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Improved Combination Weighted Prediction Model of Aquifer Water Abundance Based on a Cloud Model

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ABSTRACT: The sandstone aquifer is an important underground water storage space, and the study of its water abundance is of great significance to ensure the safety of underground engineering and to explore the occurrence mechanism of groundwater sources. Based on the correlation between geological characteristics and aquifer water abundance, this paper proposed an aquifer water abundance prediction model based on a cloud model that improved combination weighting. The model took the roof sandstone aquifer of the Qingshuiying Coalfield as an example and selected five basic geological indicators that are closely related to the water-rich influence degree of the aquifer as evaluation indicators. The model was based on the idea of game theory, combined the analytic hierarchy process (AHP) and the entropy weight method, and introduced the cloud model evaluation method. The establishment of the model was based on the idea of game theory, combining the AHP and the entropy weight method and introducing the cloud model evaluation method. The results show that most of the study areas are located in weak or relatively weak water abundance areas; relatively strong water abundance areas are mainly distributed in the central, western, and southeastern parts of the study; strong water abundance areas are scattered in parts of the northeast, southwest, and southeast. The unit water inflow data of the actual pumping test is consistent with the water-rich prediction partition, which proves the accuracy and scientificity of the method. The model provides a new idea for the study of groundwater geology and a new method for predicting the water abundance of the roof aquifer in coal mines.
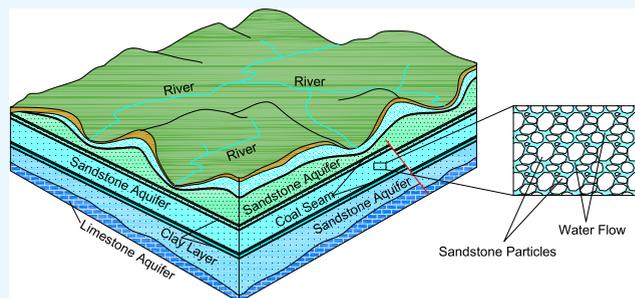
1. INTRODUCTION

The groundwater resource is one of the most extensive water resources in the world, and it plays an extremely important role in human reproduction and life, agricultural irrigation and utilization, and so forth.[1−3] Sandstone aquifers are one of the most important storage spaces for groundwater with good porosity. At present, most of the studies on water abundance of sandstone aquifers are in the field of mine water disaster prevention.[4,5] Since the 20th century, the rate of world energy consumption has been increasing, and China has become the country with the largest energy consumption in the world,[6,7] of which coal resources play an extremely important role in China's energy structure. However, sandstone aquifers can easily lead to roof water damage, threatening the mining of coal resources. Therefore, the analysis and research on the water abundance of sandstone aquifers plays an important role in the fields of engineering geology and hydrogeology.

The water abundance distribution law of the aquifer is affected by a variety of factors.[8−10] At present, the research on the water abundance of the roof aquifer is mainly divided into three methods, that is, geophysical method, pumping test method, and multifactor comprehensive analysis method.[11−15] However, the geophysical method and the pumping test method have the disadvantages of high cost, large workload,

and interpretation subjectivity. Therefore, the multifactor comprehensive analysis method, which can consider various factors and has been favored by many scholars in recent years[16−18] used the analytic hierarchy process (AHP), weighted gray relational degree method, and comprehensive weighting method to study the water abundance zoning of Taigemiao no. 3 coalfield in Inner Mongolia, China; Hou et al.[19] used the improved AHP and entropy weight method to study the coupling method to predict and compare the water abundance zone in the south wing of the Ningtiaota minefield. Han et al.[20] established a roof aquifer, water abundance evaluation model, based on the set pair analysis-variable fuzzy set coupling method, combined with the actual water inflow data, and comprehensively determined the water abundance zone of the study area.
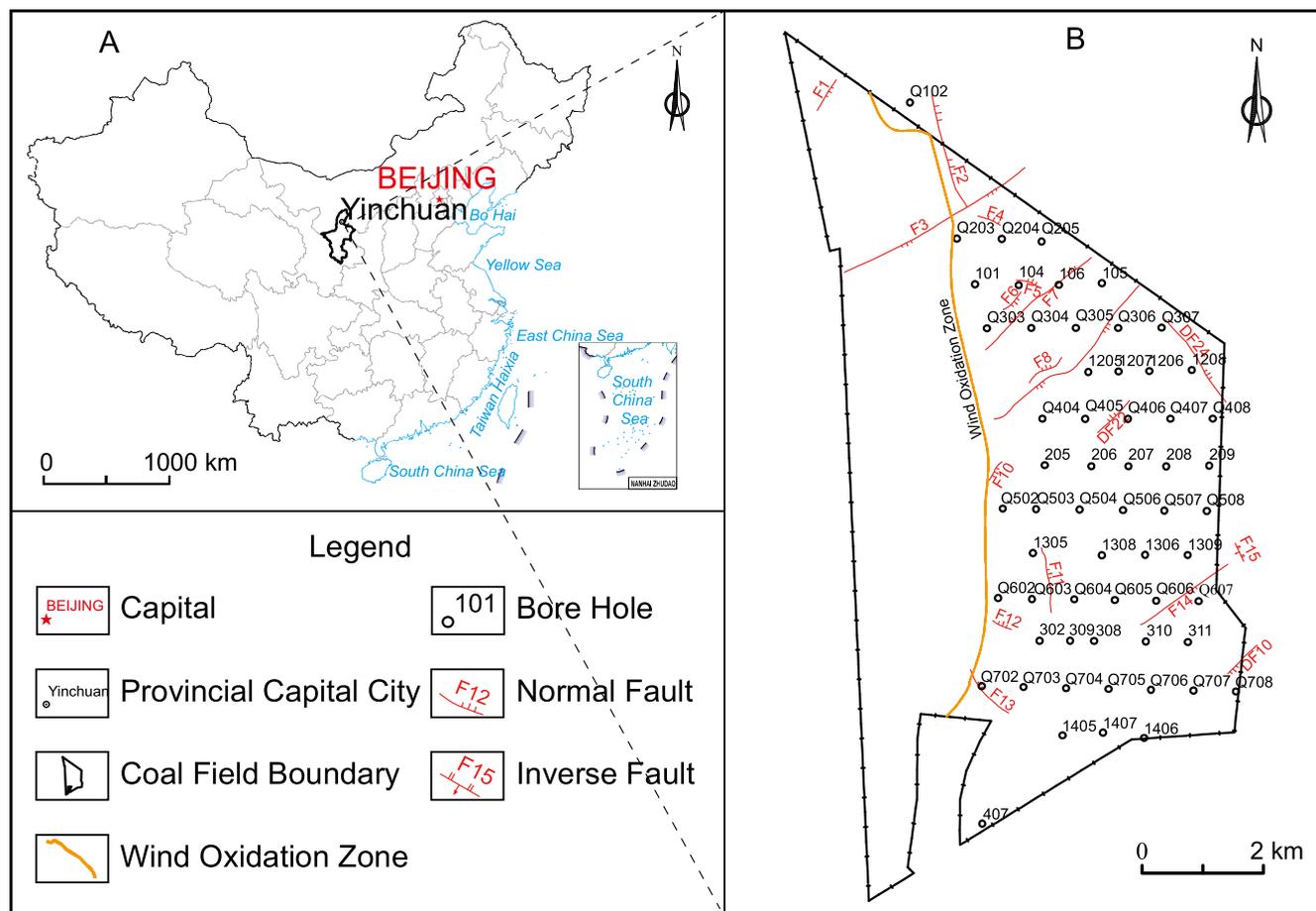
Figure 1. (A) Location map of the study area and (B) structural outline map of the study area.

At present, subjective and objective combination weighting is widely used in water abundance evaluation. However, the evaluation results suffer from randomness and fuzziness. Based on the concept of game theory, this paper carries out a combined weighting of AHP and entropy weight method and combines the cloud model to construct a more scientific and effective water abundance evaluation method for roof sandstone aquifers. Based on the geological conditions of the roof sandstone aquifer, the model selects five factors, that is, sandstone equivalent thickness, sandstone lithology coefficient, sand-mud stone interlayer number, core recovery rate, and fault fractal dimension value as the evaluation indicators of the water abundance of the aquifer. The model is based on the idea of game theory, and the AHP and entropy weights are combined to give weights through confrontation games, which greatly reduces the influence of subjective and objective single weights. In this model, a cloud model is introduced to optimize the membership degree of the comprehensive weight, which solves the problems of ambiguity and randomness existing in the conventional methods of dealing with spatial data. The model provides a new idea for the study of groundwater geology and a new method for predicting the water abundance of the roof aquifer in coal mines.

2. OVERVIEW OF THE STUDY AREA

2.1. Geographical Location. The Qingshuiying Coal Mine is located in the southwest corner of the Ordos Basin, 36 km southwest of Lingwu City, Ningxia Hui Autonomous Region, and 55 km northwest of Yinchuan City (Figure 1). The minefield area is about 18.02 km². The coal-bearing stratum is the Mesozoic Jurassic Yan'an Formation with an average thickness of 28.62 m. There are 20 numbered coal seams, and the coal-bearing coefficient is 10.38%. Currently, the main coal seam is no. 2 coal seam.

The terrain of the mining area is generally characterized by low and gentle low mountains and hills. The terrain is high in the west and low in the east, high in the south, and low in the north. There is no perennial surface stream in the area. There is only water flow in the side ditch on the south side of the Great Wall at the northern end. The source is in the Qingshuiying area.

2.2. Geological Features. Most of the strata in the minefield are covered by the Quaternary (Q). Sporadic bedrocks are exposed in the southwest of the minefield. The minefield strata mainly include Triassic (T), Jurassic (J), Cretaceous (K), Paleogene (E), and Quaternary (Q), among which the Middle Jurassic Yan'an Formation (J_2y) is mainly composed of feldspar quartz sandstone, siltstone, mudstone, aluminous mudstone, and so forth. The strata are in pseudoconformity contact.

The minefield is generally a gently sloping monoclinic structure, and the structure as a whole strikes north–south, dipping from west to east. There are secondary fold structures developed, and most of them are wide and gently undulating, and the dip angle is less than 10°. There are 15 faults developed, namely, F1−F15 faults (11 normal faults and 4 reverse faults).

2.3. Hydrogeological Features. The main water-filled aquifers in the minefield are the Jurassic clastic rock fractured pore confined aquifer, the interlayer confined aquifer of cretaceous conglomerate fissure pore and the Quaternary loose porous phreatic aquifer. The lithology of the aquifer is mainly sandstone, including siltstone, fine sandstone, medium sandstone, and coarse sandstone, and some mudstone, clay sand, and granular clay sand. Among them, the Jurassic and Cretaceous sandstone aquifers are the main research objects.

Atmospheric precipitation, Quaternary phreatic water in paleochannel, water from coarse sandstone aquifers in the lower member of the Straight Rom Group, water in mined-out areas, and water in the wind oxidation zone are the main water filling source in the study area. Faults, poorly sealed boreholes, and paleochannels or scour zones are the main water pathways.

3. METHODS

The construction of an improved combination weighted prediction model of aquifer water abundance based on the cloud model is mainly divided into five steps: (1) analyze the geological and hydrogeological conditions of the study area and select model evaluation indicators; (2) the analytical hierarchy process determines the subjective weight, and the entropy weight method determines the objective weight; (3) based on game theory, improve the combined weighting of subjective and objective weights; (4) introduce the cloud model, calculate the membership degree of the quantitative index, and determine the water abundance grade of the single hole; (5) water abundance partitioning and interpretation. The steps are shown in Figure 2:
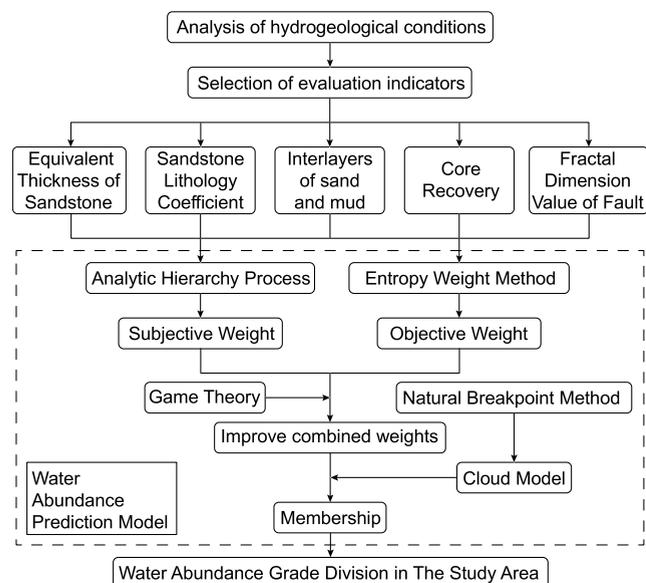

Figure 2. Research flowchart.

3.1. Overview of the Cloud Model. The cloud model is proposed to better study the randomness and ambiguity of things in nature. It draws on the advantages of natural language and realizes the natural conversion between qualitative language values and quantitative values. In addition, it usually plays the role of replacing the membership function in the fuzzy comprehensive evaluation.[21−23]

Let $U=(x)$ be a universe of discourse, which is a quantitative universe of discourse and whose only relational value is L. x is

not only the specific value of a factor when we evaluate the model but also the degree of membership $R_L(x)$ to L, which is a random number with a stable tendency and the degree of membership $R_L(x) \in [0,1]$. Each different x has a corresponding degree of certainty $\mu(x_i)$, namely

$$\mu(x_i) = \exp\left[-\frac{(x_i - E_x)^2}{2E_n'^2}\right] \quad (1)$$

In this way, a cloud droplet is obtained and the cloud is composed of multiple cloud droplets, which is the cloud model.

The numerical characteristics of clouds are the usual representation methods of cloud models, mainly including expectation Ex, entropy En, and hyperentropy He. A large number of cloud droplets are obtained through the forward or reverse cloud generator for each set of determined digital features, and a large number of cloud droplets are collected and aggregated to generate a probability distribution cloud.[24] The forward cloud generator is widely used, and it is converted into a cloud map by determining the digital characteristics, that is, from qualitative mapping to quantitative mapping.[25] This paper applies the forward cloud model.

3.2. Evaluation Index Combination Weighting Method. *3.2.1. AHP Subjective Empowerment.* The AHP belongs to the theory of operation research and is a method of subjective empowerment that has been used since the 1970s.[26−28] It is mainly divided into four steps: (1) build a hierarchical model; (2) construct a comparison judgment matrix in which the property of the judgment matrix is $a_{ij} = \frac{1}{a_{ji}}$, and the scaling method of the elements of the judgment matrix is shown in Table 1; (3) calculate the eigenvalues of the

Table 1. Proportional Scales

factor i is better than factor j	quantized value
equally important	1
slightly important	3
relatively strongly important	5
strongly important	7
extremely important	9
the median value of two adjacent judgments	2,4,6,8

judgment matrix and the corresponding eigenvectors; (4) hierarchical single sort and its consistency test. Then, the total ranking of the hierarchy can be obtained, that is, the weight; otherwise, the comparison judgment matrix needs to be adjusted until the requirements are met.[29−31]

3.2.2. Objective Weighting by Entropy Weight Method. The entropy weight method is an objective weighting method focusing on objective data and calculating the corresponding weight value through a series of mathematical formulas.[32−34] The general steps are as follows:

(1) Quantitative tempering is performed on the data, and the calculation formula is as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \quad (2)$$

$$z_{ij} = \frac{x_{ij} - \min\{x_{1j}, x_{2j}, \cdots, x_{nj}\}}{\max\{x_{1j}, x_{2j}, \cdots, x_{nj}\} - \min\{x_{1j}, x_{2j}, \cdots, x_{nj}\}} \quad (3)$$

In the formula, z_{ij} is the value of the j-th indicator after the standardization of the i-th scheme.

(2) Calculate the proportion of the j-th indicator in the i-th scheme

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{n} z_{ij}}, \qquad i = 1,2, ..., n; \ j = 1,2, ..., m \quad (4)$$

(3) Calculate the entropy value e_j of the j-th index

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln p_{ij},$$

$$j = 1,2, \cdots, m; \ k = 1/\ln n \geq 0, \ e_{ij} \geq 0 \quad (5)$$

(4) Calculate the weight ω_j of the j-th indicator

$$\omega_j = \frac{1 - e_j}{\sum_{j=1}^{m}(1 - e_j)}, \qquad j = 1,2, ..., m \quad (6)$$

3.2.3. Combination Empowerment Based on Game Theory.

Game theory can make a good balance of the weights calculated by subjective and objective weighting so as to obtain more accurate combination weights by assigning more reasonable weights.[35−37] Scilicet, taking the subjective weight $W_1 = \omega_{11}, \omega_{12}, ..., \omega_{1m}$ determined by the AHP method as one side of the game and the objective weight $W_2 = \omega_{21}, \omega_{22}, ..., \omega_{2m}$ determined by the entropy weight method as the other side of the game, the combined weight of both sides of the game in a balanced state is the optimal combined weight. The calculation steps are as follows:

(1) The combination weight W obtained by game theory is

$$W = \begin{bmatrix} \lambda_1\omega_{11} + \lambda_2\omega_{21} \\ \lambda_1\omega_{12} + \lambda_2\omega_{22} \\ \vdots \\ \lambda_1\omega_{1m} + \lambda_2\omega_{2m} \end{bmatrix} = \begin{bmatrix} \omega_{11} & \omega_{21} \\ \omega_{12} & \omega_{22} \\ \vdots & \vdots \\ \omega_{1m} & \omega_{2m} \end{bmatrix} \begin{pmatrix} \lambda_1 \\ \lambda_2 \end{pmatrix}$$

$$= \lambda_1 W_1 + \lambda_2 W_2 \quad (7)$$

In the formula, λ_1 and λ_2 are the linear combination coefficient.

(2) Based on the idea of game theory, an objective function is established to find the optimal linear combination coefficients λ_1' and λ_2' so that the combination weight and the subweight have the smallest sum of dispersion. At this time, the optimal combination weight is recorded as W', and the objective function and constraints are as follows

$$\min(\|W - W_1\|_2 + \|W - W_2\|_2)$$

$$= \min(\|\lambda_1 W_1 + \lambda_2 W_2 - W_1\|_2$$

$$+ \|\lambda_1 W_1 + \lambda_2 W_2 - W_2\|_2) \quad (8)$$

In the formula, $\lambda_1 + \lambda_2 = 1$ and $\lambda_1, \lambda_2 \geq 0$.

(3) According to the differential principle, the first-order derivative conditions that need to be satisfied for the above model to obtain the minimum value are

$$\begin{cases} \lambda_1 W_1 W_1^T + \lambda_2 W_1 W_2^T = W_1 W_1^T \\ \lambda_1 W_2 W_1^T + \lambda_2 W_2 W_2^T = W_2 W_2^T \end{cases} \quad (9)$$

Standardize the obtained λ_1 and λ_2 to get

$$\begin{cases} \lambda_1' = \dfrac{|\lambda_1|}{|\lambda_1| + |\lambda_2|} \\ \lambda_2' = \dfrac{|\lambda_2|}{|\lambda_1| + |\lambda_2|} \end{cases} \quad (10)$$

The optimal combination weight of the evaluation indicators obtained from the above calculation is

$$W' = \lambda_1' W_1 + \lambda_2' W_2 \quad (11)$$

3.2.4. Water Abundance Evaluation Model Based on the Cloud Model.

The combined weighting method based on game theory can make the weights obtained by AHP and entropy weighting method more accurate, and the cloud model can deal with the problems of ambiguity and randomness associated with conventional methods in risk assessment. Therefore, this paper combines the two to establish a comprehensive evaluation model based on the combined weighting method and the normal cloud model. The steps are as follows:

(1) Establishing the factor universe $C = \{u_1, u_2, ..., u_n\}$ of the evaluation object, and the comment domain $T = \{v_1, v_2, ..., v_n\}$;

(2) A single-factor evaluation is performed between the factor universe C of the evaluation object and the comment universe T, and a fuzzy relationship matrix R is established. The element r_{ij} in R represents the membership degree of the i-th factor u_i in the universe of discourse C corresponding to the j-th level T_j in the comment universe T. Here, the normal cloud model is used to calculate the membership degree of the evaluation factor. Assuming that the upper and lower boundary values of the level j (j = 1, 2, ..., m) corresponding to the factor I (i = 1, 2, ..., n) are x_{ij}^1 and x_{ij}^2, the qualitative concept of the level j corresponding to the factor i can be represented by a normal cloud model, where

$$E_{xij} = \frac{(x_{ij}^1 + x_{ij}^2)}{2} \quad (12)$$

$$E_{nij} = \frac{(x_{ij}^1 - x_{ij}^2)}{6} \quad (13)$$

$$H_{eij} = k \quad (14)$$

(3) Due to the ambiguity of the membership matrix generated by the cloud model, in order to improve the accuracy and achieve the results we need, the X-condition cloud generator is used, and it is set to run N times. The obtained results are averaged, and finally, the membership matrix $Z = (z_{ij})_{n \times m}$ of the normal cloud model corresponding to different levels of each index is obtained.

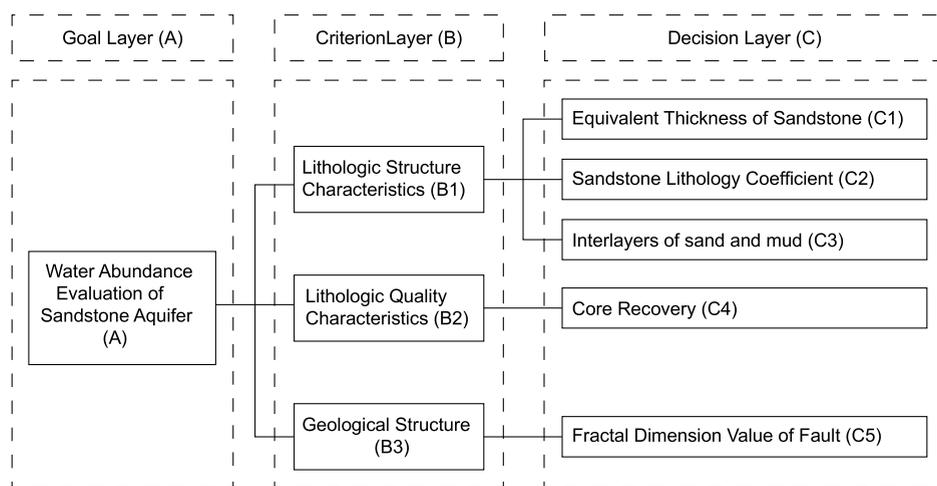$$Z_{ij} = \frac{1}{N} \sum_{k=1}^{N} z_{ij}^k \quad (15)$$

Figure 3. Prediction index system of water abundance in the roof aquifer of no.2 coal seam.

(4) Weight $W = \{w_1, w_2, ..., w_n\}$ of the combination weighting method based on game theory;

(5) Using the weight set W and the membership matrix Z to perform a fuzzy transformation to obtain the fuzzy subset B on the evaluation set V

$$B = W \cdot Z = (b_1, b_2 \cdots b_m) \qquad (16)$$

In the formula, $b_j = \sum_{i=1}^{n} w_i z_{ij}(j = 1,2, ..., m)$ represents the membership degree of the object to be evaluated to the j-th comment. Finally, according to the principle of maximum membership degree, the grade corresponding to the maximum membership degree is selected as the comprehensive evaluation result of the evaluation object.

4. DATE

4.1. Construction of Water Abundance Prediction Index System for the Roof Aquifer of No. 2 Coal Seam. By analyzing the geological, hydrogeological, and structural conditions of Qingshuiying, it was found that the geological structure of the mining area is relatively developed, and the lithology is mainly sandstone. Combined with the actual mining conditions and drilling data, three factors, including lithological structure characteristics, lithological quality characteristics, and the development degree of structural fissures, were determined as the main discriminating indicators affecting the water abundance of the roof aquifer of no. 2 coal seam. The lithological structure characteristics are judged by three indicators: equivalent thickness of sandstone, sandstone lithological coefficient, and interlayers of sand and mud; the lithological quality characteristics are judged by the core recovery, and the geological structure is judged by the fractal dimension value of faults. The water abundance prediction index system of the aquifer constructed based on the AHP is shown in Figure 3.

4.2. Analysis of Influencing Factors. *4.2.1. Equivalent Thickness of Sandstone.* Sandstone is an important factor affecting the underground water storage space. Sandstone in the aquifer in the study area occupies a large part, including coarse sandstone, medium sandstone, and fine sandstone. The equivalent thickness of sandstone is the product of the thickness of sandstone encountered in each borehole and the equivalent coefficient, which can represent the overall thickness of the sandstone to the greatest extent. Larger

thickness suggests stronger water abundance. Based on the measurement results of the porosity and permeability of various types of sandstones on the roof of the coal seam in other coal mines in the study area and the relevant information, 1, 0.8, and 0.6 were selected as the equivalent coefficients for calculating coarse sandstone, medium sandstone, and fine sandstone, respectively. The calculation formula is

$$M_1 = a \times M_2 + b \times M_3 + c \times M_4 \qquad (17)$$

where a, b, and c are the equivalent coefficients of coarse sandstone, medium sandstone, and fine sandstone, which are 1, 0.8, and 0.6, respectively. Also, M_1, M_2, M_3, and M_4, respectively, represent the equivalent thickness of sandstone, thickness of coarse sandstone, thickness of medium sandstone, and thickness of fine sandstone.

4.2.2. Sandstone Lithological Coefficient. The lithology of the roof aquifer of the no. 2 coal seam in the study area is mainly sandstone and mudstone, among which the sandstone has better water abundance. The thickness of the sandstone is directly proportional to the water abundance. The sandstone lithology coefficient is the proportion of the cumulative thickness of the sandstone relative to the statistical section, which can better reflect the overall water abundance of the roof strata of the coal seam. The higher the sandstone lithology coefficient, the stronger the water abundance roof.

4.2.3. Interlayers of Sand and Mud. Interlayers of sandstone and mudstone are commonly found in the roof strata of no. 2 coal seam in the study area. It is generally believed that the greater the thickness of the sandstone, the more sandstone layers, and the stronger the water abundance roof. Therefore, the greater the number of interlayers of sandstone and mudstone, the greater the number of sandstone layers, and the stronger the water conductivity.

4.2.4. Core Recovery. The core recovery refers to the percentage of the total length of the extracted cores to the current footage. The total length includes relatively complete cores and broken fragments, debris, and crushed materials, reflecting the integrity of the rock. The integrity of the rock is proportional to this value. The smaller the value, the greater the degree of damage to the rock formation, the more developed the fractures, and the stronger the water conductivity and water abundance.

4.2.5. Fractal Dimension Value of Faults. The structure of the study area is relatively developed, and many small cracks are often formed when the fault structure occurs, which is easy to make such faults (or fault zones) having water conductivity. Because of the large amount of water-bearing space, the fault can easily become a water body, and it can easily become a water-filled water source. The fractal dimension value of faults is a quantitative, effective, and accurate index for evaluating the complexity of the structure, and it is a quantitative evaluation to reflect the complexity of the structure development.[38,39] The larger the fractal dimension value of the fault value, the more developed the fault structure, and the better the water abundance.

4.3. Indicator Data and Standards. Based on the actual drilling data in the study area, the thickness of various types of sandstone, mudstone thickness, and interlayers of sand and mud on the no. 2 coal seam roof of each drilling hole is counted. The equivalent thickness of sandstone and sandstone lithological coefficient are calculated by actual data; The interlayers of sand and mud is obtained by statistical drilling data; the core recovery is determined according to the actual drilling situation; the fractal dimension value of the fault is obtained by statistics and calculation of the fault through grid division.

According to the "Exploration Specification Hydrogeology and Engineering Geology in Mining Area (GB/T 12719-2021)", water abundance can be divided into four grades: weak, medium, strong, and extremely strong, as defined by the unit water inflow volume of the borehole. Based on the division criteria of the "Code" and the actual situation that the hydrogeology in the study area belongs to a simple type, the water abundance grades of the sandstone aquifer on the roof of Qingshuiying no. 2 coal seam are divided into weak water abundance areas, relatively weak water abundance areas, relatively strong water abundance areas, and strong water abundance areas. Using the Natural Breaks (Jenks) method of ArcGIS software to classify the index data, this paper establishes the water-rich evaluation index standard of Qingshuiying 2 coal roof sandstone (Table 2).

Table 2. Water Yield Evaluation Index Standard of Roof Sandstone in Qingshuiying No. 2 Coal Seam

index	weak water abundance areas	relatively weak water abundance areas	relatively strong water abundance areas	strong water abundance areas
C1	(27.333, 51.967)	(51.967, 69.211)	(69.211, 88.097)	(88.097, 131.616)
C2	(0.558, 0.696)	(0.696, 0.786)	(0.786, 0.855)	(0.855, 0.938)
C3	(1.081, 1.460)	(1.460, 1.777)	(1.777, 2.089)	(2.089, 2.385)
C4	(0.559, 0.634)	(0.634, 0.689)	(0.689, 0.744)	(0.744, 0.808)
C5	(0.000, 0.354)	(0.354, 0.547)	(0.547, 0.716)	(0.716, 1.025)

5. RESULTS AND DISCUSSION

5.1. Comprehensive Weight Determination of Evaluation Indicators. *5.1.1. AHP Method to Determine the Weight. (1) Build a Hierarchical Model.* After comparing and analyzing the main controlling factors affecting the water richness of the boundary sandstone aquifer, the paper established a hierarchical structure model for the water

Table 3. Judgment Matrix A−Bi (i = 1−3)

A	B1	B2	B3	W
B1	1	4	2	0.5714
B2	1/4	1	1/2	0.1429
B3	1/2	2	1	0.2857

Table 4. Judgment Matrix B1∼Ci (I = 1∼3)

B1	C1	C2	C_3	W
C1	1	1/5	1/3	0.1095
C2	5	1	2	0.5816
C3	3	1/2	1	0.3090

Table 5. Subjective Weights of the Main Controlling Factors

index	C1	C2	C3	C4	C5
subjective weight	0.0626	0.3323	0.1766	0.1429	0.2857

Table 6. Calculation Results of the Entropy Weight Method

index	C1	C2	C3	C4	C5
objective weight	0.2436	0.0891	0.3375	0.1761	0.1537

Table 7. Mixed-Weighting Table of the AHP Coefficient of the Variation Method

index	subjective weight	objective weight	combination weight
C1	0.0626	0.2436	0.1475
C2	0.3323	0.0891	0.2183
C3	0.1766	0.3375	0.2520
C4	0.1429	0.1761	0.1584
C5	0.2857	0.1537	0.2238

richness evaluation of the sandstone aquifer, as shown in Figure 3.

(2) Construction of the AHP Judgment Matrix and Consistency Test. According to the influence degree of each main control factor in the water richness evaluation of the boundary sandstone aquifer, combined with expert opinions, the main control factors are scored by experts, and a hierarchical judgment matrix is established for the main control factors. This paper establishes the judgment matrix between the water abundance (goal layer A), lithological structure characteristics and fracture characteristics (criterion layer B), and the main controlling factors (decision layer C) of the boundary sandstone aquifer respectively, as shown in Table 3 and Table 4.

The consistency ratio of all judgment matrices is CR < 0.1, which meets the consistency requirements. Therefore, the subjective weight values of the main controlling factors affecting the water richness of the boundary sandstone aquifer are obtained through the above judgment matrix, as shown in Table 5.

5.1.2. Entropy Weight Method to Determine Weight. Using formulas 2) to 6) to calculate the data of each index, the weights of the five indicators that affect the water richness of the roof aquifer are finally obtained, as shown in Table 6:

5.1.3. Determining Combination Weight Based on Game Theory. The paper uses the AHP method and the entropy weight method to obtain the weight values of the five indicators that affect the water richness of the roof aquifer. The standardized linear-scale coefficients calculated by eqs 7−11 are 0.5310 and 0.4690, respectively. Therefore, the optimal

Table 8. Normal Cloud Standard for the Water Yield Evaluation Index of Area Studies

index	weak water abundance areas	relatively weak water abundance areas	relatively strong water abundance areas	strong water abundance areas
C1	(39.650,4.106,0.01)	(60.589,2.874,0.01)	(78.654,3.148,0.01)	(109.857,7.253,0.01)
C2	(0.627,0.023,0.001)	(0.741,0.015,0.001)	(0.821,0.012,0.001)	(0.897,0.014,0.001)
C3	(1.271,0.063,0.001)	(1.619,0.053,0.001)	(1.933,0.052,0.001)	(2.237,0.049,0.001)
C4	(0.597,0.013,0.001)	(0.662,0.009,0.001)	(0.717,0.009,0.001)	(0.776,0.011,0.001)
C5	(0.177,0.059,0.001)	(0.451,0.032,0.001)	(0.632,0.028,0.001)	(0.871,0.052,0.001)
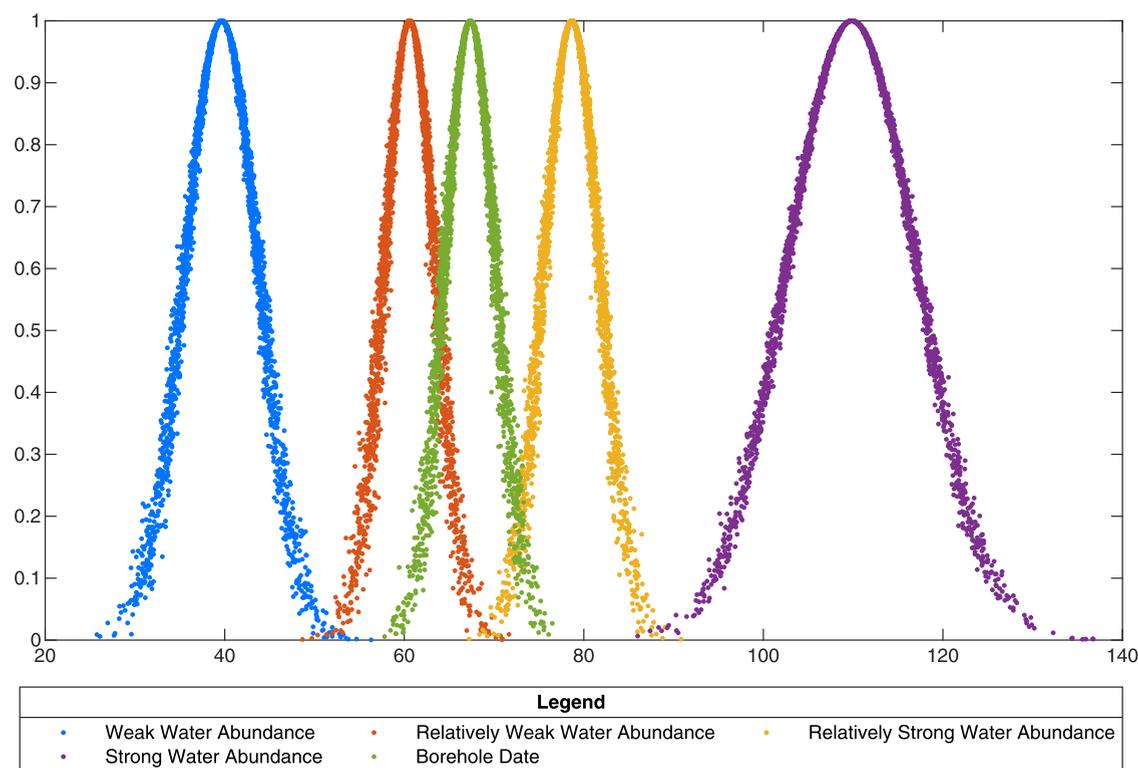
Figure 4. Cloud chart of the equivalent thickness of sandstone water abundance grade of 1305 hole.

Table 9. Membership Degree of Water Abundance of Sandstone Aquifers in the 1305 Borehole

1305 hole	weak water abundance areas	relatively weak water abundance areas	relatively strong water abundance areas	strong water abundance areas
C1	0.0000	0.0631	0.0016	0.0000
C2	0.0000	0.0000	0.0000	0.2131
C3	0.0002	0.2395	0.0000	0.0000
C4	0.0000	0.0000	0.0000	0.8433
C5	0.0004	0.4859	0.0000	0.0000

combination weight value can be obtained by Formula 11. The results are shown in Table 7.

5.2. Water Abundance Evaluation Based on Cloud Model. *5.2.1. Cloud Model Membership.* On the basis of the factor domain C (evaluation index) of the evaluation object and the comment domain T (Evaluation Level), according to formulas 17, 12, and 13, the three numerical expected expectation Ex, entropy En, and hyperentropy He of the cloud model are calculated.

The water abundance evaluation index standard (Table 2) was converted into the cloud language (Table 8), combined with formula 1 and the code of the normal cloud generator, repeated 3000 times in MATLAB, and the cloud maps

corresponding to different levels of each index (Figure 4) were obtained.

According to formula 15, the drilling data are substituted into the X-condition cloud generator in turn, and the operation is repeated 3000 times; the water-rich membership degree of the 1305 hole in the Qingshuiying no. 2 coal seam was obtained (Table 9). The water-rich membership degree of other holes was the same as that of the 1305 hole.

5.2.2. Results of Water Abundance Evaluation. The mixed weight W of each index is combined with the membership degree Z of each borehole by the fuzzy mathematical transformation method, and the water-rich grade evaluation of the coal roof sandstone aquifer of each drill hole in Qingshuiying is obtained according to the principle of maximum membership degree. With the help of ArcGIS software, the Empirical Bayesian Kriging method was used to process the water-rich grade data of each borehole in Qingshuiying, and finally, the water-rich distribution map of Qingshuiying no.2 coal roof sandstone aquifer was obtained, as shown in Figure 5.

The figure shows that most of the study areas are located in weak or relatively weak water abundance areas; relatively strong water abundance areas are mainly distributed in the central, western, and southeastern parts of the study; strong
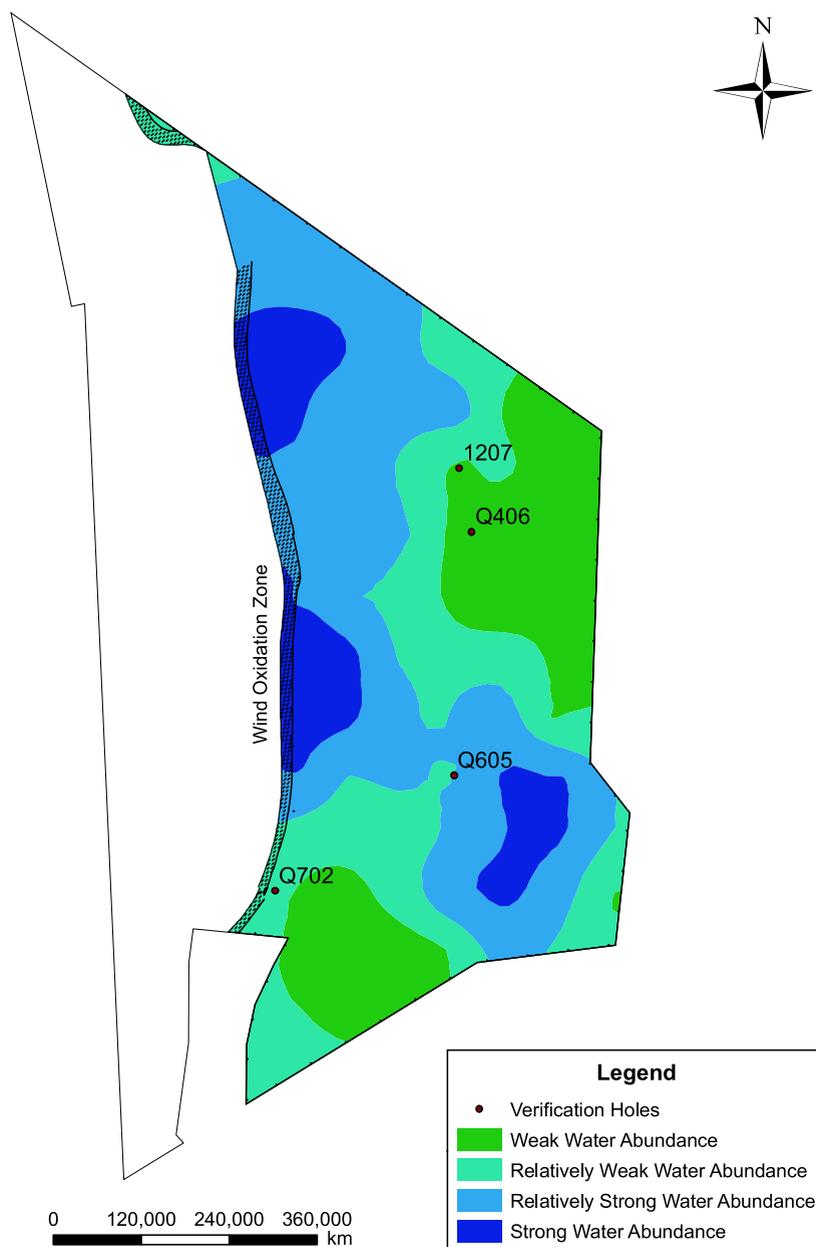
Figure 5. Water-rich distribution of sandstone aquifers in the roof of Qingshuiying no. 2 Coal Seam.

Table 10. Value Range Comparison Table

index	range of raw data	range of Kriging interpolated data
C1	(6.63,228.00)	(27.33,132.03)
C2	(0.38,1.00)	(0.56,0.94)
C3	(1.00,3.00)	(1.15,2.32)
C4	(0.30,0.95)	(0.56,0.81)
C5	(0.00,1.29)	(0.00,1.02)

water abundance areas are scattered in parts of the northeast, southwest, and southeast.

5.2.3. Result Verification. According to the actual pumping test data of the early hydrological hole, the pumping horizon is the no. 2 coal roof sandstone aquifer group, the unit water inflow volume of the 1207 borehole is $q = 0.0137$ L/(s·m), the unit water inflow volume of the Q406 borehole is $q = 0.0401$ L/(s·m), the unit water inflow volume of the Q702 borehole is $q = 0.2450$ L/(s·m), and the unit water inflow volume of the

Q605 borehole is $q = 0.0336$ L/(s·m). According to the water abundance distribution of the Qingshuiying no. 2 coal roof sandstone aquifer shown in Figure 5, it can be found that most of the boreholes are located in the corresponding partitions, which proves the rationality and accuracy of the above partitions.

5.3. Discussion. Groundwater is an important part of water resources and plays an indispensable role in human reproduction and life. Among them, the occurrence conditions of water resources in deep confined aquifers are extremely complex and are jointly affected by various factors such as geological conditions and geological structures, so it is extremely difficult to detect and evaluate their water richness. At present, the water abundance detection of deep confined aquifers mostly uses the "big well method" to predict the water inflow or use the pumping experiment to calculate the unit water inflow. However, due to the influence of geological
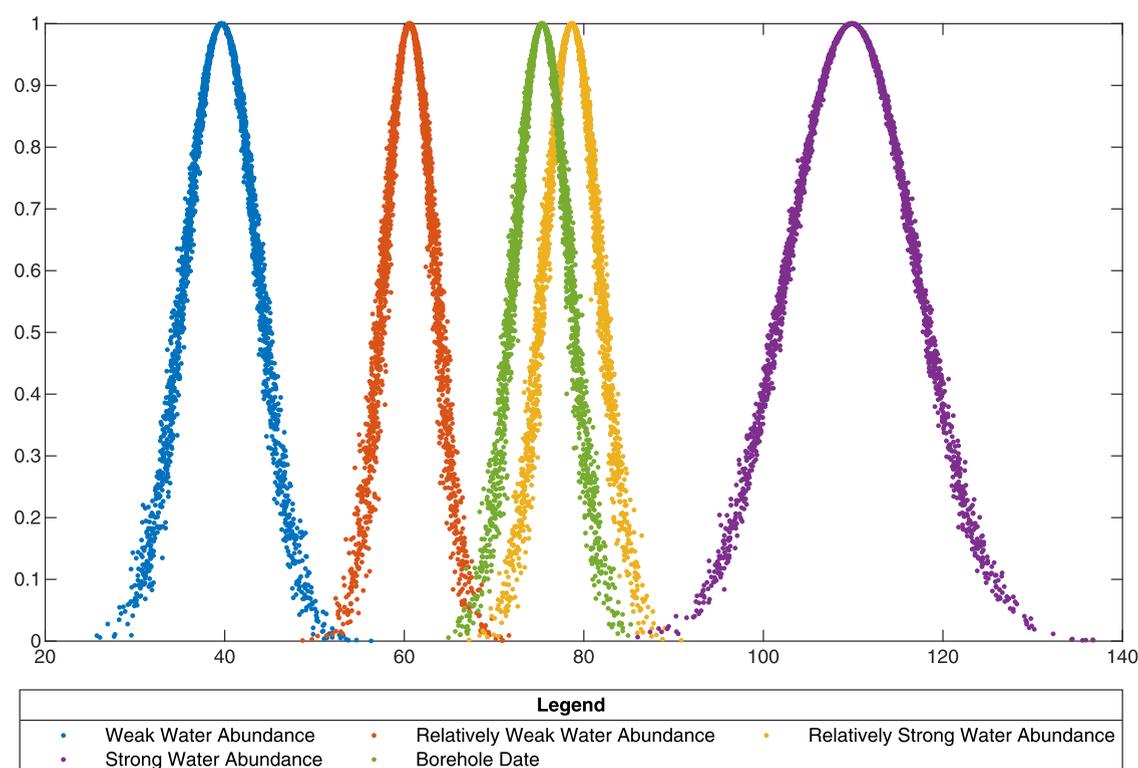
Figure 6. Cloud chart of the original data of equivalent thickness of sandstone water abundance grade.

conditions, the research is mostly limited to local or extremely small areas.

Based on the above problems, this paper proposes a new combined weighting method applied to the evaluation of water abundance of aquifers, which supplements the research on the potential relationship between water abundance and hydrogeological conditions of deep confined aquifers. The previously used evaluation method has been improved in two aspects. First, the subjective and objective evaluation methods are combined by game theory so that the weights obtained by AHP and the entropy weight method are more accurate. Second, the membership degree analysis of the cloud model is introduced into the evaluation model. Through the cloud model processing, the problems of ambiguity and randomness in the risk assessment of the conventional combination weighting method are solved.

However, when using the combined weighting method proposed in this paper, it becomes a necessary process to re-extract the contour map obtained by Kriging interpolation of the original data. In this paper, when using the Kriging space interpolation method to classify the original data with natural breakpoints, the range of the original data is reduced, as shown in Table 10, so the original data of each borehole has also changed accordingly. In order to compare the influence of the Kriging interpolation method on the cloud model membership, taking the 1305 borehole as an example, the original drilling data and Kriging interpolation were used to extract the data to calculate the cloud model membership.

Taking the equivalent thickness of sandstone of the 1305 borehole as an example, Figure 4 shows the grading cloud map obtained by re-extracting the borehole data, which is obtained by performing Kriging interpolation on the equivalent thickness of the sandstone in the study area to obtain a contour map and then re-extracting the values obtained by re-

extracting the cloud model membership degree calculation. Figure 6 shows the grading cloud map of the original data of the equivalent thickness of the sandstone in the 1305 borehole.

It can be seen in Figure 6 that the water abundance grade of the sandstone equivalent thickness index after re-extraction by Kriging interpolation belongs to the relatively strong water abundance grade, while the water-rich grade of the original borehole data belongs to the relatively weak water abundance grade. Therefore, the natural breakpoint grading after Kriging interpolation and then using the original data to calculate the membership degree will produce a certain error, which is also proven in the final water abundance grade evaluation.

After applying Kriging interpolation for natural breakpoint grading, the membership degree of the water-rich grade is calculated through the original drilling data, the water abundance of the Q204 borehole belongs to the relatively strong water abundance, and the Q406 borehole water abundance belongs to the strong water abundance. The predicted results are quite different from the actual water inflow.

Therefore, it is a necessary process to use the combined weighting method proposed in this paper to re-extract the contour map obtained by Kriging interpolation of the original data. In addition, in other scenarios where Kriging interpolation is used to perform natural breakpoint grading operations, it is also necessary to analyze and verify whether the subsequent calculations can use the original data.

6. CONCLUSIONS

(1) The water richness evaluation method based on the cloud model comprehensively considers the main factors affecting the water richness of roof sandstone. The AHP and entropy weight method consider the influence of subjective and objective. The combined weighting

method of game theory improves subjective and objective weights. The idea of the cloud model deals with the ambiguity and randomness of conventional methods in risk assessment.

(2) The results show that most of the study areas are located in weak or relatively weak water abundance areas; whereas relatively strong water abundance areas are mainly distributed in the central, western, and southeastern parts of the study; and strong water abundance areas are scattered in parts of the northeast, southwest, and southeast. The actual pumping test data verifies the prediction results and proves the accuracy and validity.

(3) There are many factors that affect the water richness of sandstone aquifers. In follow-up research, the interference of subjective factors of human empowerment should be minimized. Research should use big data and artificial intelligence to establish the relationship between geological and hydrogeological conditions and unit water inflow to improve accuracy and universality.

(4) When applying Kriging interpolation for natural breakpoint classification, the original data should be re-extracted through Kriging interpolation results in the subsequent membership calculation so as to ensure the uniformity of the data and the accuracy of the prediction results. In addition, in other scenarios where Kriging interpolation is used to perform natural breakpoint grading operations, it is also necessary to analyze and verify whether the subsequent calculations can use the original data.

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Notes

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