

Article

Comprehensive Water Inrush Risk Assessment Method for Coal Seam Roof

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Abstract: In order to prevent coal mine water inrush accidents, it is necessary to appropriately assess the water abundance of coal mines based on drilling and geophysical data. This paper studied a comprehensive risk assessment method of water inrush. First, a water inrush risk index was proposed based on the analytic hierarchy process-entropy method (AHP-EM) and the water-rich structure index was proposed based on the geological data coupled calculation, then weighted two indices above which established the comprehensive water inrush risk assessment method. Secondly, eight factors were chosen as risk control factors of water inrush: core recovery, aquifer thickness, distance from the indirect aquifer to the coal seam, aquiclude thickness, height of water-conducting fracture zone, sand-mud ratio, total layers of aquifer and aquiclude, and the equivalent thickness of sandstone. Finally, the No. 2 coal seam of Dahanze coal mine was taken as the research object, the factors were calculated, and a comprehensive water inrush assessment model was constructed. With site investigation and observation, the water inrush risk assessment model of the No.2 coal seam roof is consistent with the actual mining situation, which verifies the validity of the model. In addition, this method was used to evaluate the water-richness of the weathered bedrock fractured aquifer in the Zhangjiamao coal mine. The practical application of the two mines has verified the generality of the approach. The research could provide scientific assistance for mine water hazard mitigation and mining safety.

Keywords: risk assessment; water inrush risk index; water-rich structure index; Dahanze coal mine; Zhangjiamao coal mine



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1. Introduction

Coal resources still make up a significant proportion of China's energy consumption. The development of China's economy is inextricably linked to the extraction of coal resources [1]. However, since the 21st century, hundreds of water inrush accidents have occurred in China's coal mines, which seriously affected the safety of coal miners and coal production [2]. The Jurassic coal field of Ordos Basin is the one of the 14 large-scale coal bases in China. However, its mine production and construction are generally affected by roof water hazards. Water risks in coal mines are caused by a variety of factors. Coal mine hydrogeological conditions are not clear, and the groundwater occurrence lacks in-depth research; furthermore, the water-rich areas lack scientific predictions. Resolving the potential groundwater yield zonation of sandstone aquifers occurring at depths of several hundred meters has been an important and challenging objective of the hydrogeological research focused on preventing flood hazards in coal mines [3]. Although, many studies have been carried out on mine hydrogeology, there are still many problems such as imperfect groundwater hazard prevention plans and measures, abnormal water inrush, and water inrush in coal mines [4]. In the early stage of mine construction, fully understanding hydrogeological conditions of the mine would benefit water hazard prevention and shorten the construction period.

Scholars have conducted extensive research in the Ordos Basin Jurassic coal field on the prevention and control of roof and floor water inrush hazards in coal mining. The existing studies mainly focus on numerical simulation, theoretical analysis, and laboratory tests. Chen et al. [5] used the Visual Modflow, which predicted water inflow in the first mining working face of Dahanuozhai coal mine, Yulin. Gao et al. [6] used PHASE to analyze the water inflow with different influencing factors and used SPSS software for nonlinear regression analysis to obtain the evaluation model of control factors of coal seam water inrush. Zeng et al. [7] obtained the relative important control factors through the coupling calculation of the analytic hierarchy process (AHP) to compile the thematic map of water-rich evaluation, and finally superimposed on the thematic map of roof fracture safety evaluation to comprehensively evaluate the risk of water inrush.

Many academics have investigated the hazard analysis of coal mine water inrush in other regions. Wu et al. [8,9] proposed the “three maps-two predictions” method to solve the quantitative evaluation of water inrush in coal roofs, which has been successfully applied in the Jinggezhuang coal mine and Donghuantuo coal mine. Nampak and Lee et al. [10,11] applied the Dempster–Shafer theory of evidence model to the groundwater productivity potential map, using the geographic information system (GIS) technique. Subsequently, Ruan et al. [12] used the Dempster–Shafer evidence theory to expand the improved AHP, obtained the weight coefficient of influencing factors, and evaluated the risk of water inrush in the air return roadway of Wangjialing coal mine. Cheng et al. [13] established a prediction and assessment model of roof water inrush risk in multi-coal seam mining by combining the traditional AHP and the entropy method (EM) using the least square method. Lu et al. [14] used the fuzzy analytic hierarchy process (FAHP) and EM to analyze the hydrogeological and engineering geological conditions of Yangliu coal mine, obtained the overall weighting of each factor, and created a risk assessment zoning map using the spatial superposition capability of GIS. To determine the location of water-rich areas, Zhang and Wang [15,16] applied Fisher Discriminant Analysis (FDA) dimensional reduction technology to project original normalized data into low-dimensional space and create a thorough zoning map of water-rich levels in the study area. Bo et al. [17] combined the risk evaluation index system with set pair analysis (SPA), integrated quantitative and qualitative indicators, and established the risk evaluation model of coal floor water inrush. In order to prevent and cure water inrush from sealed holes in the wellbore, Han et al. [18] proposed a new risk assessment model and concentric annular hole grouting method, predicted the water inflow area, and effectively inhibited the groundwater migration of multiple aquifers.

Some academics have done extensive research to address the problem of water disasters caused by geological circumstances of thin bedrock and a thick loose layer. Yang et al. [19] constructed a fuzzy comprehensive evaluation model to study the water inrush caused by coal mining. Zeng et al. [20] introduced the methods of information entropy and unascertained measure to establish a prediction model for coal mine safety. Wang et al. [21] combined the extensive evaluation method with borehole measurement data to establish a matter element model for the evaluation of coal mine safety. Lian et al. [22] studied the causes of water inrush from loose aquifers, and established the importance ranking and correlation degree of each influencing factor, accurately assessed the risk of water inrush from loose aquifers, and improved theoretical approaches for water inrush accident prediction and prevention.

The roof water hazard prediction and assessment processes have been used for many years, such as the “three maps-two predictions” method, nonlinear regression analysis, FDA model, AHP, EM, etc. The AHP only considers the experience evaluation of experts. The EM only uses objective data to calculate weights. However, there has been little research on the prediction of water inrush from coal seam roofs coupling of multiple evaluation methods, and the results need to be improved to meet the requirements of fine study of mining hydrogeological conditions. In this study, developed the water inrush risk model using the AHP-EM and proposed the water-rich structure index model based on the geological data-coupled calculation then weighted two indices above, which established

the comprehensive water inrush risk assessment method. It is critical to provide scientific guidance for mine water hazards prevention and control.

2. Materials and Methods

2.1. Geological and Hydrogeological Conditions

Dahaize Coal Mine is located in Yulin city, Shaanxi Province, China (Figure 1). It is about 14.7 km wide from north to south and 12.5–23.3 km long from east to west, covering an area of about 280 km². The coal-bearing stratum of the mine is the Yan'an Formation of Jurassic, and the Dahaize coal mine is designed to produce 15 million tons per year. The Dahaize coal mine belongs to the Jurassic coal field of Ordos Basin. The mine production is greatly affected by roof water hazards. Therefore, it is urgent to fully understand the mine hydrogeology and improve prevention methods and control measures for water hazards.

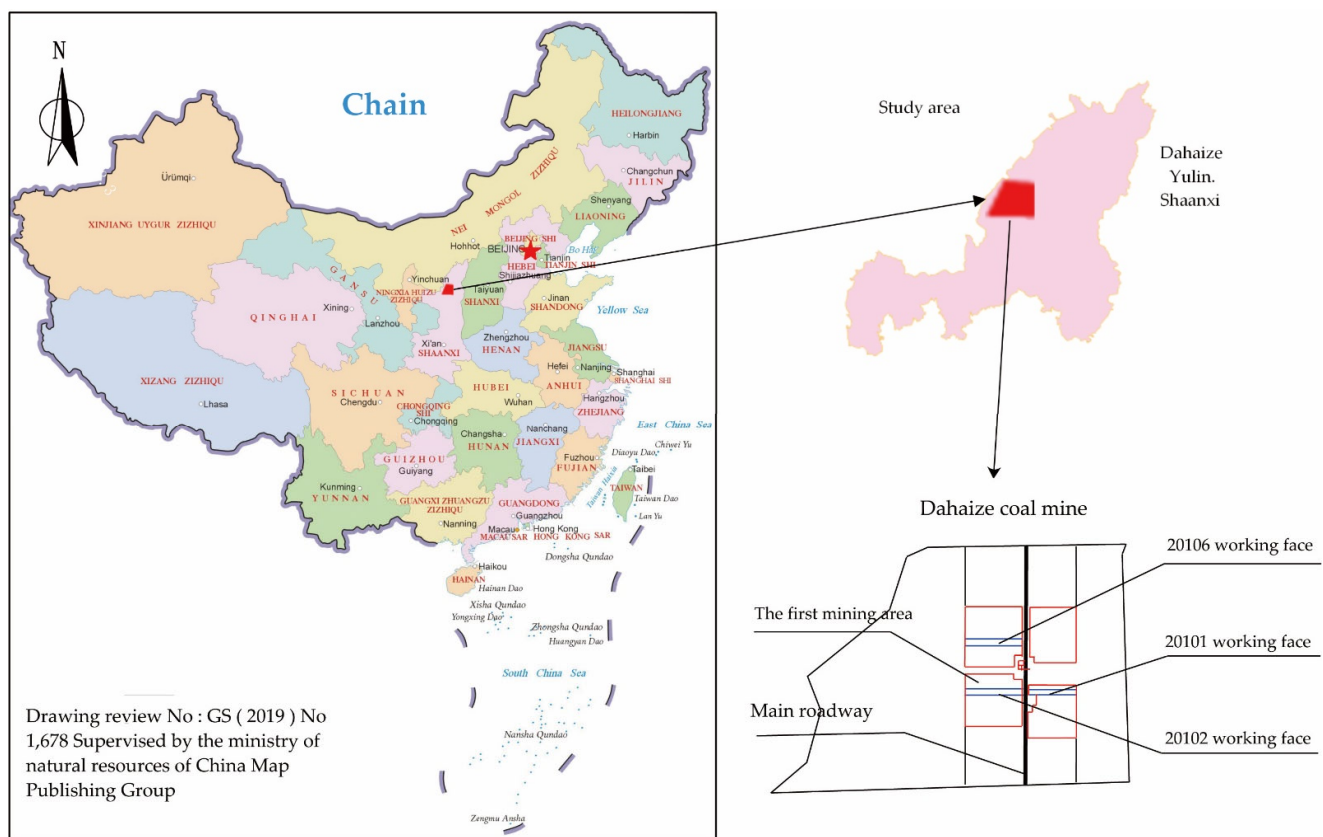


Figure 1. The location of the mining area.

The strata of Dahaize coal mine belong to the Ordos Basin subdivision of northern China, and the sedimentary and geological structure characteristics of each age are nearly consistent with the strata of north China. According to the drilling data, the strata are successively from old to new as Middle Jurassic Yan'an Formation (J_2y), Middle Jurassic Zhiluo Formation (J_2z), Middle Jurassic Anding Formation (J_2a), Lower Cretaceous Luohe Formation (C_1l), Neogene system (N_2j), and Quaternary system (Q). The mine is located in the center of the northern slope of Shaanxi, a secondary structural unit in the central Ordos Basin. On the whole, the stratum is slightly dipped westward, the dip angle of the stratum is nearly horizontal, and the folds are not developed. There are no major faults in the mine, and there is no magmatic intrusion, which results in the simple type of the strata structure type. The No. 2 coal seam of Dahaize coal mine is shallowly buried, covers the whole study area, and gradually becomes thinner from south to north with an average thickness of 5.95 m. According to groundwater occurrence conditions, the water in the aquifers of Dahaize coal mine can be classified into the following three categories: the unconsolidated rock

pore phreatic water of Quaternary, the fracture or pore confined water of Cretaceous, and the fracture confined water of Jurassic. The geological profile of the mining area is shown in Figure 2. Petrological characteristics, hydraulic properties, tempo-spatial structure, and variation characteristics of aquifer and aquiclude are the basic hydrogeological conditions.

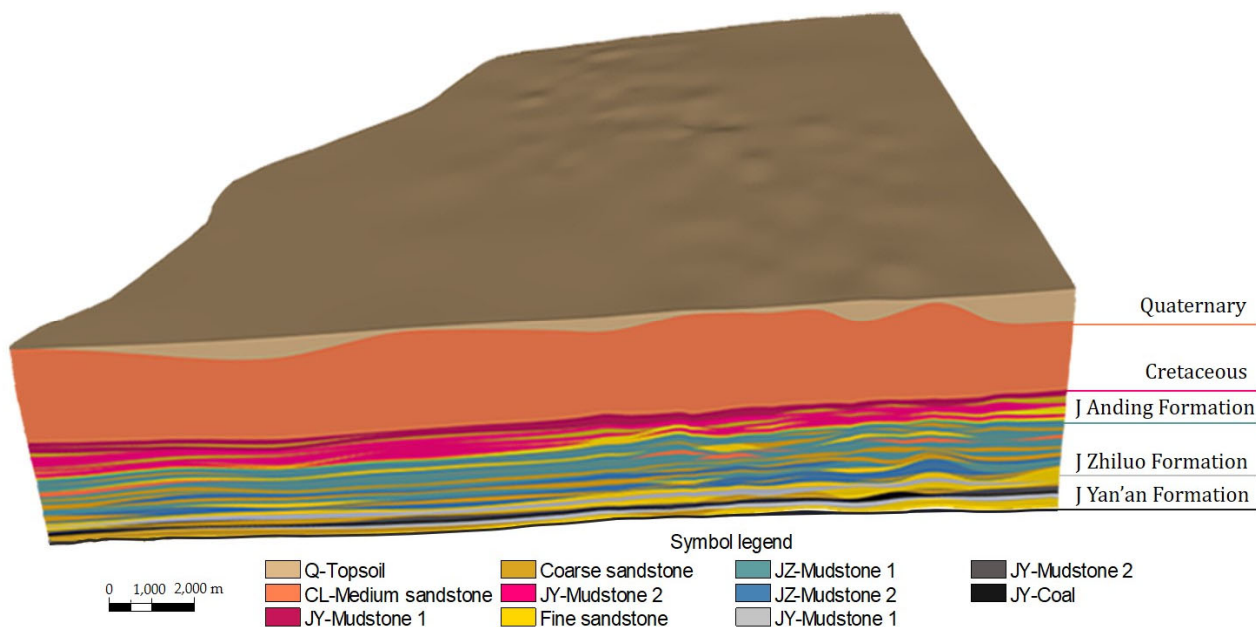


Figure 2. Geographical profile of mining area.

The aquifers are mainly composed of (gravel) coarse grained sandstone, medium grained sandstone, and fine sandstone. The microscopic characteristics of these aquifers are the developed pores, the good connectivity, the low density, the high effective porosity, and the good permeability. The average resistivity of aquifers is greater than $50\Omega\cdot\text{m}$. The logging curve of the sandstone section shows high resistivity, although they have fluctuation. The average resistivity is lower than that of mud rock, and the logging curve is concave, which means that is a low resistivity stratum in the Jurassic range and can be judged as an aquifer [23]. The aquicludes are mainly composed of some fine-grained sedimentary rocks with argillaceous (silty) sandstone, silty mudstone, sandy mudstone, and mudstone. The microscopic characteristics, resistance, and potential values of these rocks are the opposite of aquifers.

2.2. Comprehensive Water Inrush Risk Assessment Method

A new approach for forecasting and evaluating the water hazard of coal seam roofs is provided based on the geologic and hydrogeological characteristics of the Dahanze coal mine. The working steps of the methodology shown in Figure 3. These are the evaluation steps.

1. The water inrush risk index was established by combining AHP and EM with the moment estimation method;
2. The water inrush structure index was used to calculate the water-rich in the study area, and establish the water inrush model;
3. The weighted superposition of the above two models were carried out by using the weighted formula to establish a comprehensive water inrush risk assessment model.

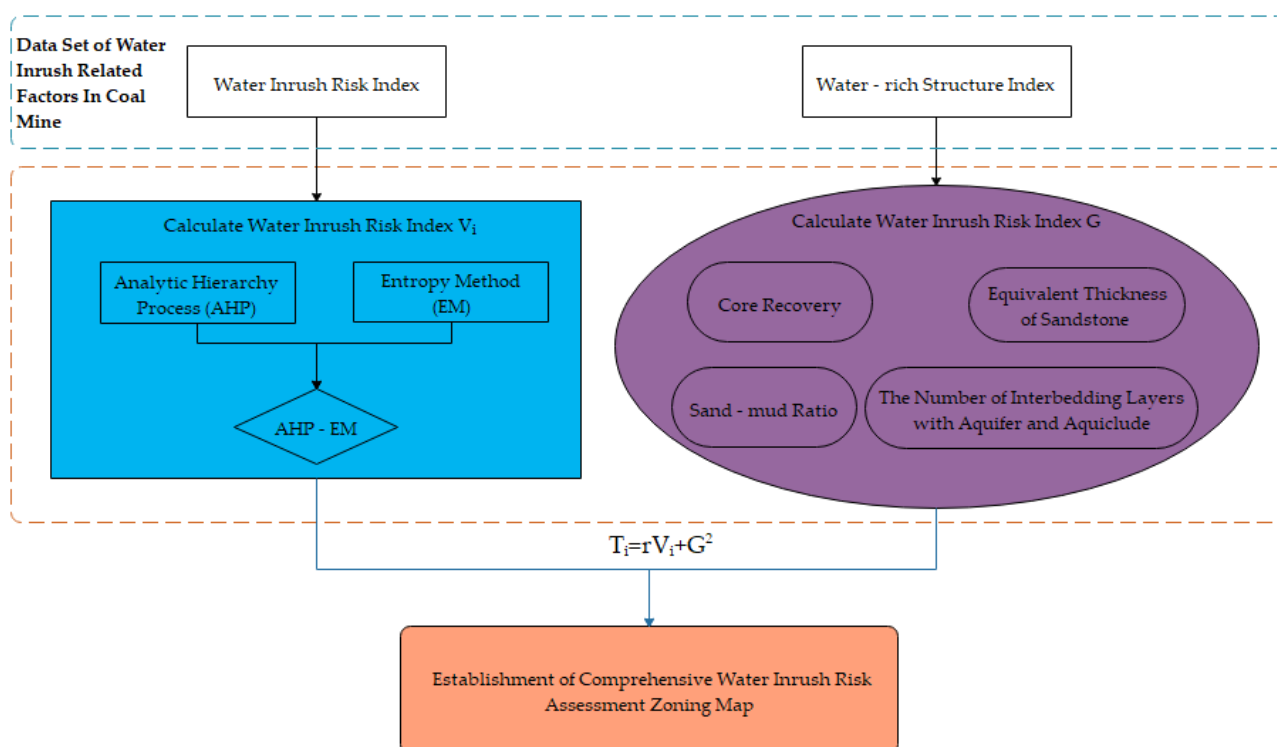


Figure 3. The working steps of the methodology.

By analyzing borehole exploration data (i.e., geophysical data, underground mining data) from the research area, and calculating the data of various control factors, the basic geological data of water inrush in the Dahaize mining area were obtained. The data used to support the results of the study are available from the corresponding researchers according to the requirements. It is important to normalize the data to avoid the effect of the different dimensions and units of the data on the analysis outcomes [24]. After the standardization, the source data were of the same scale, so it could be a good starting point for a full comparison. The basic data could be normalized by Equations (1) and (2).

$$r_{ji} = \frac{x_{ij} - \min_j(x_{ij})}{\max_j(x_{ij}) - \min_j(x_{ij})}, \quad (1)$$

$$r_{ji} = \frac{\min_j(x_{ij}) - x_{ij}}{\max_j(x_{ij}) - \min_j(x_{ij})}, \quad (2)$$

where r_{ji} represents the normalized value of the j th evaluation object in the i th evaluation index, and x_{ij} represents the initial value.

2.2.1. Water Inrush Risk Index

Analytic Hierarchy Process (AHP)

The AHP is more suitable for decision-making problems where the target system has hierarchical and interlaced evaluation indicators, and the target value is difficult to quantitatively describe [25,26]. The judgment matrix was created by analyzing the influence of related factors on the target and determining the weight of each element on the target. At present, a great number of studies on AHP and its application in diverse domains have been undertaken by many professionals and scholars [27,28]. The following steps are usually taken when using the AHP to calculate the weight of indicators:

On the basis of the scale type, the relative importance of indicators at each level was quantified by using expert experience, and the judgment matrix $T = (a_{ij})_{n \times n}$ was constructed, as shown in matrix (3).

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

where $a_{ij} > 0$, and $i, j = 1, 2, \dots, n$.

x_i is obtained by multiplying each row vector of the judgment matrix; the root of x_i is calculated n times to obtain $\bar{q}_i$; finally, the relevant weight q_i is obtained by normalization. The calculation steps are as in Equation (4).

$$x_i = \prod_{j=1}^n a_{ij}, \bar{q}_i = \sqrt[n]{x_i}, q_i = \frac{\bar{q}_i}{\sum_{i=1}^n \bar{q}_i}, (i = 1, 2, \dots, n) \quad (4)$$

In the end, $q = (q_1, q_2, \dots, q_n)^T$ is the required weight vector.

Entropy Method (EM)

The EM is an objective weighting approach to determine the weight of indicators according to the correlation degree between indicators or the amount of information contained in them [29,30]. In general, the greater the difference between indicators are, the lower the formation entropy weight is, indicating that the more effective information indicators provided, the higher the weight of effective information was to indicators [14]. The specific steps of evaluating weight by EM are as follows:

If there are n evaluation indicators and m evaluation objects, the original data matrix was standardized by Equation (1) to obtain the normalized data matrix R (5).

$$R = (r_{ij})_{m \times n} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (5)$$

The entropy of the i th index was defined by Equations (6) and (7) when evaluating m objects with n indexes.

$$e_i = -k \sum_{j=1}^n f_{ij} \ln f_{ij}, \quad (6)$$

$$f_{ij} = \frac{r_{ij}}{\sum_{j=1}^n r_{ij}}, k = \frac{1}{\ln m} \quad (7)$$

where $i = 1, 2, \dots, m$; $j = 1, 2, \dots, n$. and if $f_{ij} = 0, f_{ij} \ln f_{ij} = 0$

After the entropy value of i th index, the entropy weight of the i th index was defined by using Equation (8).

$$u_i = \frac{1 - e_i}{n - \sum_{i=1}^n e_i} \quad (8)$$

where $0 \leq u_i \leq 1, \sum_{i=1}^n u_i = 1$.

AHP-EM

When it comes to calculating index weights, the AHP is more subjective because it relies purely on expert opinion and ignores actual geological data. Furthermore, the EM is more objective to calculate the index weights as it considers the geological data [13]. Therefore, the AHP and EM were combined based on the moment estimation method in

this research, and the AHP-EM weight of each factor was derived as a water inrush risk index. The optimization model is as follows:

For each index K_i ($1 \leq i \leq n$), there is:

$$\alpha_i = \frac{q_i}{q_i + u_i}; \beta_i = \frac{u_i}{q_i + u_i}, \quad (9)$$

$$\alpha = \frac{\sum_{i=1}^n \alpha_i}{\sum_{i=1}^n \alpha_i + \sum_{i=1}^n \beta_i}; \beta = \frac{\sum_{i=1}^n \beta_i}{\sum_{i=1}^n \alpha_i + \sum_{i=1}^n \beta_i} \quad (10)$$

Then, AHP-EM index combination weight is:

$$\omega_i = \alpha \times q_i + \beta \times u_i \quad (11)$$

where $\alpha, \beta > 0$ and $\alpha + \beta = 1$, $i = 1, 2, \dots, n$.

The normalized factors were evaluated using Equation (12) to calculate the mine water inrush risk model.

$$V_i = \sum_{i=1}^n \omega_i f_i(x, y) \quad (12)$$

2.2.2. Water-Rich Structure Index

Considering the factors such as aquifer hosting space, lithology, and hydraulic characteristics, the method of water-rich structure index was introduced to evaluate the water-rich of aquifer in the study area. The water-rich index method could fuse the selected index data and make a quantitative evaluation. The key point was to convert the thickness of aquifer and the properties of rock particles into a unified clastic thickness by mathematical expressions, at the same time considering the layers of sand-mudstone interaction, core recovery, and sand-mudstone ratio. The water abundance was evaluated after standardized data processing. The specific steps are as follows:

Different sandstones have different water-bearing capacities. The calculation formula of sandstone equivalent thickness is as Equation (13).

$$L = s_1 \times 1 + s_2 \times 0.8 + s_3 \times 0.6 \quad (13)$$

where L is the equivalent thickness of sandstone, s_1 is the coarse sandstone, s_2 the medium sandstone, and s_3 the fine sandstone.

Through the analysis and establishment of the evaluation index structure of aquifer water abundance, the indexes are sandstone and sand-mud ratio, which are positively correlated with aquifer water abundance, while the negative correlation indexes are sand-mudstone interaction layers and core recovery. As a result of the above analysis, the expression of the water-rich structure index model was constructed as follow Equation (14).

$$G = \frac{L \times r}{K_1 \times N} \quad (14)$$

where G is the water-rich structure index, L is the equivalent thickness of sandstone, r is the sand-mud ratio, K_1 is the core recovery, and N number of sand-mudstone interbeds.

2.2.3. Comprehensive Water Inrush Risk Assessment

The AHP-EM weight method not only comprehensively considered the experience evaluation of experts but also made full use of the actual geological data; the water-rich structure index calculated the water-filled strength of aquifer by using the formula. The basic geological data were used by the two methods, which are related to each other. In this paper, a new approach was proposed to comprehensively assess the risk of water inrush. From the approach, the risk of water inrush with a strong water-rich index from AHP-EM weight method was not as great as the region from AHP methods.

After normalizing T_i , the water inrush comprehensive risk assessment index was obtained rT_i . The comprehensive assessment model weighted by the two models improves the accuracy and fault tolerance of the model.

$$T_i = rV_i + G_i^2 \quad (15)$$

where T_i is the comprehensive water inrush risk assessment index; rV_i is the normalized water inrush risk index; and G_i is the water-rich structure index.

2.3. Determination of Risk Control Factors of Comprehensive Water Inrush in Dahaize Coal Mine

The water inrush of the coal roof occurs mainly in the process of mining, with the aquifer at the top of coal seam gushing down from the weak part of the stratum and flooding the mine roadway. The reasonable selection of risk control variables determined the accuracy of the risk analysis and evaluation of water inrush of coal seam roof. Therefore, on the basis of the hydrogeological and geological conditions of Dahaize coal mine, eight comprehensive evaluation factors were selected considering the drilling and pumping test results.

The control factors of water inrush risk index include core recovery, aquifer thickness, distance between indirect aquifer and coal seam, aquiclude thickness, and height of water-conducting fractured zone.

The control factors of the water-rich structure index include core recovery, the number of interbedding layers with aquifer and aquiclude, sand-mud ratio, and equivalent thickness of sandstone.

The factors, which are positively correlated with coal seam water inrush, are aquifer thickness, sand-mud ratio, and equivalent thickness of sandstone. The factors, which are negatively correlated with coal seam water inrush, are core recovery, distance from the indirect aquifer to coal seam, aquiclude thickness, the height of water-conducting fracture zone, and the number of interbedding layers with aquifer and aquiclude. In other words, the larger the positive correlation value, the greater the chance of separate bed water inrush; the lower the correlation coefficients value, the lower the risk of water inrush.

2.3.1. Control Factors of Water Inrush Risk Index

Core Recovery (K1)

The core recovery is the percentage of the total length of the core and the current footage, which reflects the integrity of the rock mass. When the core recovery is larger, the fracture development is worse and the rock layer is more intact. When the core recovery is smaller, the rock is more fractured, the water-bearing performance is better, and the risk of water inrush is higher. The core recovery could be as an index to evaluate water inrush, and the normalized thematic map is shown in Figure 4a.

Aquifer Thickness (K2)

The aquifers are mainly composed of (gravel) coarse grained sandstone, medium-grained sandstone, and fine sandstone. The thickness of various sandstones is an important index for determining aquifer capacity. The thicker sandstones formation, the larger the space to accommodate water and the higher water inrush risk of the mine. Therefore, the aquifer thickness was selected as the evaluation index, and the normalized thematic map is shown in Figure 4b.

Distance from Indirect Aquifer to Coal Seam (K3)

An indirect aquifer has hydraulic links to a directly connected aquifer. As a result of coal mining, water in the indirect aquifer may supplement the direct aquifer and eventually flow into the working face, posing a threat to coal mine workers' safety. The distance between the coal seam and the indirect aquifer can be used to assess the indirect aquifer's impact on mine water inrush. The closer the coal seam is to the indirect aquifer, the greater the risk of mine water inrush. The normalized thematic map is shown in Figure 4c.

Aquiclude Thickness (K4)

Mudstone and siltstone have poor permeability and can be regarded as effective water-repellent media. In the mining process, mudstone in roof overburden can be used as a good waterproof layer, which could effectively block the channel between the recharge source and the working face space, preventing aquifer water from flowing into the working face. Therefore, it affects mine water inrush, and the normalized thematic map is shown in Figure 4d.

Height of Water-Conducting Fracture Zone (K5)

Coal seam mining can form water-conducting fissure, which is the main channel for mine water to enter the working face. The most important parameter reflecting the influence range of mining disturbance is the height of the water-conducting fractured zone. Furthermore, it has a direct effect on mine water inrush. Many researchers and academics have now obtained the empirical formula for calculating the development height of a coal seam water-conducting fracture zone under various combination conditions through measurement and data analysis of the "upper three zones". According to empirical Formula (16) [31,32], the maximum height of the water-conducting fractured zone of the coal seam can be determined according to the thickness of the coal seam. The maximum height of the water-conducting fractured zone of the coal seam can be calculated using the coal seam thickness.

$$H = \frac{20\sqrt{M}}{n} + 10 \quad (16)$$

where M is the thickness of the coal seam (m), H is the height of water-conducting fractured zone (m), and n is the number of mining layers. The normalized thematic map is shown in Figure 4e.

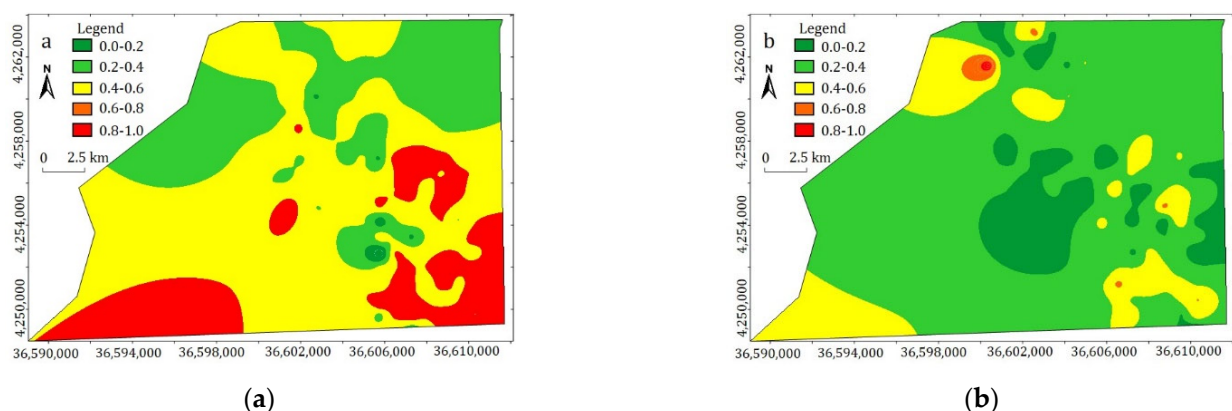


Figure 4. Cont.

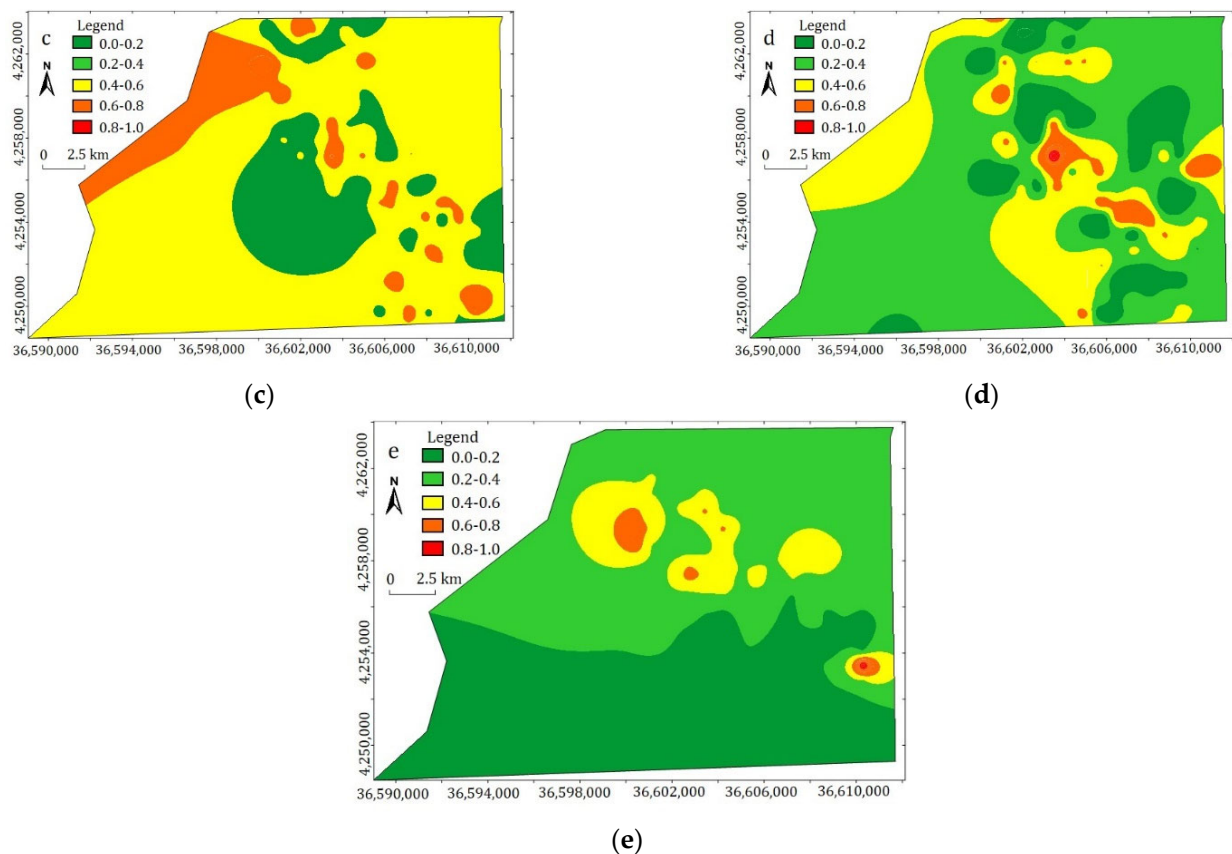


Figure 4. Water inrush risk control factors are depicted on a thematic map. (a) Core Monitor Rate; (b) Aquifer Thickness; (c) Distance from Indirect Aquifer to Coal Seam; (d) Aquiclude Thickness; (e) Height of Water-conducting Fracture Zone.

2.3.2. Control Factors of Water-Rich Structure Index Core Recovery (K1)

It is consistent with the analysis of risk control factor K1 of water inrush.

The Number of Interbedding Layers with Aquifer and Aquiclude (N)

Whether it is a loose or hard aquifers, the aquifer is not integral, but segmented. There is a layer or multi-layer-resisting section within the aquifer. Although these isolation sections are not distributed regionally, they can also isolate water in aquifers. When there is less interaction between aquifer and aquiclude, the water abundance is stronger and there is higher risk of water inrush.

Sand-Mud Ratio (s)

Sand-mud ratio is the ratio of sandstone thickness to mudstone (siltstone) thickness in the target strata group, which is an indirect reflection of the sandstone thickness and the interaction of layers interaction between aquifer and aquiclude. That means the greater the sand-mud ratio, the more the sandstone content, the thinner the mudstone aquifer, the weaker the water insulation, and the higher the risk of mine water inrush. Therefore, the proportion of sandstone in aquifer group was chosen as one of the factors to control roof water hazards.

Equivalent Thickness of Sandstone (L)

The water abundance capacity of sandstone with different grain sizes is also different, among which the water abundance capacity of coarse sandstone is the strongest, medium sandstone is the second, and fine sandstone is the weakest. The equivalent thickness of sandstone is the total thickness of coarse sandstone after multiplying the thickness of sandstone with different particle sizes by a certain proportion coefficient. The equivalent thickness of sandstone is the important index to determine the aquifer water abundance capacity. When its thickness is larger, its space holding water is relatively larger, and the water content would be higher. Therefore, the equivalent thickness of sandstone was selected as an evaluation index of water abundance.

3. Results and Discussion

3.1. Calculation Results of Water Inrush Risk Index

3.1.1. Weight Calculation Based on AHP

Researchers have examined the elements influencing water inrush and used AHP to calculate the index weight q_i . The evaluation criteria were based on a 1–9 level. Saaty created the judging matrix T [24], as shown in Table 1. The judgment matrix suggests that the weight vector of every factor was calculated as shown in Table 2. The maximum eigenvalue $\lambda_{\max} = 5.207$ was calculated. To determine the random consistency ratio of matrix T , perform the following operations.

$$C.R = \frac{C.I}{R.I}, \quad (17)$$

$$C.I = \frac{\lambda_{\max} - m}{m - 1} \quad (18)$$

where $\lambda_{\max}$ is the maximum eigenvalue of T ; m is the number of evaluation indicators. The eigenvalues of random judgment matrix were repeatedly calculated more than 500 times, and then the arithmetic average of eigenvalues, namely the random consistency index was calculated. When $m = 5$, $R.I = 1.12$, then $C.R = 0.0462 < 0.1$, so the judgment matrix met the consistency test. After normalized the row vector of judgment matrix, the weight value q_i of each indicator was obtained using Equation (4), as shown in Table 2.

Table 1. Single-level AHP judgment matrix of water inrush factors.

Factor	K1	K2	K3	K4	K5
K1	1	1/4	2	1/3	1/4
K2	4	1	3	2	1/2
K3	1/2	1/3	1	1/2	1/3
K4	3	1/2	2	1	1/2
K5	4	2	3	2	1

3.1.2. Weight Calculation Based on EM

According to the 129 drilling wells exploration data of Dahaize coal mine, the data of influencing factors on the roof of the third member of Jurassic Yan'an Formation were sorted out from the No.2 coal mine. After normalization, the data matrix R was constructed, and Equations (7) and (8) were solved to obtain entropy and entropy weight of the matrix. The entropies were: $e_1 = 0.993$, $e_2 = 0.978$, $e_3 = 0.986$, $e_4 = 0.978$, $e_5 = 0.968$. The entropy weights u_i are shown in Table 2.

Table 2. The influencing factors weight of Dahaize coal mine.

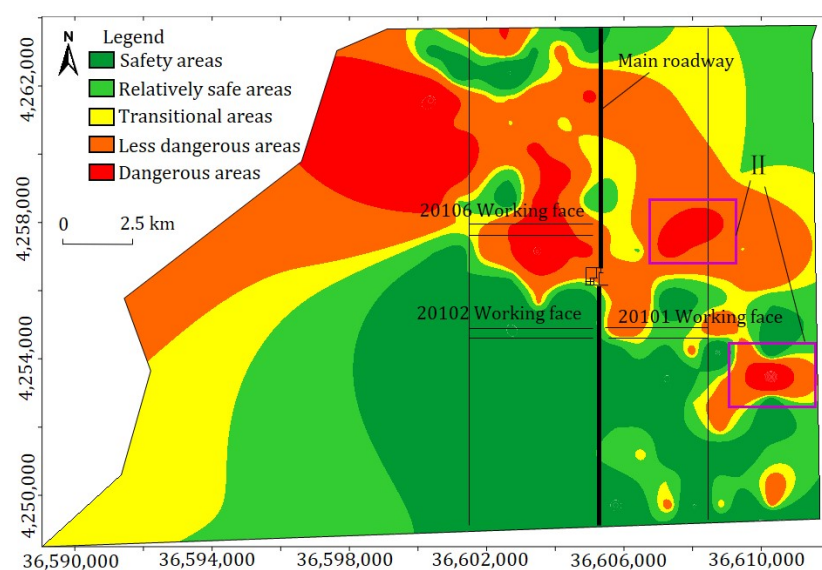
Weight	K1	K2	K3	K4	K5
AHP (q_i)	0.0923	0.2770	0.0835	0.1818	0.3654
EM (u_i)	0.0725	0.2244	0.1477	0.2235	0.3319
AHP-EM (ω_i)	0.0821	0.2502	0.1163	0.2031	0.3483

3.1.3. Weight Calculation Based on AHP-EM

The moment estimation method was used to couple AHP and EM with Equations (9)–(11), and the AHP-EM comprehensive weight ω_i of each factor was obtained as shown in Table 2. The importance of each evaluation index is determined by its weight. In Table 2, normalized factors could be evaluated using Equation (12). The risk index model of water intrusion was established in the study area (Equation (19)).

$$V_i = 0.0821f_1(x, y) + 0.2502f_2(x, y) + 0.1163f_3(x, y) + 0.2031f_4(x, y) + 0.3483f_5(x, y) \quad (19)$$

According to the final calculation results of the risk index model, the relative linear equilibrium classification method was used to classify regions as $0 < V_i \leq 0.334$ safety areas, $0.334 < V_i \leq 0.366$ relatively safe areas, $0.366 < V_i \leq 0.384$ transitional areas, $0.384 < V_i \leq 0.435$ less dangerous areas, and $0.435 < V_i \leq 1$ dangerous areas were prepared, as shown in Figure 5.

**Figure 5.** Water intrusion risk index zoning map.

3.2. Calculation Results of Water-Rich Structure Index

According to Equations (13)–(15), the normalized water-rich structure index value G_i could be obtained. Using the relative linear equalization classification method, the top aquifer from the No.2 coal seam of Dahaize coal mine to the third member of the Jurassic Yan'an Formation could be divided into various water-rich zones. The classification thresholds of G_i were 0.0021, 0.0368, and 0.32. The areas were classified as weak water-rich areas, relatively weak water-rich areas, transitional areas, medium water-rich areas, and relatively strong water-rich areas. The water-rich zoning is shown in Figure 6.

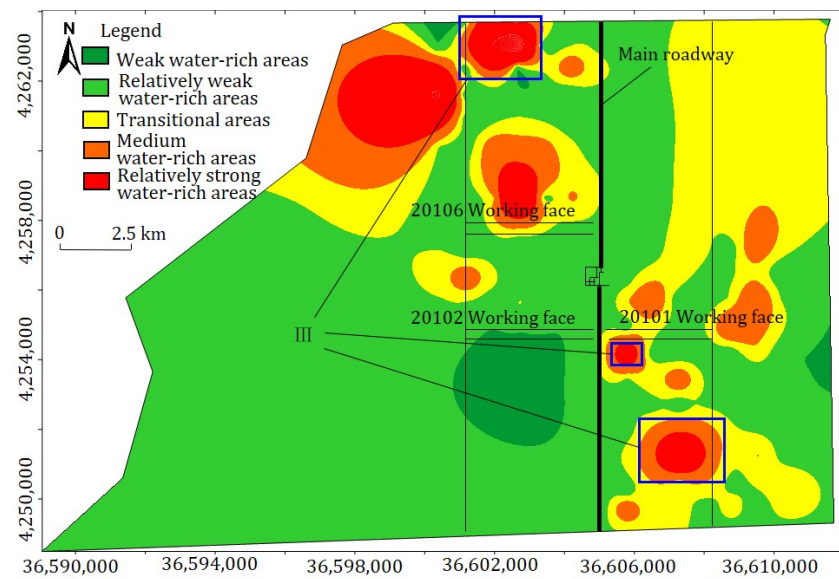


Figure 6. Water-rich structure index zoning map.

3.3. The Result of Comprehensive Water Inrush Assessment

In this paper, the comprehensive risk assessment model was constructed by weighting water inrush risk assessment index and water-rich structure index. The specific steps are as follows Equation (16):

1. Normalize water inrush risk index model V_i to obtain rV_i ;
2. Squared the index (G_i^2), because the overall value of the water-rich structure index is too small;
3. Add the normalized value rV_i to G_i^2 , and establish the comprehensive risk assessment model of water inrush.

The final comprehensive water inrush risk assessment index was normalized to get rT_i . The relative linear equilibrium grading method was used to distinguish the studies $0 < rT_i \leq 0.2068$ as safety areas, $0.2068 \leq rT_i \leq 0.2545$ as relatively safe areas, $0.2545 \leq rT_i \leq 0.3006$ as transition areas, $0.3006 \leq rT_i \leq 0.3760$ as less dangerous areas, $0.3760 \leq rT_i \leq 1$ as dangerous areas (Figure 7).

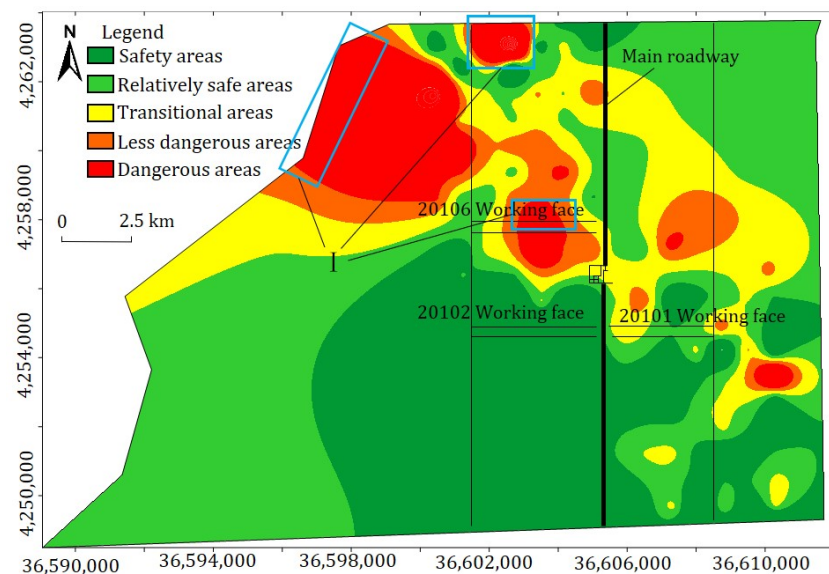


Figure 7. Comprehensive water inrush assessment zoning map.

Dahaize coal mine's first mining area is primarily divided into 20106 working face, 20102 working face, and 20101 working face. According to the water inrush risk assessment diagram, the conclusion is that the water inrush risk area is mainly located in the middle of 20106 working face, and the water abundance of the aquifer in the third member of Jurassic Yan'an Formation gradually increases from southeast to northwest. The actual mining situation of the 20106 working face showed that the water inflow in the middle section of the working face was relatively large, but other unmined areas cannot be verified in a short time. For the working face of the first mining area, for the areas with high risk of water inrush, under the two conditions of the high-water season and the flat-water season, the drainage should be started one month in advance according to the predicted water inflow. These results verify that the model has reliable practical application significance and provides a basis for the prevention and control of water hazards in the Dahaize coal mine.

3.4. Discussion

The method of water inrush risk of coal seam roof based on AHP has been verified and widely used. The water inrush risk assessment model established only by the AHP is shown in Figure 8. After comparing this method with the comprehensive water inrush risk assessment proposed (CWIRA) in this paper, the water inrush risk areas in the middle section of the 20106 working face and the northwest are basically similar, but the CWIRA has more dangerous areas (I in Figure 7) than the single AHP method. In addition, after comparing the results of the water inrush risk index (WIRI) which was calculated by AHP-EM (Figure 5) and the water-rich structure index (WRSI) (Figure 6), it was found that the two indexes were basically the same in the middle section of the 20106 working face and in the northwest of the study area. However, the II in Figure 5 areas in the WIRI were different from the WRSI, and the III in Figure 6 areas in the WRSI were different from the WIRI.

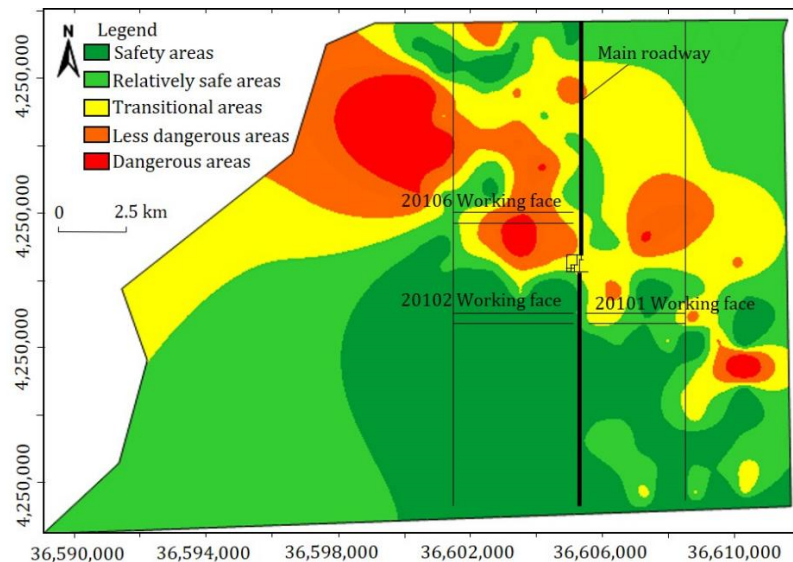


Figure 8. Water inrush assessment zoning map based on AHP.

In addition, the Zhangjiamao coal mine was selected as the validation area in this paper. By analyzing the geological data of the mining area, the control factors of water inrush risk index include specific capacity (Z1), hydraulic conductivity (Z2), aquifer thickness (Z3), core recovery (Z4), and ratio of brittle and tenacity terrane (Z5). The weights required for each control factor are shown in Table 3. Finally, the water inrush risk index model (Figure 9a), water-rich structure index model (Figure 9b), and comprehensive assessment model (Figure 9c) were established.

Table 3. The influencing factors weight of Zhangjiamao coal mine.

Weight	Z1	Z2	Z3	Z4	Z5
AHP (q_i)	0.375	0.125	0.250	0.125	0.125
EM (u_i)	0.299	0.298	0.141	0.010	0.252
AHP-EM (ω_i)	0.341	0.203	0.201	0.073	0.182

The dangerous area of water inrush from the weathered bedrock fissure aquifer in Zhangjiamao coal mine is shown in the red area in Figure 9c. The central area of the 15207 working face has a large amount of water inflow. The evaluation model is consistent with the actual mining, which shows that this method can be used for the coal mine hydrological assessment with similar geological conditions.

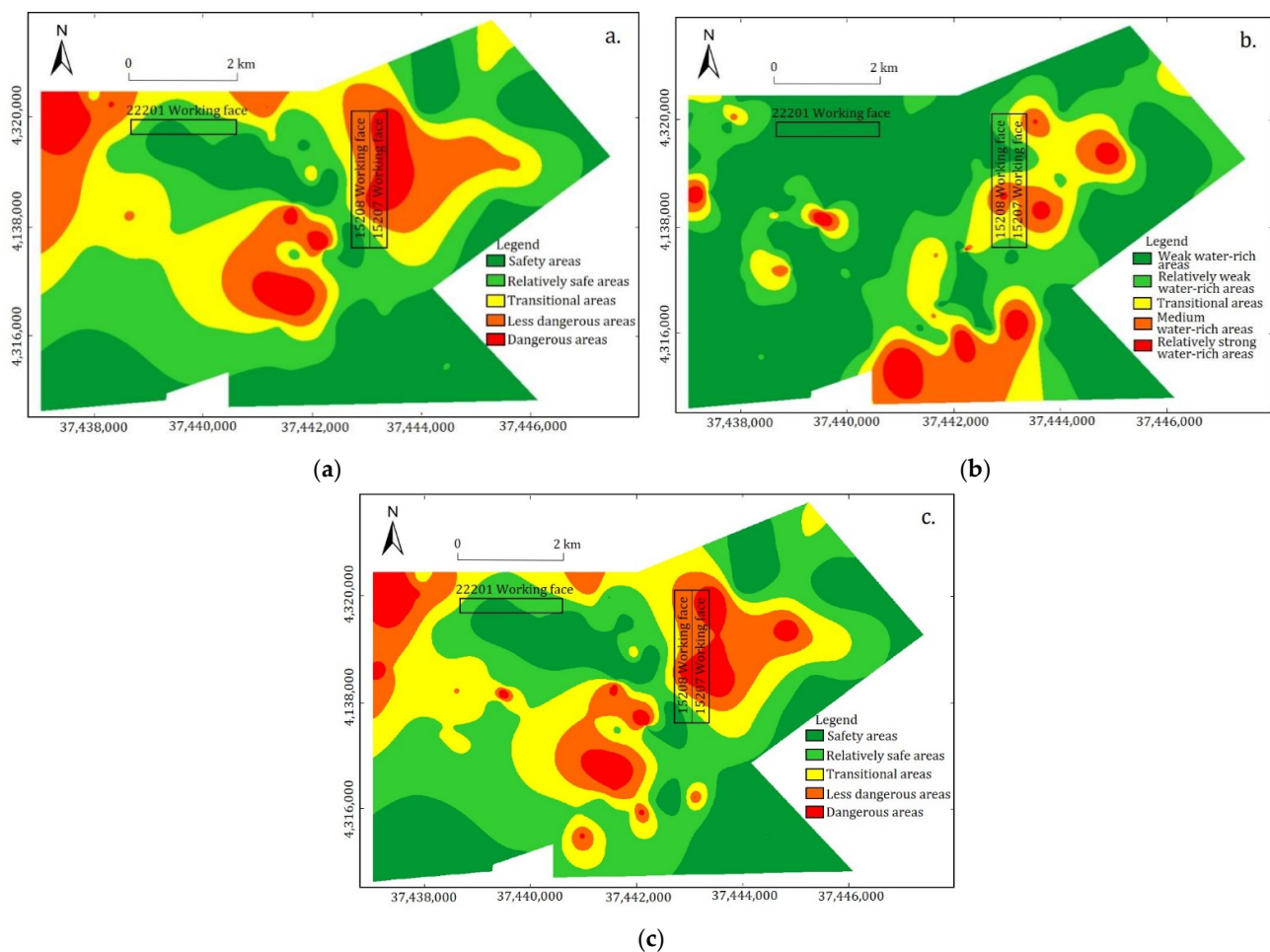


Figure 9. Water inrush assessment zoning map of the Zhangjiamao coal mine. (a) Water inrush risk index zoning map; (b) Water-rich structure index zoning map; (c) Comprehensive water inrush assessment zoning map.

4. Conclusions

In this study, a new method for comprehensive assessment of water inrush from coal seam roof was proposed, which is weighted by water inrush risk index and water rich index. The conclusions are summarized as follows:

1. The water inrush risk index was calculated by combining AHP with EM by the moment estimation method, and the water inrush risk index zoning map of the study area was compiled. In addition, the water content of coal seam roof was calculated by

the water rich structure index. Finally, the two indexes were weighted to established comprehensive assessment model.

2. On the basis of fully studying the geological and hydrogeological conditions of the coal mine, combined with the drilling data, the control factors of the water inrush risk indexes of Dahaize coal mine and Zhangjiamao coal mine were determined.
3. According to the analysis of the comprehensive water inrush assessment model, the high-risk areas of water inrush were clearly identified. The investigation of the actual mining situation in the mining area showed: the water inflow in the middle section of the 20106 working face of Dahaize coal mine was relatively large, and the water inflow in the central area of 15207 working face of Zhangjiamao coal mine was large.
4. The comprehensive assessment method is consistent with the actual mining status, which shows that this method can be used for the coal mine hydrological assessment with similar geological conditions and demonstrated its reliability and versatility. This method is of great significance for formulating corresponding measures to prevent water inrush in mining areas and ensuring safe production of coal mines.

Author Contributions: Z.S., W.B. and M.L. conceived and designed the experiment idea; W.B. analyzed the data and conducted the validation; Z.S. and W.B. focused on writing—original draft preparation; M.L. managed the project administration and supervision; Z.S. and M.L. did the writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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