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Research Article

Risk Assessment of Water Inrush from Coal Floor Based on Karst Fractal-Vulnerability Index Method

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Hidden karst structures are developed irregularly in the Middle Permian Maokou Formation aquifer from the northern part of the Guizhou coalfield, China. Mining operations associated with the exploitation of coal seams from the lower part of the Upper Permian Longtan Formation are threatened by karst waters from the underlying strata. To improve the accuracy of water inrush risk assessment of the karst aquifer floor in the northern Guizhou coalfield, the karst fractal quantification technique is implemented. In this study, the karst aquifer of the Maokou Formation located under the floor of the No. 15 coal seam from the Honglin Coal Mine is considered as the research object. Based on the karst results predicted by geophysical exploration methods, the fractal theory is used to quantify the degree of karst development, while the risk of water inrush from the floor of the coal seam is evaluated by applying ArcGIS information processing technology combined with the vulnerability index method. The results indicate the following observations: the mean fractal dimension of karst in the study area is 1.53, the karst structures are highly developed, and the overall distribution of karst is characterized by an irregular NW-SE direction; the main controlling factors affecting water inrush from the floor of the No. 15 coal seam are expressed by the water pressure of the aquifer, the abundance of water in the aquifer, the degree of karst development, the thickness of the effective impermeable layer, the mining depth, the coal seam dip angle, and the degree of fault complexity; the areas with the highest risk of floor water inrush are predominantly concentrated in the northwestern and central parts, but there is also a risk of floor water inrush in the first mining area of the No. 15 coal seam. This study takes into consideration complex factors such as the typical karst aquifer and the hydrogeological conditions in the northern part of the Guizhou coalfield, which results in a more realistic interpretation and can provide further guidance for water control activities in the mining area.

1. Introduction

The karst water disaster of the coal seam floor is one of the main hazards threatening the safety of mining operations of coal resources in the northern Guizhou coalfield [1, 2]. In this region, the coal-bearing strata of the Upper Permian Longtan Formation lie on the limestones of the Middle Permian Maokou Formation, which are characterized by strong karst features and different volumes of water. Moreover, the aquifer located between the Maokou Formation aquifer and the bottom mineable coal seam is thin (less than 4 m), which seriously affects the safe and efficient mining of the coal seam deposits. Therefore, the prediction and evaluation of water inrush from the karst floor of the coal seam beds are the major problem influencing the safe production activities in the northern Guizhou coalfield.

In recent years, the methods used to evaluate the risk of floor water inrush mainly include the water inrush coefficient method [3], the five-figure double coefficients method [4], and the vulnerability index method [5, 6]. Among these, the vulnerability index method comprehensively considers multiple essential control factors and their relative weights of floor water inrush, reflecting the nonlinear dynamic process of water inrush. This method has been widely used [7, 8] because it has a better solution for the problem of predicting water inrush from coal floor strata. Floor karst water damage is a typical geological hazard encountered during the production of “karst” coal mines. The factors which led to its formation are complex and its distribution is extremely irregular. The evaluation of the vulnerability index method in this area considers the floor karst aquifer as a unified aquifer and ignores the degree of karst development. Although it has significance in guiding coal mining operations, the accuracy has a certain deviation from the actual scenario [9–11]. The karst development of the aquifer is an important factor affecting the water inrush from the coal seam floor in the northern part of the Guizhou coalfield. However, karst development can be measured by applying indirect geophysical exploration or drilling techniques, while direct observation or measuring methods are not applicable [12, 13]. Additionally, the obtained data represents the quantitative results of karst development and distribution inferred from inversion, which cannot be combined with the vulnerability index method for qualitative and quantitative evaluation of water inrush from the coal seam floor. Therefore, the scientific and rational quantification of karst development and the integration of the vulnerability index to comprehensively evaluate and predict the risk of water inrush from the coal seam floor in the northern part of the Guizhou coalfield have become an important subject.

To apply the vulnerability index method, domestic and foreign researchers used the fractal theory to quantify the complex structural characteristics of faults, which improved the prediction accuracy of water inrush from coal seam floors. Li et al. [14] substituted the fault fractal dimension with the fault distribution density, size, and nature to improve the accuracy of water inrush prediction by applying the vulnerability index method. Qiao et al. [15] calculated the fractal dimension index of the fault syncline and anticline and combined the vulnerability index method to predict the vulnerability zoning of the study area. The Maokou Formation limestone karst located at the bottom of the No. 15 coal seam in the Honglin Coal Mine is well developed; however, the aquifer is thin, which means that there is a possibility of water inrush from the floor. Therefore, based on the results obtained from geophysical exploration techniques, this study introduces the fractal theory to quantify the degree of karst development, while the comprehensive evaluation of the floor water inrush was analyzed in combination with the vulnerability index method. The karst fractal-vulnerability index method thoroughly analyzes the typical complex karst geology in the northern part of the Guizhou coalfield, making the evaluation results more realistic and providing a theoretical basis for water control measures in this area.

2. Overview and Engineering Background of the Study Area

The Honglin Coal Mine is in the northwestern part of Guizhou Province, to the east of Wumeng Mountain and at the junction of Qianxi and Dafang counties. The boundary of the mining area represents an irregular polygon, with a length of approximately 4 km from east to west and a width of approximately 3.7 km from north to south, covering an area equal to circa 12.55 km^2. The quasi-mining elevation ranges from +1750 m to +1100 m above sea level. The overall topography of the region is high in the northeast and low in the southwest. It is a monoclinal structure that belongs to the Zhongshan landform and develops an erosion-dissolution landform. The existing structural features in the area are mainly shaped by the Yanshan Movement tectonic events. Small- and medium-sized faults are well developed in the region. These are mainly distributed in the northeastern part of the mining area, while the fault strike has a predominantly east-west direction. The encountered strata from bottom to top are represented by the Maokou Formation, Longtan Formation, Changxing Formation, Yelang Formation, and Quaternary sediments. The most important water-bearing aquifers are the medium aquifers from the Changxing Formation, the medium aquifers from the Yulongshan section of the Yelang Formation, the weak aquifers from the Longtan Formation, and the strong aquifers from the Maokou Formation (Figure 1). In the mining area, the Longtan Formation consists of coal-bearing strata. It is rich in water and weak in water capacity, which represents the direct water source of the mine, but it does not pose a threat to mine production after long-term mining dredging. The major coal seams of the entire area are the No. 9 and the No. 15 coal seams. The bottom plate of the No. 15 coal seam is the limestone aquifer of the Maokou Formation, and the average thickness of the impermeable layer (mainly aluminium mudstone) is 4 m. The water-bearing medium primarily consists of pure carbonate rock karst water, with dissolved pores and caves.

According to the hydrogeological drilling survey, the water level of this aquifer has an elevation of 1599.7 m in borehole 505, accompanied by the presence of a local water head. At the same time, there is no water level in borehole 606, which is located not too far from borehole 505. This indicates that the karst development of the Maokou Formation is strong, water-bearing, and irregular, which threatens the safety of mining activities of the No. 15 coal seam. Physical exploration has been performed in the first and the second mining areas by using controllable audio frequency magnetotelluric methods and seismic resonance frequency imaging methods to better understand the karst development of the existing aquifers. The analysis of the development degree of limestones (elevation +1350 m) of the Maokou Formation in the No. 15 coal seam floor was carried out in combination with the hydrogeological conditions. The results indicate that the karst fractures of the Maokou Formation limestones in the floor of the No. 15 coal seam may have various degrees of development in the survey area, and the distribution area is different. A large, banded karst fractured zone is developed in the northwestern, southeastern, and southern parts of the survey area, and several small elliptic karst fracture zones are extended in the middle and western parts of the survey area (Figure 2).

3. Basic Theory

3.1. Fractal Theory. The fractal theory is a nonlinear discipline founded by Mandelbrot. Its principle is to enlarge a part of a complex object, whose type and complexity are like those of the whole object [16–18]. It can be used to quantify

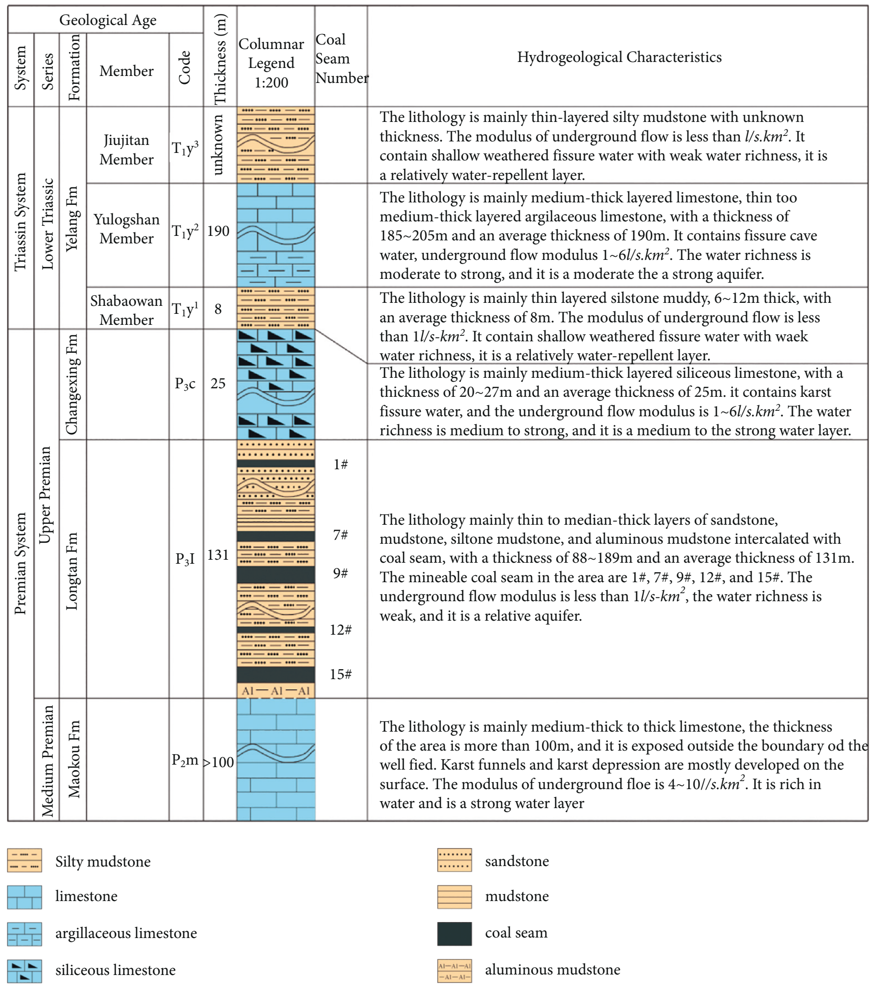


FIGURE 1: Hydrogeological generalized model of the Honglin Coal Mine.

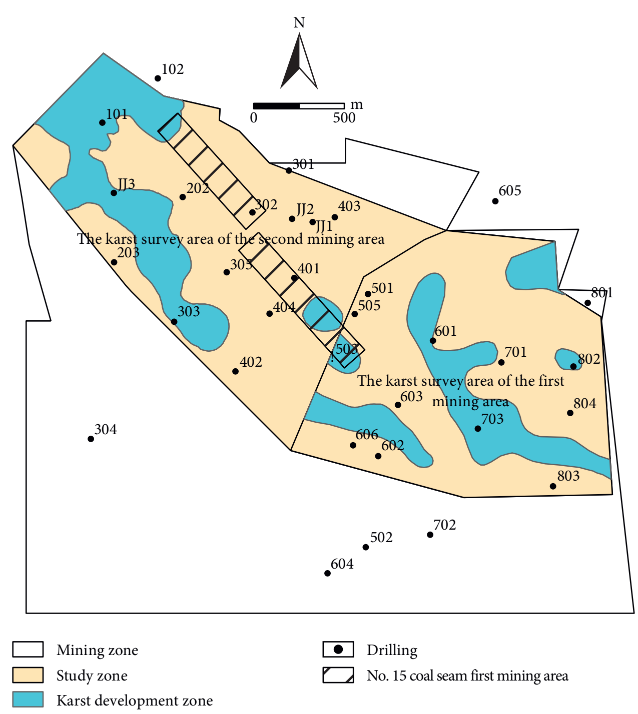


FIGURE 2: Schematic diagram of the limestone karst development in the Maokou Formation in the Honglin Coal Mine research area.

complex structures and irregular structures and is widely used in geological engineering applications. In recent years, the box dimension method has been the main method used to calculate the fractal dimensions. The process mainly includes the three following steps: (1) Cover the research object with a grid composed of square blocks with the side length equal to r_0, and count the number of grids covered by the research object $N(r)$. (2) Reduce the side length of the grid by applying the method of $r = r_0/2, r_0/4, rr_0/8_0, r_0/16$, respectively, and count the number of grids $N(r)$ covered by the research object under different scale grids. (3) Plot the results to the $\ln r - \ln N(r)$ coordinate system, obtain a straight line through function fitting, and consider the absolute value of its slope as the fractal dimension D_s. The equation is expressed as

$$\ln N(r) = A - D_s \ln r, \tag{1}$$

where r is the side length of the square grid; $N(r)$ is the number of grids covered by the research object; D_s is the fractal dimension; and A is a dimensionless constant.

3.2. Vulnerability Index Method. The application of the vulnerability index method is based on ArcGIS software. It analyzes and determines the main controlling factors of coal seam water inrush, establishes each main controlling factor thematic layer, uses the Analytic Hierarchy Process to determine the weight of each main controlling factor, applies the ArcGIS information fusion technology to establish a comprehensive topic figure, and finally introduces the vulnerability index to establish a regional evaluation model. The formula is expressed as

$$\mathrm{VI} = \sum_{k=1}^{n} W_k \times f_k(x, y), \tag{2}$$

where VI is the vulnerability index; n is the number of main controlling factors; k is the serial number of the factor; W_k is the weight of the kth factor; and $f_k(x, y)$ is the normalized value of the kth element, where (x, y) are geographic coordinates.

3.3. Application of the Karst Fractal Theory. The major particularity of a fractal theory is self-similarity; that is, a certain structure or process has similar characteristics on different spatial scales [19]. In recent years, some researchers consider that several geological phenomena show evident self-similarity and iterative patterns in distribution and geometric forms [20, 21]. Specifically, fault fractal technology has gradually advanced, which combined with the vulnerability index method, has improved the prediction accuracy of the vulnerability index method, and has been widely used in the field of coal seam floor water inrush hazard evaluation [22, 23]. Previous studies have shown that karst development morphology has a wide range of complex structures with iterative patterns, as well as irregular shapes and phenomena, which correspond to the statistical analysis of the fractal theory [24, 25]. At present, the fractal theory of karst development is predominantly used in karst tunnel engineering operations and rarely applied in coal seam floor water inrush evaluation methods [26, 27]. Therefore, this paper aims to include the karst fractal and the fault fractal theories into the vulnerability index method to improve the accuracy of coal floor water inrush predictions.

Based on the map illustrating the karst geophysical prospecting results, this paper divided the study area into two regions, and, for the convenience of performing calculations, as shown in Figure 3, grids i and ii consist of $200\text{m} \times 200$ m square blocks which were assigned distinct numbers. The total number of blocks covering the karst area is equal to 103. According to the previously mentioned steps, the number of $100\text{m} \times 100$ m, $50\text{m} \times 50$ m, $25\text{m} \times 25$ m, and 12.5 m $\times$ 12.5 m grids covered by each block in the study area was counted in separate stages; then the linear fitting procedure was performed in accordance with equation (1) to calculate the karst fractal dimension of all the blocks. The results are illustrated in Tables 1 and 2. It is noticeable that in both cases the mean value $R^2 = 0.97$, which indicates that the fitting effect is reasonable.

After assigning the calculated fractal dimension values to the center point of each block, the Surfer software tools were applied to perform kriging interpolation and to draw the contour maps, while the ArcGIS software was used to perform statistical partitioning to obtain the karst thematic map (Figure 4). It is observed that larger karst fractal dimensions generate stronger karst development characteristics; therefore, the risk of water inrush from the floor increases. According to Tables 1 and 2, the average value of the karst fractal dimension in the study area is 1.53, and the overall karst development is relatively strong. Based on the ArcGIS platform software, the fractal dimension of karst in the study area was calculated, while the threshold of karst zoning was determined by applying the natural discontinuity method, specifically: $D_s \geq 1.65$ is a strong karst development area; $1.25 \leq D_s < 1.65$ is a relatively strong karst development area; $0.95 \leq D_s < 1.25$ is a medium karst development area; $0.95 \leq D_s < 1.25$ is a weak karst development area; and $D_s < 0.65$ is an underdeveloped area. The karst terrain of the Maokou Formation aquifer presents an irregular distribution with a northwest-southeast direction (Figure 4).

4. Evaluation of Water Inrush from the Coal Seam Floor

4.1. Calculation and Analysis of the Main Controlling Factors. The rationality of the main controlling factors determines the accuracy of the vulnerability index evaluation method. The floor of the No. 15 coal seam in the Honglin Coal Mine is primarily threatened by the karst aquifer of the Maokou Formation, but the thin impermeable floor and the occasional water heads are also important factors. The evaluation method combines the hydrogeological characteristics with the geophysical prospecting data of the Honglin Coal Mine and considers the four aspects of the Maokou limestone aquifer, the floor impermeable layer, the coal seam mining conditions, and the geological structure. The comprehensive analysis identified seven major controlling factors affecting the water inrush from the floor of the No. 15 coal seam:

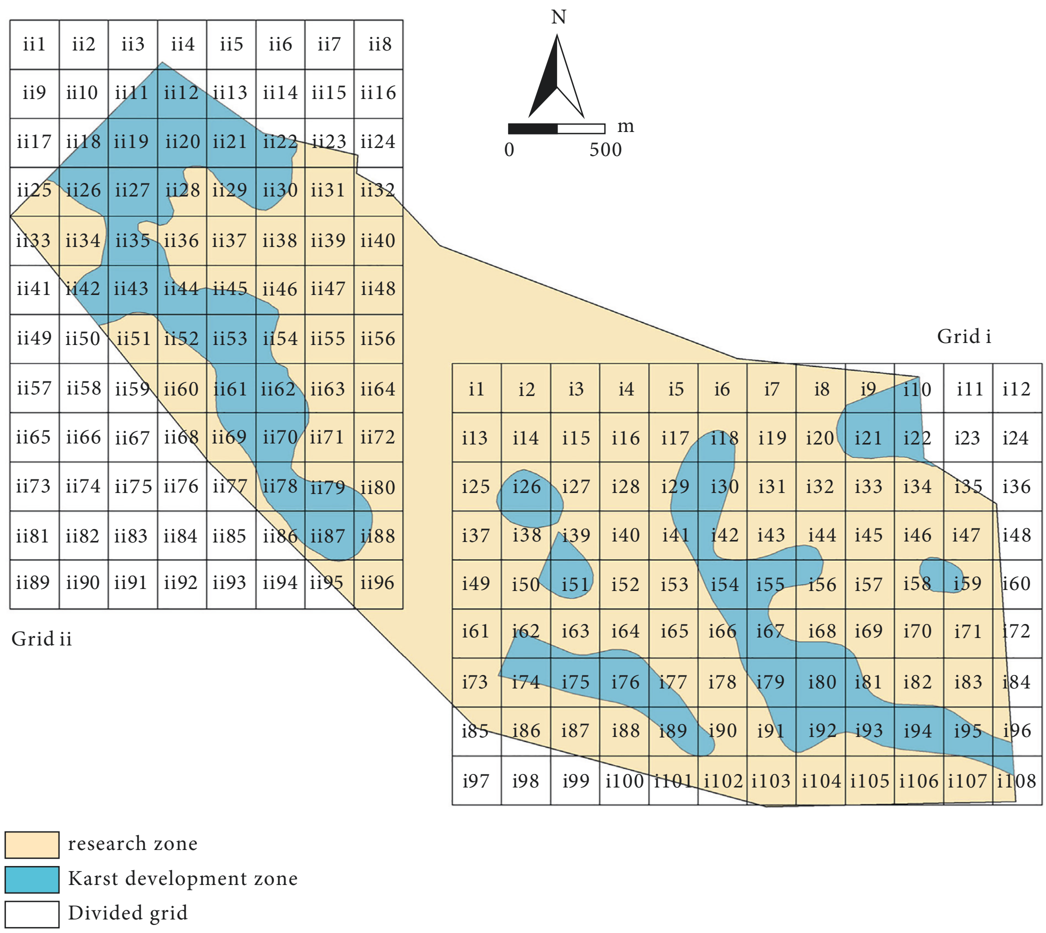


Figure 3: Grid division map of the karst area of the Honglin Coal Mine.

Table 1: Calculation results of the karst fractal dimension of grid i in the research area of the Honglin Coal Mine.

No.	D_s	No.	D_s	No.	D_s	No.	D_s	No.	D_s
i8	0.3170	i30	1.8311	i54	1.9486	i73	0.4170	i90	1.4195
i9	1.6984	i34	0.7585	i55	1.9224	i74	1.7696	i91	1.6618
i10	1.6087	i38	1.5590	i56	1.5066	i75	1.8930	i92	1.8915
i17	1.2510	i39	1.5853	i58	1.6030	i76	1.9874	i93	1.8616
i18	1.6901	i41	1.6481	i59	1.5567	i77	1.6595	i94	1.9791
i20	1.2634	i42	1.6962	i62	1.6723	i78	0.8644	i95	1.8738
i21	1.9802	i43	1.3726	i63	1.3370	i79	1.9473	i96	1.4485
i22	1.7872	i44	1.3229	i64	1.3196	i80	2.0000	i102	0.2000
i25	0.9400	i46	0.7615	i66	1.6163	i81	1.7585	i107	1.1170
i26	1.8987	i50	1.2925	i67	1.8799	i82	0.9814	i108	1.4451
i27	1.2634	i51	1.8325	i68	1.6601	i88	1.0136		
i29	1.7567	i53	0.5000	i69	0.8229	i89	1.8585		

Table 2: Calculation results of the karst fractal dimension of grid ii in the research area of the Honglin Coal Mine.

No.	D_s	No.	D_s	No.	D_s	No.	D_s	No.	D_s
ii4	0.9241	ii25	1.1955	ii42	1.7907	ii54	1.7370	ii79	1.7856
ii11	1.7903	ii26	1.9059	ii43	2.0000	ii61	1.9369	ii80	1.3078
ii12	1.9422	ii27	2.0000	ii44	1.8569	ii62	1.9447	ii86	1.4540
ii13	1.4219	ii28	1.7152	ii45	1.7652	ii63	0.7585	ii87	1.9804
ii18	1.7903	ii29	1.7465	ii46	1.3497	ii69	1.7633	ii88	1.5662
ii19	2.0000	ii30	1.7665	ii50	1.1592	ii70	1.9672	ii95	0.6755
ii20	2.0000	ii34	1.2136	ii51	1.0147	ii71	0.8229		
ii21	1.9966	ii35	1.9672	ii52	1.7926	ii77	0.5000		
ii22	1.7605	ii36	1.3081	ii53	2.0000	ii78	1.9383		

aquifer water pressure, aquifer water richness, degree of karst development, effective impermeable layer thickness, mining depth, coal seam inclination, and fault complexity. The thematic map of each major controlling factor was created (Figure 5) and analyzed based on the mining data combined with the Surfer and the ArcGIS software tools:

(1) *Hydraulic Pressure in the Aquifer*. When the aquifer's water level is higher than the coal seam floor, specific water pressure will exist. If the water pressure increases, the possibility of water inrush from the coal seam floor also increases. The changing trend of the water pressure in the aquifer occurs in the southeast direction, and the water pressure in the northwestern part has the highest values (Figure 5(a)).

(2) *Water Abundance of the Aquifer*. This controlling factor is defined by the unit water influx. The unit water influx in the study area is within the range of 0~0.0039 ($q \leq 0.1$ L/s·m). Therefore, the mining area is characterized by a weak water richness, and the

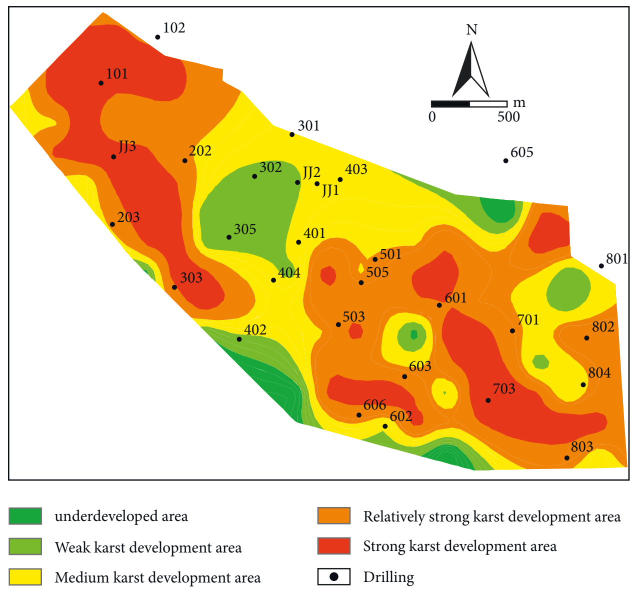
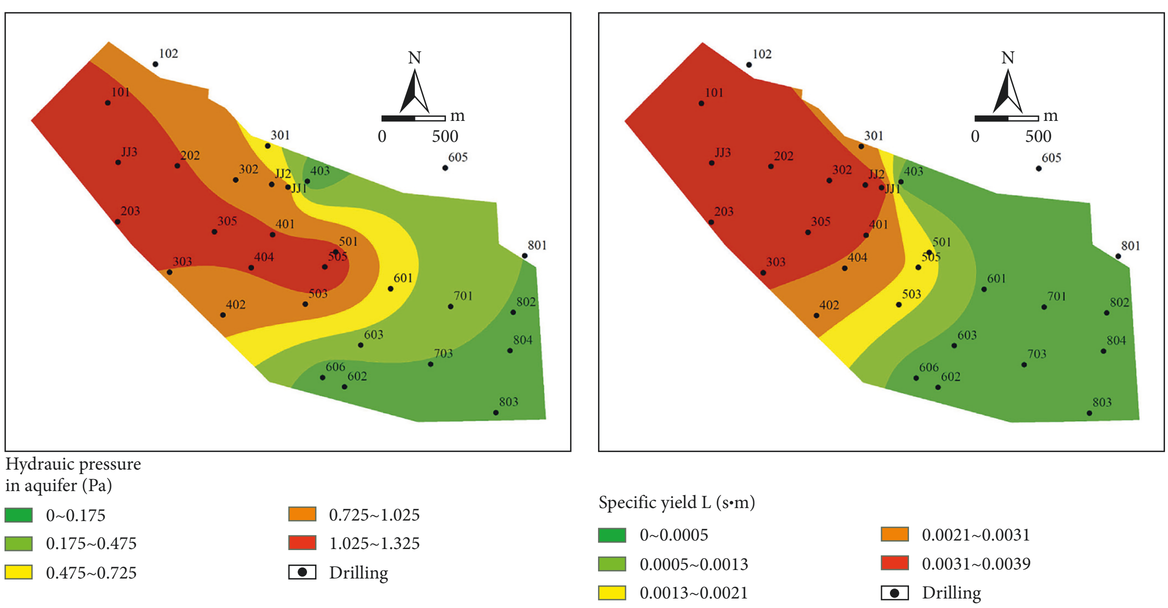


FIGURE 4: Thematic map of the karst development zoning in the research area of the Honglin Coal Mine.



(a) (b)

FIGURE 5: Continued.

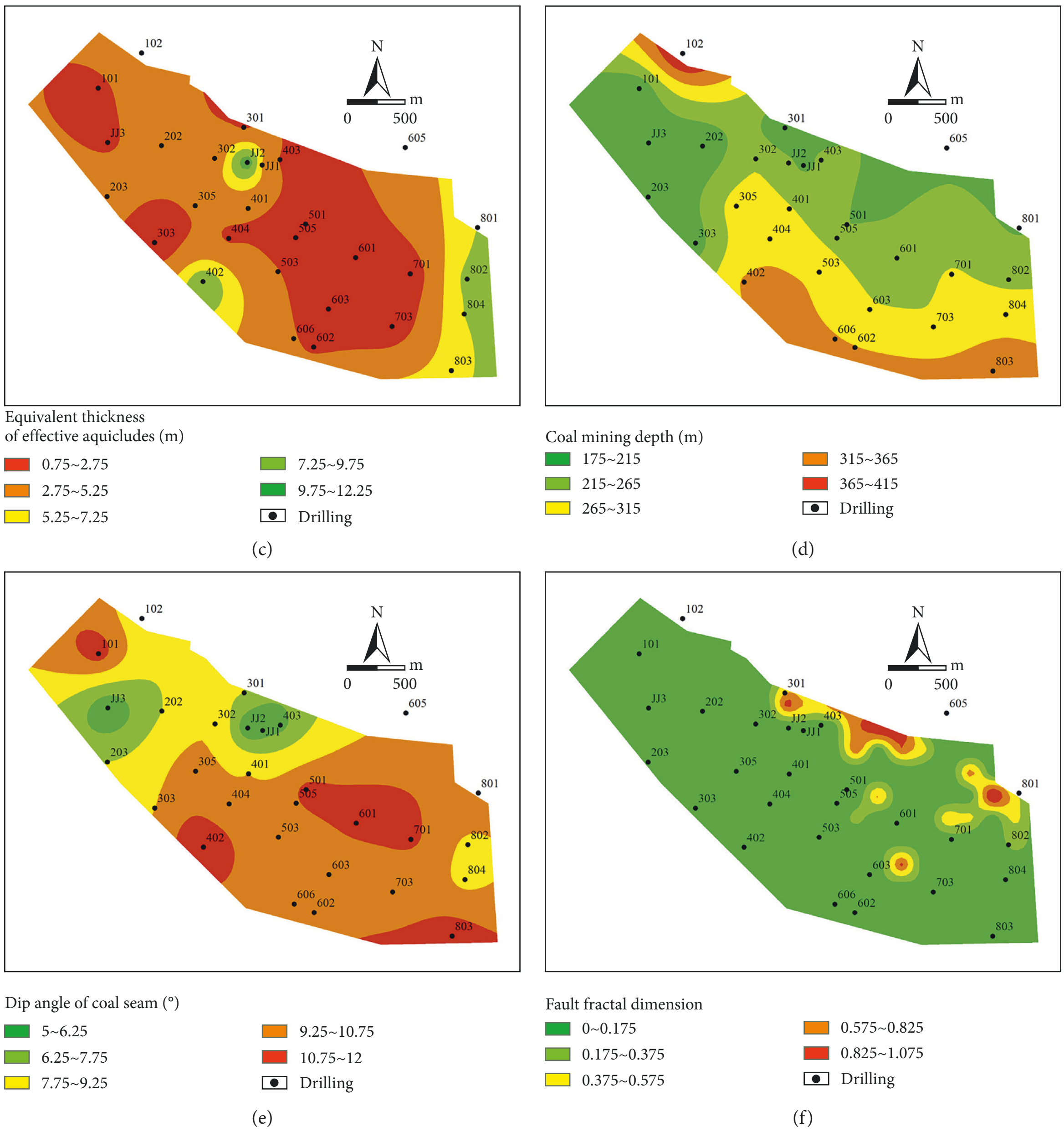


FIGURE 5: Thematic map of the main controlling factors in the research area of the Honglin Coal Mine. (a) Thematic map of the hydraulic pressure in the aquifer; (b) thematic map of the water abundance of the aquifer; (c) thematic map of the equivalent thickness of the effective aquiclude; (d) thematic map of the coal mining depth; (e) thematic map of the dip angle of the coal seam; (f) thematic map of the fault complexity.

relative water richness increases from east to west. The changing trend is similar to the water pressure trend (Figure 5(b)).

(3) *Degree of Karst Development*. It is characterized by the karst fractal dimension. The aquifers of the Maokou Formation predominantly consist of carbonate rocks and are susceptible to the dissolution of groundwaters. Consequently, karst failure zones and caves of varying sizes and shapes are created, which become water storage facilities of different volumes. During coal mining operations, the water-conducting fissure zones represent accessible paths for the water-bearing karst areas, therefore increasing the possibility of water inrush. The overall karst development of the Maokou Formation aquifer in the study area is extremely irregular, indicating that the strong karst development zones are concentrated in the northwest and southeast (Figure 4).

(4) *Equivalent Thickness of the Effective Aquiclude*. This determines the strength of the water-blocking capacity. If the impermeable layer becomes thinner, then the water-blocking effect is worse, which means

that it is easier to provoke a water inrush. The thickness of the impermeable layer located below the coal seam deposits is relatively thin, with a thickness in the range of 0.75~12.25 m, which has an immense impact on the water inrush from the coal seam floor (Figure 5(c)).

(5) *Coal Mining Depth*. When the mining depth increases, the stress on the two walls of the mining face becomes more concentrated, while the bottom plate is prone to damage and cracks, which increases the number of water channels. Thus, the possibility of water inrush from the bottom layer grows. The overall trend of the mining depth in the study area increases from north to southeast, and the maximum mining depth located in the northernmost part is equal to 415 m (Figure 5(d)).

(6) *Dip Angle of the Coal Seam*. During the mining process, as the inclination angle of the coal seam increases, the mineral pressure formed on the working face becomes more evident. Consequently, the damage done to the coal seam floor is greater, and the risk of water inrush increases. The inclination angle of the No. 15 coal seam is in the range of 5°~12°, which represents a gently inclined sedimentary layer. The coal seam inclination angles are relatively inclined in a sizable area in the southeastern part and a small area in the northwestern part (Figure 5(e)).

(7) *Fault Complexity*. This controlling factor is characterized by the fractal dimension of the fault, which is identical to the method used for describing the complexity of the karst system. The No. 15 coal seam in the study area comprises a small number of small faults and no large faults. Most of the small faults are predominantly distributed in the northern and eastern parts of the study area. Among these, there are several normal faults, with a drop height between 0.5 and 2 m. The fractal dimension values of the faults range between 0 and 1.075. Although the complexity of the faults in the study area is relatively low, it is still an important factor that affects the possibility of water inrush from the floor (Figure 5(f)).

4.2. Calculating Weights by the Analytic Hierarchy Process. Analytic Hierarchy Process (AHP) is a practical subjective decision-making analysis technique, which represents the core method of the vulnerability index method [28]. The method decomposes a complex problem into different factors and forms a multilevel structure model according to the mutual influence relationship and membership relationship between factors. By analyzing and comparing the importance of each factor, the judgment matrix was created, and, finally, the qualitative and quantitative analyses of multiple factors were completed [29–31]. There are generally four steps: (a) establishment of a hierarchical structure model, (b) construction of a comparative judgment matrix, (c) calculation of the largest eigenvalue of the matrix and the corresponding eigenvector, and (d) hierarchical ranking and consistency check.

4.3. Establishment of the Hierarchical Model. By analyzing the main controlling factors affecting the water inrush from the floor of the No. 15 coal seam, the research object is divided into three levels, namely, A (target layer), B (criterion layer), and C (index layer), as illustrated in Figure 6.

4.4. Construction of a Judgment Matrix to Determine the Weight of the Main Controlling Factor. By taking into consideration the index system of the water inrush risk from the floor of the No. 15 coal seam and associating it with the analysis of the previously mentioned main controlling factors, the importance of each factor was evaluated according to the 1~9 scale method. This scaling method was established by T. L. Saaty, by soliciting the experts' opinions and by analyzing data from the available literature. Thus, a judgment matrix was constructed. The judgment matrix of the first-level index is $A_i = \begin{bmatrix} 1 & 5/3 & 5/2 & 3/2 \\ 3/5 & 1 & 3/2 & 4/5 \\ 2/5 & 2/3 & 1 & 3/5 \\ 2/3 & 5/4 & 5/3 & 1 \end{bmatrix}$, where the weight is $w_{A_i} = (0.375, 0.218, 0.15, 0.257)$. The judgment matrix of the secondary index is $B_{1j} = \begin{bmatrix} 1 & 4 & 2 \\ 1/4 & 1 & 1/2 \\ 1/2 & 2 & 1 \end{bmatrix}$, where the weight is $w_{B_{1j}} = (0.513, 0.182, 0.305)$; $B_{2j} = [1]$, where the weight is $w_{B_{2j}} = (1)$; $B_{3j} = \begin{bmatrix} 1 & 4/5 \\ 5/4 & 1 \end{bmatrix}$, where the weight is $w_{B_{2j}} = (0.444, 0.556)$; $B_{4j} = [1]$, where the weight is $w_{B_{2j}} = (1)$. At the same time, all the judgment matrices passed the consistency test. By applying the linear weighting method, the weight value of the first-level index is multiplied with the weight value of the related second-level index, and, finally, the weight value of the influence of each main controlling factor on the risk of water inrush from the floor is obtained; namely, $w = (0.192, 0.068, 0114, 0.218, 0.067, 0.083, 0.257)$. The weight of each main controlling factor is illustrated in Table 3.

4.5. Data Normalization of Each Main Controlling Factor. To eliminate the influence of the data of different main controlling factor dimensions on the evaluation results and to make the factors comparable, the data were normalized. Considering the positive and the negative correlation of the main controlling factors with the evaluation results, the positive correlation factors (water pressure of the aquifer, water aquifer, degree of karst development, mining depth, coal seam inclination, and fault complexity) are unified by applying the maximum value processing equation (3), where the minimum value is 0 and the maximum value is 1. At the same time, the negative correlation factor (effective water barrier thickness) is normalized to the minimum value

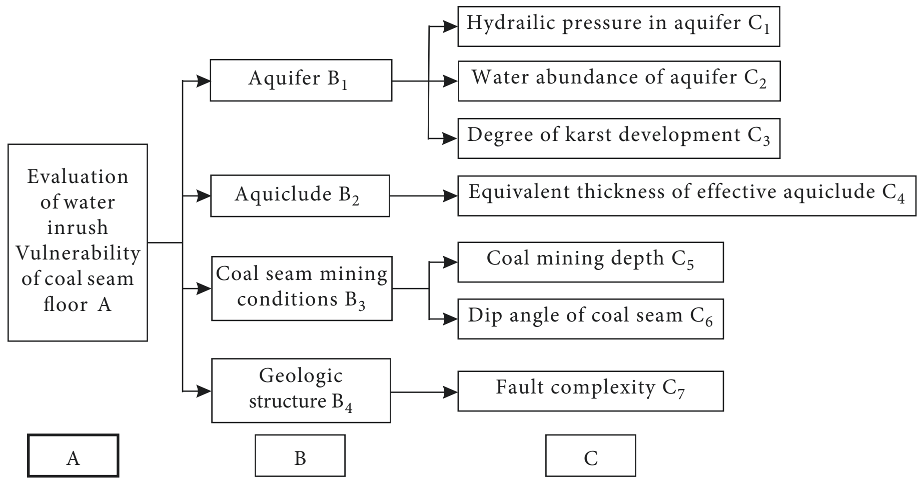


Figure 6: Evaluation index of water inrush from the floor of the No. 15 coal seam in the Honglin Coal Mine.

Table 3: Weights of the main controlling factors for water inrush.

Influential factors	Hydraulic pressure in the aquifer (w_1)	Water abundance of the aquifer (w_2)	Degree of karst development (w_3)	Equivalent thickness of the effective aquiclude (w_4)	Coal mining depth (w_5)	Dip angle of the coal seam (w_6)	Fault complexity (w_7)
Weights (w_i)	0.192	0.068	0.114	0.218	0.067	0.083	0.257

processing equation (4), with the minimum value equal to 1 and the maximum value equal to 0. The formula is expressed as

$$Y_{ij} = \frac{X_{ij} - \min(X_i)}{\max(X_i) - \min(X_i)}, \tag{3}$$

$$Y_{ij} = \frac{\max(X_i) - X_{ij}}{\max(X_i) - \min(X_i)}. \tag{4}$$

4.6. Creation of a Model of the Vulnerability Index of the Floor. The vulnerability assessment model of the karst floor water inrush of the Maokou Formation in the No. 15 coal seam of the Honglin Coal Mine was proposed based on the application of formula (2), on the vulnerability index VI, as well as the weights of the main controlling factors determined by the Analytic Hierarchy Process. The formula is expressed as

$$\begin{aligned} \mathrm{VI} = \sum_{k=1}^{7} W_k \times f_k(x,y) &= 0.192 \times f_1(x,y) + 0.068 \times f_2(x,y) + 0.114 \times f_3(x,y) + 0.218 \times f_4(x,y) \\ &\quad + 0.067 \times f_5(x,y) + 0.083 \times f_6(x,y) + 0.257 \times f_7(x,y). \end{aligned} \tag{5}$$

4.7. Water Inrush Hazard Zoning of the Coal Seam Floor. The main controlling factors are normalized on the thematic map by using the ArcGIS information fusion and data processing functions. Consequently, a comprehensive evaluation model for water inrush vulnerability of the coal seam floor is proposed. The natural discontinuity method was used to assess the frequency statistics of the vulnerability index of each block in the study area (Figure 7), and the unified partition thresholds for the vulnerability evaluation were determined to be 0.35, 0.41, 0.46, and 0.51. When the vulnerability index has greater values, the possibility of floor water inrush increases. According to the partition threshold, the research area is divided into 5 areas, specifically: $\mathrm{VI} \geq 0.51$ is the dangerous area; $0.46 \leq \mathrm{VI} \leq 0.51$ is the less dangerous area; $0.41 \leq \mathrm{VI} \leq 0.46$ is the transition area; $0.36 \leq \mathrm{VI} \leq 0.41$ is the safer area; and $\mathrm{VI} < 0.35$ is the safe zone. Afterwards, the risk assessment map of the No. 15 coal seam floor is created (see Figure 8).

5. Results

As illustrated in Figure 8, the relative risk of water inrush decreases from northwest to southeast. The floor water inrush risk area is primarily concentrated in the middle, northwestern, and western parts, which indicates a large area of bands and a small area represented by an ellipse. The safe zone is mainly concentrated in the southeastern and north-

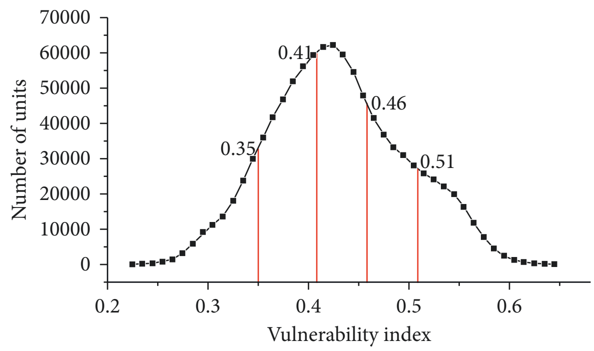


FIGURE 7: Frequency broken line chart of vulnerability index of coal seam floor in Honglin Coal Mine research area. The broken line represents the frequency distribution of the vulnerability index in the study area. The values at the intersection with the red lines represent the partition threshold calculated by the natural discontinuity method.

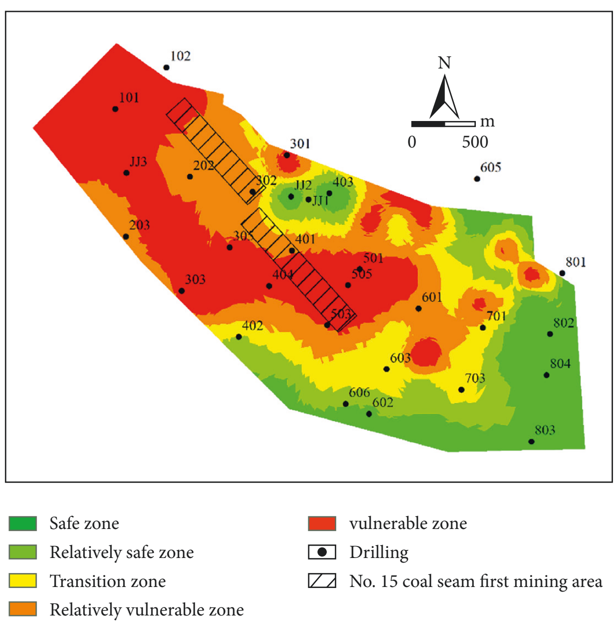


FIGURE 8: Water inrush risk zoning map of the No. 15 coal seam floor of the Honglin Coal Mine.

central parts. The arguments for such conclusions are as follows:

(1) In the northwestern part, the relative head pressure is high, water is abundant, and the perimeter is characterized by the presence of a karst fracture zone. Therefore, it is easy to produce a water channel.

(2) The water abundance in the central part of the study area shows a weakening trend, while the degree of karst development is low. However, the thickness of the effective impermeable layer becomes thinner, which cannot adequately prevent the water pressure accumulated below this layer.

(3) The aquifer and the water richness in the western part of the study area also indicate a weakening trend, while the thickness of the effective impermeable layer shows a thickening trend. However, this area is characterized by the presence of several complex faults and a karst fracture area, which facilitates the formation of a water channel and, consequently, may lead to water inrush.

(4) The mining depth of the No. 15 coal seam in the north-central part of the study area is shallow. The coal seam inclination angle is slow. The stress and the mine pressure on the floor and the two sides are small. Additionally, the effective impermeable layer is thicker, and the depth of the flood damage is not enough to penetrate the effective impermeable layer. Therefore, this perimeter is considered a safe zone.

(5) Karst fractures exist in the southeastern part of the study area. However, the water pressure and the water richness of the aquifer show a weakening trend, while the thickness of the relative aquifer is increasing. Consequently, the possibility of water inrush from the coal seam floor is negligible.

At present, there are no exploitation activities in the first mining area of the No. 15 coal seam in the Honglin Coal Mine, but the risk of water inrush from the floor in this area is relatively high. The main concerns are related to the high water pressure and the thin thickness of the impermeable layer. Therefore, the exploration operations should be strengthened, while the measures related to water exploration, water release, and thickening of the floor concreting should be adopted to ensure a safe mining environment.

6. Conclusions

(1) Based on the karst fractal-vulnerability index method, the water inrush hazard of the No. 15 coal seam floor of the Honglin Coal Mine is evaluated. Complex factors such as the typical karst aquifer in the northern Guizhou coalfield and the hydrogeological conditions of the study area are fully examined, which makes the evaluation results more reasonable and practical.

(2) To improve the accuracy of the karst geophysical prospecting evaluation results, the karst fractal dimension is used to quantify the degree of karst development of the coal seam floor. The overall fractal dimension value of the research area is equal to 1.53, and the degree of karst development is relatively high. By applying the natural discontinuity method, the karst development is divided into five categories: underdeveloped karst area, weak karst development area, medium karst development area, relatively strong karst development area, and strong karst development area. Furthermore, the karst development area is characterized by an irregular northwest-southeast direction.

(3) The water inrush danger zone of the No. 15 coal seam floor in the study area is primarily concentrated in the middle, northwestern, and western parts, with a large area of bands and a small area represented by

an ellipse. The safety zone is concentrated in the southeastern and north-central parts. There is a risk of water inrush from the floor in the first mining area of the No. 15 coal seam, and water prevention measures should be improved and strengthened.

Data Availability

Some or all data, models, or codes generated or used during the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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