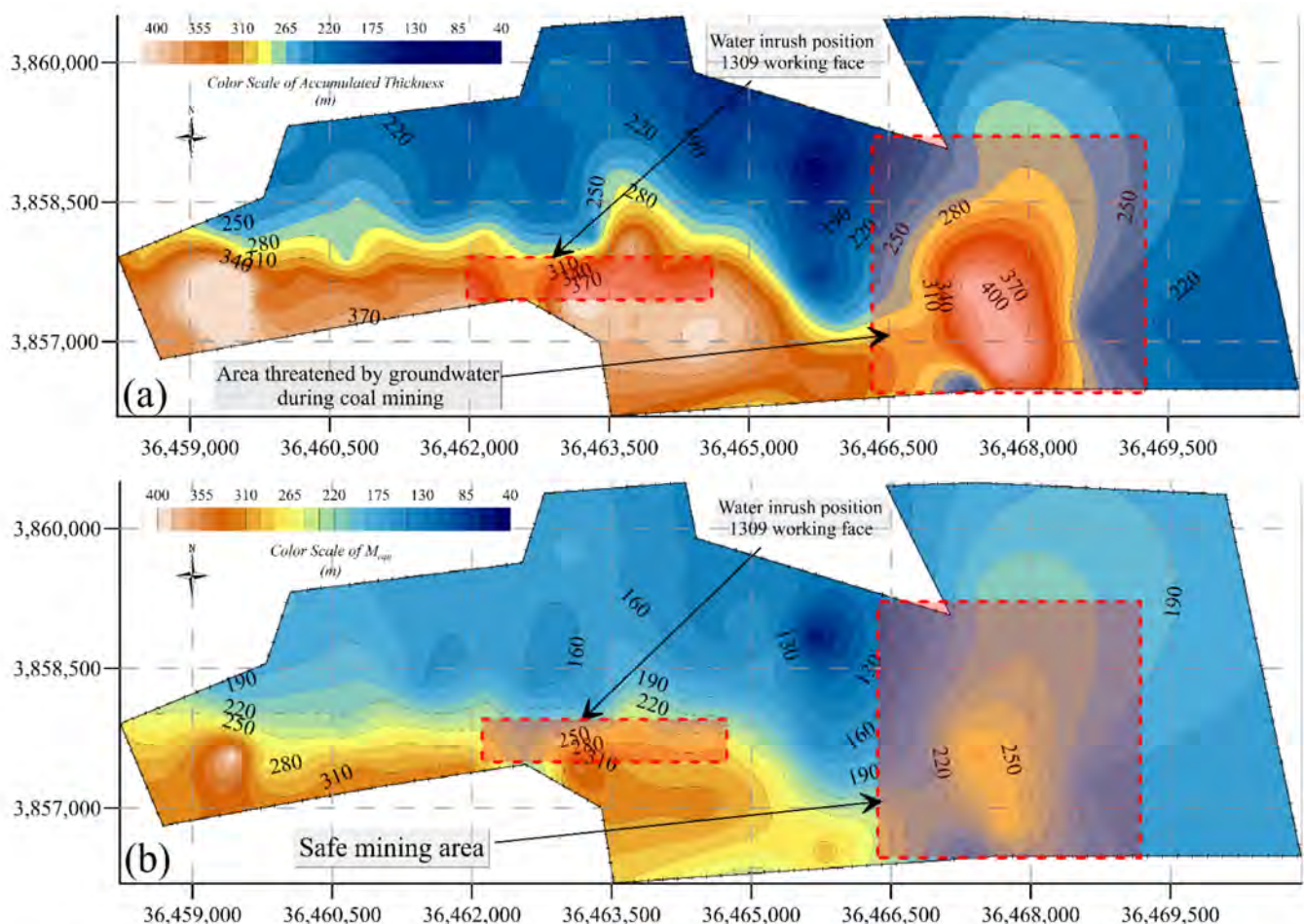


Figure 10. Contour map of the equivalent thickness of sandstone on the roof of 3[#] coal seam. (a) Contour map of cumulative thickness of sandstone in roof of 3[#] coal seam. (b) Contour map of equivalent thickness of sandstone in roof of 3[#] coal seam.

Figure 10a presents the contour map of cumulative thickness of 3[#] coal roof aquifer in the study area. In the 1309 working face water inrush, the aquifer thickness was 380 m, and its maximum thickness was large. In the study area in the east, a piece of aquifer thickness was a >400 m area (red rectangle). If the region is in high-risk areas, drilling should be performed in advance before pumping water, which is not only costly but also destroys the groundwater resources and affects the ecological balance of the region.

Figure 10b displays the contour map of equivalent thickness of coal roof aquifer in the third research area and reveals the water inrush that occurred in the 1309 working face, with aquifer thickness of up to 330 m, which is similar to that presented in Figure 10a. By contrast, in the east, the red rectangle area within the aquifer thickness decreased to 250 m and was less dangerous primarily because the aquifer in the area of Yan'an group was large and thick. The water capacity was weak and the impact on mining was small. When mining in this area, geophysical exploration surveys can guarantee safety.

5. Conclusions

The following conclusions can be drawn from the study:

- (1) The results of the microscopic experiment showed that the APD and PSC of Luo'he formation sandstone were larger than those of Zhi'luo formation sandstone, but the APD and PSC of Zhi'luo and Yan'an formation sandstone do not differ considerably. The pore connectivity of Luo'he formation sandstone was much better than that of Zhi'luo and Yan'an formation sandstone. The Luo'he formation is the main aquifer in this region.
- (2) The results of the macroscopic experiment revealed that the average porosity of Luo'he formation sandstone was 7.39% higher than that of Zhi'luo formation sandstone and 13.41% higher than that of Yan'an formation sandstone. The Luo'he and Zhi'luo formations exhibit weak compaction, develop pores and have strong water-bearing capacity. The porosity of the Yan'an formation is low, and its water-bearing capacity is weak. In addition, the NWA difference between sandstone in the Zhi'luo and Yan'an formations was 0.62%, and the difference between sandstone in the Luo'he and Zhi'luo formations was 2.31%. The water-carrying capacity of the sandstone in Luo'he and Zhi'luo formations was considerably higher than that of the sandstone in the Yan'an formation.
- (3) An objective weighting model based on the similarity between indexes was proposed. This model was used to analyze pore structure parameters of various formations in the Guojiahe coal mine. The calculation model of water-bearing capacity of various formations was established. According to this model, the water-carrying capacity of 3[#] coal roof in the study area was analyzed. The results of previous mining studies indicated that there is a large-scale area with strong water inrush risk in the east of the study area, which is prone to water inrush if normal mining continues in the future. However, according to the model analysis in this paper, it was found that the actual water capacity in this area is medium, and there is no need to perform large-scale pumping, drilling or geophysical exploration before mining. The research results can save money for coal mining, which is beneficial for protecting the ecological environment and groundwater resources.

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Abbreviations

PP	Plane Porosity
APD	Average Pore Diameter
ASS	Average Specific Surface
PSC	Pore Sorting Coefficient
THC	Throat Homogenization Coefficient
NWA	Natural Water Absorption
SEM	Scanning Electron Microscope
GRA	Grey Relational Analysis
GCC	Grave Correlation Coefficient
GRG	Grey Relational Grade
W_m	Natural Water Absorption
$\xi_i(k)$	Grave Correlation Coefficient
ρ	Resolution coefficient
$G(n,i)$	Grey Relational Grade
W_i	Eigenvectort
CI	Consistency Index
RI	Random Consistency Indicator
CR	Consistency Ratio

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