Hindawi
Geofluids
Volume 2021, Article ID 5520351, 9 pages
https://doi.org/10.1155/2021/5520351

Research Article

A New Quantitative Method for Risk Assessment of Coal Floor Water Inrush Based on PSR Theory and Extension Cloud Model

Bingyou Jiang[1,2] **Bo Ren**[3,4] **Mingqing Su**[4] **Bao Wang**[1] **Xin Li**[1] **Guofeng Yu**[3] **Tingshuang Wei**[5] **and Yunchun Han**[3]

[1]*Key Laboratory of Industrial Dust Prevention and Control & Occupational Health and Safety, Ministry of Education, Anhui University of Science and Technology, Huainan 232001, China*
[2]*State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China*
[3]*State Key Laboratory of Deep Coal Mining & Environment Protection, Coal Mining National Engineering Technology Research Institute, Huainan 232000, China*
[4]*School of Emergency Management and Safety Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China*
[5]*Coal Industry Branch of Huaihe Energy Group, Huainan 232000, China*

Correspondence should be addressed to Bo Ren; renbocumt@163.com

Received 29 January 2021; Revised 16 February 2021; Accepted 22 February 2021; Published 11 March 2021

Academic Editor: Feng Xiong

In order to scientifically and reasonably assess the risk of water inrush from the coal seam floor, considering the influence of natural environmental factors such as hydrogeology, mining, and human intervention, the PSR model of ecosystem health evaluation was introduced, and the risk evaluation indicator system of water inrush from the coal seam floor was established. In order to solve the randomness and fuzziness of water inrush event evaluation, the evaluation model is constructed based on extension cloud theory and is applied in the *12123 working face of Pan Er coal mine of Huainan Mining Group*. The application results show that the evaluation results are basically consistent with the actual situation, which shows that the model can be used in the actual evaluation work and is scientific.

1. Introduction

China is the most important coal producer and consumer in the world, and the proportion of coal consumption will remain above 50% for a long time. With the gradual depletion of shallow coal resource reserves and the deepening of coal mining depth, the mine hydrogeological conditions are becoming increasingly complex, the influencing factors of mine water inrush are increasing, and the mechanism and types of water inrush are complex and changeable, which affect the normal production of a coal mine. Mine water inrush accidents will not only cause casualties but also cause obvious economic losses. For example, five people died in a water leakage accident at Shanmushu Coal Mine in Yibin City, Sichuan Province, on December 14, 2019. A water leakage accident occurred in Xiaoyun coal mine in Jining City, Shandong Province, on September 10, 2018. Although there were no casualties, the mine was submerged, resulting in a direct economic loss of 25.6614 million yuan in this accident. Therefore, the reasonable and accurate risk assessment of water inrush in coal mine is of great practical significance to grasp the state of water disaster prevention and control in a coal mine and ensure the safety production in a coal mine.

In the 1960s, Chinese scholars first proposed the concept of water inrush coefficient, which is defined as the value of water pressure borne by the coal seam floor unit thickness of the water-resistant layer, and continuous improvement has been widely used [1]. Wang et al. determined a comprehensive evaluation system of coal mine floor water inrush risk consisting of 4 first-level indicators and 13 second-level indicators and used the analytic hierarchy process to distribute the indicator weights [2]. Meng et al. proposed a water inrush risk assessment method based on the impermeability and resistance to water pressure of floor aquifuge. The specific method is to simultaneously consider floor lithology and structural characteristics as parameters for water inrush prediction and use the maximum principal curvature of the floor surface to characterize floor structure characteristics. Compared with the conventional water inrush coefficient method, this method takes into account the lithology and structure features of the floor and utilizes a maximum principal curvature of the floor surface to predict the floor structure features [3]. Li et al. aimed at the problem that the traditional water inrush coefficient method cannot accurately assess the water inrush risk of a floor under specific conditions, through the analysis of the distribution of water inrush points and the scale of water inrush events, combined with the three indicators of Ts, M, and q, the water inrush vulnerability is divided into four levels: safety, medium safety, potential danger, and high risk [4]. Fan et al. analyzed the mechanical mechanism of water inrush (WIFSL) from separated layers, derived theoretical discriminants of the first stage and periodic WIFSL based on this, and used the water inrush coefficient method to divide the water inrush risk [5].

With the development of modern information technology and related knowledge theories, the application of these methods for evaluation and prediction has gradually become a hot research field. Wu et al. established a floor water inrush assessment model based on an artificial neural network and geographic information system [6]. Liu et al. established a coal seam floor water inrush prediction system using the neural network and decision tree algorithm and obtained the coal seam floor water inrush law. The results show that the prediction system based on data mining classification technology is a practical and feasible system [7]. Through the statistical analysis of water inrush accident data, Shi et al. concluded that when evaluating the risk of water inrush from the coal seam floor, the water inrush coefficient of the coal seam floor and the water content of aquifer should be considered at the same time and used support vector machines to establish a mine safety evaluation grade prediction model [8].

Li et al. established a floor water inrush evaluation model based on grey relational analysis and analytic hierarchy process [9]. Wu et al. obtained 4 types and 12 scenario elements of mine water inrush evolution through case analysis of typical water inrush accidents and, combined with the Bayesian network, proposed a water inrush accident probability assessment framework [10]. Qiu et al. proposed an evaluation system combining attribute mathematics theory and analytic hierarchy process [11]. Li et al. used 8 kinds of water chemical components as indicators, combined with principal component analysis and Fisher discriminant analysis, to construct a water inrush water source identification model, and used the hydrological data of Xiandewang coal mine to verify the results. The results show that the model can improve the accuracy of mine water inrush source identification [12].

Water inrush from the floor of the coal seam is a complex geological phenomenon. The above evaluation of water inrush from the floor of the coal seam only considers natural environmental factors such as hydrogeology, while neglecting the influence of mining and the effect of human intervention. As a result, the assessment indicator system established may be incomplete. Based on this, this paper uses the PSR model to establish the assessment indicator system of coal floor water inrush risk. In view of the randomness and fuzziness of water inrush events, the extension cloud theory is introduced to construct the assessment model, and the actual data of the site is collected to verify the validity of the model.

2. Evaluation Index System Construction

2.1. Pressure-State-Response (PSR) Model. In order to evaluate the health of the ecosystem, Canadian statisticians David J. Rapport and Anthony Marcus Friend proposed the *Pressure-State-Response* (PSR) model in 1979, which was later developed by the Organization for Economic Co-operation and Development (OECD) and the United Nations Environment Program (UNEP) improvement and development [13]. The core idea of the model is that human social and economic activities will exert *pressure* on the natural environment and resources and *pressure* will cause changes in the *state* of the environment. In order to cope with these changes, human society takes measures to *response*, thereby reducing the environmental pressure caused by human activities and ensuring the sustainability of the environmental system. The PSR model reveals the internal relationship between social development, human activities, and the environment and can represent a continuous feedback mechanism between various indicators. PSR and its improved models have been applied in water resource sustainability evaluation [14], primary energy production capacity evaluation [15], food chain safety analysis [16], and environmental risk management of marine protected areas [17].

2.2. Comprehensive Evaluation Index System. Water inrush from coal floor is a complex system event with continuous feedback. The mining disturbance of coal can be regarded as *pressure*, which has an impact on the *state* of the hydrological environment around the coal seam, and then, the production department takes measures to *respond*, as shown in Figure 1. Based on this idea, combined with literature [2–12], the risk assessment of coal floor water inrush is established. For the *pressure* type indicators, it mainly refers to the mining factors. Mining is the inducing factor of water inrush, including coal seam conditions and mining methods. Coal seam conditions include mining depth, mining thickness, and inclined length of working face. For the *state* indicators, there are mainly geological structure, aquifer, and aquiclude indicators. The geological structure is the main factor and control factor of water inrush. The development degree of the geological structure is closely related to water inrush from the coal seam floor, which can be characterized by structural properties and the development of the geological anomaly body, which includes the karst collapse column. The existence of a confined aquifer under the coal seam floor is the prerequisite of floor water inrush. The water pressure of the aquifer is the power source of floor water inrush, and the aquifer water yield property is the material basis of water inrush, so the water pressure and aquifer water yield property

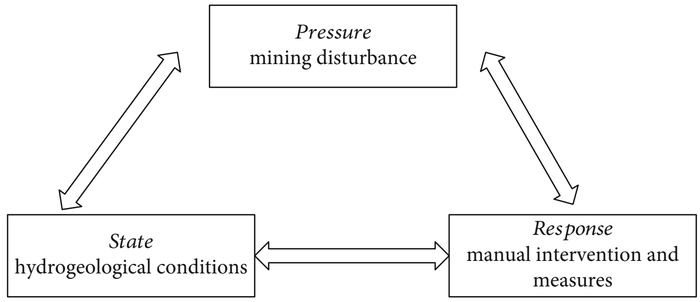

Figure 1: PSR framework to assess coal floor water inrush.

can be used as indicators. Aquiclude is the condition to prevent water inrush from the floor, and its ability to prevent water inrush depends on the thickness of effective aquiclude and the integrity of aquiclude. For *response* indicators, it mainly refers to the subjective activities of production departments or teams, including personnel factors, equipment factors, and management factors, specifically including personnel refuge awareness, personnel safety skills, integrity of waterproof and drainage equipment, availability of waterproof and drainage equipment, perfection of water prevention and control system, and implementation of water prevention and control measures. The risk indicator system of water inrush from the coal floor is shown in Figure 2, the first-level indicator is the water inrush risk of the coal seam floor, and the second- and third-level indicators are shown in the figure.

3. Evaluation Model Establishment

3.1. Extension Cloud Theory. Coal floor water inrush is affected by internal and external factors, which have the characteristics of dynamic and nonlinear. The assessment of its risk also has the characteristics of uncertainty, especially randomness and fuzziness. The cloud model is proposed by Deyi et al., considering both fuzziness and randomness, which realizes the transformation of uncertainty between qualitative concept and quantitative value [18]. For the risk of water inrush, there are both positive and negative indicators. Matter-element extension analysis can transform the contradiction of indicators into compatibility, which is proposed by Chinese scholar Professor Cai [19]. Therefore, the cloud model theory and matter-element extension theory are introduced to establish the coal floor water inrush risk evaluation model based on the extension cloud theory.

In order to clearly explain the steps of applying this model to assessment, the specific principles of the extension cloud theory are explained. Suppose C is a qualitative concept in the quantitative domain V, $x \in V$ represents a random realization on C, denoting the certainty of x to C as $\mu(x) \in [0, 1]$, and $\mu(x)$ is a random number with a stable tendency, then the distribution of x on V forms a cloud $C(x)$; the dots are called *cloud drops*. The cloud model is generally represented by three eigenvalues of expectation Ex, entropy En, and hyperentropy He. Assuming cloud $C(\mathrm{Ex}, \mathrm{En}, \mathrm{He})$, Ex is the central value after the qualitative concept C which is transformed into a numerical value, that is, the average value. En is a measure of the uncertainty of the qualitative concept C, and the degree of ambiguity of the qualitative concept C increases as the value of En increases. He is a measure of entropy uncertainty, and the degree of dispersion of C increases with the increase of He value. Due to the universality of the normal cloud model, for the qualitative fuzzy concept C of real problems, the normal cloud model is selected for analysis [20].

In the matter-element theory, the matter-element is defined as the basic element R of things, where N represents the name of the thing, c represents the feature of the thing, and V represents the value of the feature of the thing; using the feature value $(\mathrm{Ex}, \mathrm{En}, \mathrm{He})$ in the cloud model instead of V gets the cloud matter-element model:

$$R = \begin{pmatrix} R_1 \\ \cdots \\ R_n \end{pmatrix} = \begin{pmatrix} N, & c_1 & (\mathrm{Ex}_1, \mathrm{En}_1, \mathrm{He}_1) \\ & \cdots & \cdots \\ & c_n & (\mathrm{Ex}_n, \mathrm{En}_n, \mathrm{He}_n) \end{pmatrix}. \quad (1)$$

3.2. Weight Distribution Determination. The accuracy of the indicator weight will directly affect the accuracy of the evaluation results, mainly subjective weight method and objective weight method. By using the analytic hierarchy process, the importance of all the second- and third-level indicators is evaluated, respectively, and the fuzzy evaluation matrix A is obtained. Using formula (2), matrix A is calculated, and the corresponding weight vector $W = [W_1, W_2, W_n]^T$. Using formula (3), the characteristic matrix $W* = (W_{ij})_{n\times n}$ of fuzzy evaluation matrix A is obtained. Finally, the consistency indicators $I(A, W*)$ of fuzzy judgment matrix A and characteristic matrix $W*$ are obtained by formula (4), and the consistency test is carried out to judge whether the weight is reasonable.

$$W_i = \frac{\sum_{i=1}^{n} \alpha_{ij} - 1 + n/2}{n(n-1)}, \quad (2)$$

$$W_{ij} = \frac{W_i}{W_i + W_j}, \quad (3)$$

$$I(A, W^*) = \frac{1}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} \left| \alpha_{ij} + W_{ij} - 1 \right|, \quad (4)$$

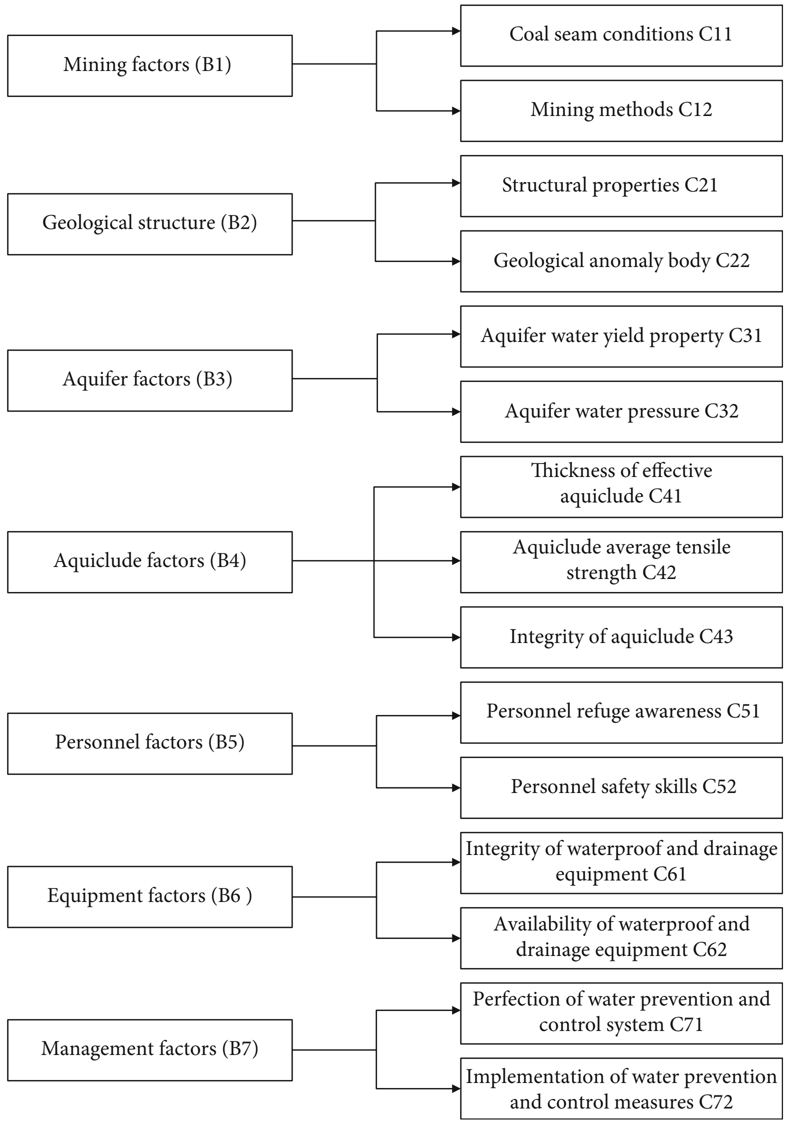

FIGURE 2: Risk assessment indicator system of coal floor water.

where α_{ij} is the element of row i and column j in fuzzy judgment matrix A $(i, j = 1, 2, 3, \cdots, n)$ and $W_{i,j}$ is the element of row i and column j in the characteristic matrix $W*$ $(i, j = 1, 2, 3, \cdots, n)$, n is the number of indicators.

Compare the value of $I(A, W*)$with the value of t, and adjust the fuzzy judgment matrix until $I(A, W*) \leq t$, where t represents the attitude of the decision-maker, and $t = 0.1$.

3.3. Cloud Generation and Computing. When using an extension cloud model to evaluate, one of the core tasks is to transform the evaluation information into the form of a *cloud*. This paper introduces the grade range of the evaluation comment, the evaluation value of the index, and the *cloud* transformation of the evaluation result value.

3.3.1. Evaluation Grade and Standard Cloud. According to the actual implementation of coal mine floor water inrush evaluation and Reference [2], the floor water inrush risk is divided into extremely high (I), high (II), general (III), low (IV), and extremely low (V). Suppose that the upper and lower limits of the evaluation index grade are T_{max} and T_{min}, respectively. Each grade of the evaluation index cannot be strictly distinguished and has fuzziness. The formula (5)~(7) is used for transformation. When there is only a single boundary limit in the grade interval, the default boundary parameters or expected values are determined according to the maximum upper or lower limit of the data, and then, the numerical characteristics are calculated by reference, where f is a constant, which needs to be adjusted according to the uncertainty of the index and the actual situation [21]:

$$\mathrm{Ex} = \frac{T_{max} + T_{min}}{2}, \tag{5}$$

$$\mathrm{En} = \frac{T_{max} - T_{min}}{2.3584}, \tag{6}$$

$$\mathrm{He} = f. \tag{7}$$

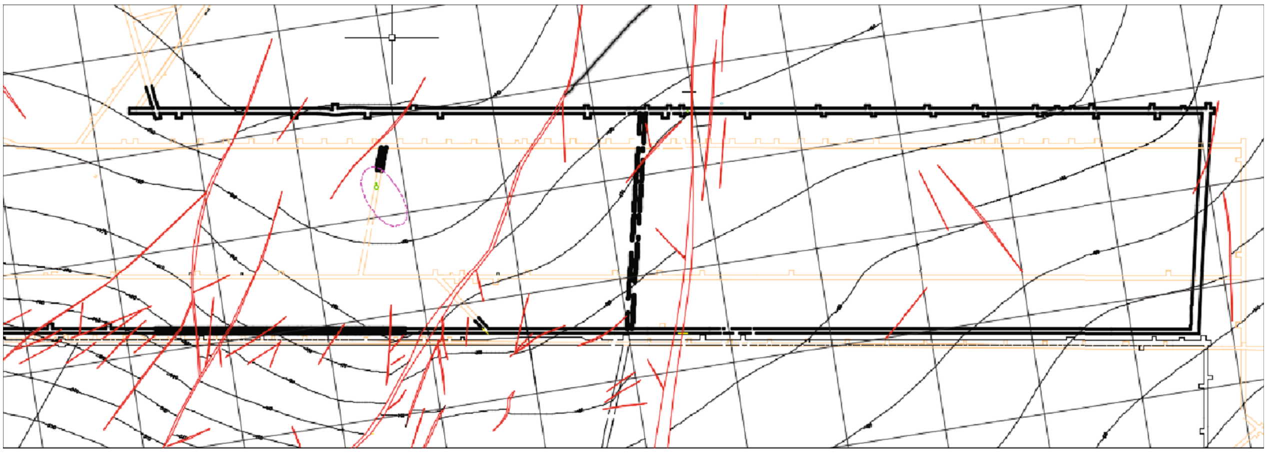

Figure 3: 12123 working face diagram.

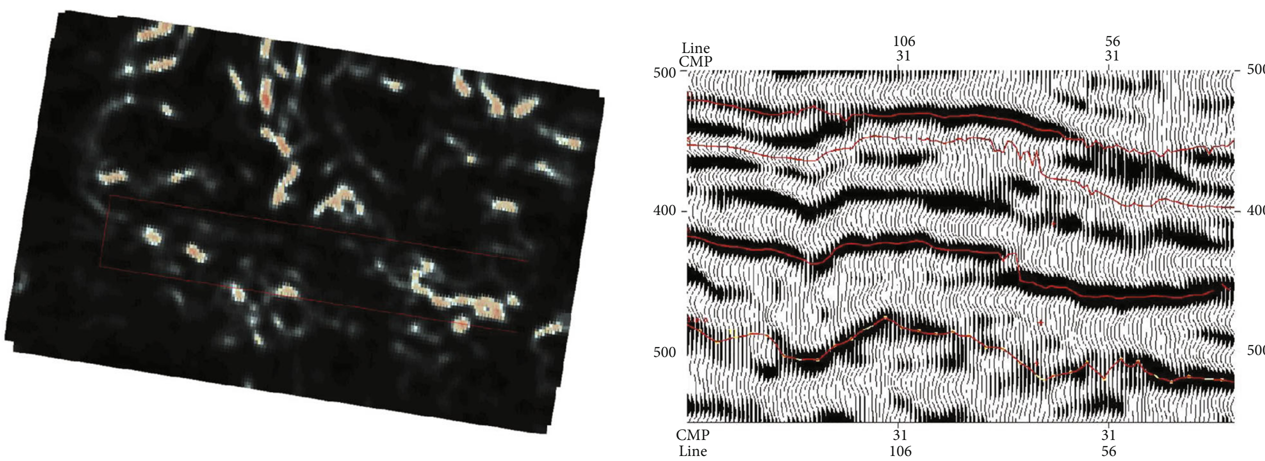

Figure 4: 3D seismic map of working face.

3.3.2. Evaluation Cloud of Indicators. The qualitative indicators are scored and assigned by experts, the quantitative indicators are collected, and the evaluation values are transformed into cloud eigenvalues to eliminate the fuzziness of subjective scoring. The approximate method is used for calculation [22]:

$$\mathrm{Ex} = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad i = 1, 2, \cdots, n, \tag{8}$$

$$\mathrm{En} = \sqrt{\frac{\pi}{2}} \cdot \frac{1}{n} \cdot \sum_{i=1}^{n} \left| x_i - \mathrm{Ex} \right|, \tag{9}$$

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n} (x_i - \mathrm{Ex})^2, \tag{10}$$

$$\mathrm{He} = \left| S^2 - \mathrm{En}^2 \right|, \tag{11}$$

where x_i is the scoring value or data value of an indicator given by the i expert and n is the number of data values of an indicator; then, $(\mathrm{Ex}, \mathrm{En}, \mathrm{He})$ is the cloud eigenvalue of the evaluation result of the indicator.

3.3.3. Comprehensive Cloud of Evaluation Results. According to the data value of each index, the *assessment cloud* of each indicator can be obtained through the transformation of eigenvalues. The similarity between each index and the *standard cloud* of each level can be calculated by using formula (12) [23]. The normalized similarity is used as the membership value to judge the evaluation level:

$$\mu = \frac{1}{2} + \frac{1}{2\Phi\left(\left(\mathrm{Ex} - \mathrm{Ex}'\right)/\sqrt{\mathrm{En}^2 + \mathrm{He}^2} + \sqrt{\mathrm{En}'^2 + \mathrm{He}'^2}\right) - \Phi\left(\dfrac{\mathrm{Ex} - \mathrm{Ex}'}{\sqrt{\mathrm{En}^2 + \mathrm{He}^2} + \sqrt{\mathrm{En}'^2 + \mathrm{He}'^2}}\right)}. \tag{12}$$

For the three-level indicators of the same measurement, formula (12) can be used to fit, and the *evaluation cloud* corresponding to the two-level indicators can be obtained.

4. Engineering Applications

In order to verify and explain the index system and algorithm, *12123* working face of *Pan Er coal mine* of *Huainan Mining Group* is selected as the engineering background.

Table 1: Indicator weight and three-level indicator risk classification.

Secondary indicator weight value	Three-level indicator weight value	Risk classification I	II	III	IV	V
B1 (0.141)	C11 (0.402)	0~60	60~70	70~80	80~90	90~100
	C12 (0.598)	0~60	60~70	70~80	80~90	90~100
B2 (0.213)	C21 (0.523)	0~60	60~70	70~80	80~90	90~100
	C22 (0.477)	0~60	60~70	70~80	80~90	90~100
B3 (0.205)	C31 (0.468)	>10	5~10	1~5	0.01~1	0~0.01
	C32 (0.532)	>7	5~7	3~5	1~3	0~1
B4 (0.216)	C41 (0.405)	0~20	20~40	40~60	60~80	>80
	C42 (0.233)	0~1	1~2	2~3	3~4	>4
	C43 (0.362)	>100	10~100	1~10	0.01~1	0~0.01
B5 (0.066)	C51 (0.544)	0~60	60~70	70~80	80~90	90~100
	C52 (0.456)	0~60	60~70	70~80	80~90	90~100
B6 (0.058)	C61 (0.384)	0~60	60~70	70~80	80~90	90~100
	C62 (0.616)	0~60	60~70	70~80	80~90	90~100
B7 (0.101)	C71 (0.367)	0~60	60~70	70~80	80~90	90~100
	C72 (0.633)	0~60	60~70	70~80	80~90	90~100

Table 2: Coal seam condition (C11) scoring.

Number	1	2	3	4	5	6	7	8
Score value	82	84	81	79	84	83	82	77

The working face has been formed and has not been mined yet. It is threatened by Ordovician limestone water, so it is necessary to evaluate the risk of floor water inrush.

4.1. Coal Mining Face Survey. The *12123* working face is located in the first stage of West *No.2* Mining Area. It starts from the West *No.2* group, a coal mining area in the East, takes *DF14* fault as the boundary in the west, drives along *12223* upper channel in the north, and takes the design elevation as the standard in the south. In the next stage, *12223* working face is being mined, with 337 m left in the strike; the overlying working faces *14124*, *12124*, and *12224* have been mined; there is no mining activity in the underlying coal seam 1, with 350 m left in the upper and 129 m left in the lower floor of *12123*. The design length of the upper channel of *12123* is 1059 m, and the elevation is -431.4~-484.3 m; the design length of the lower channel of *12123* is 1225 m, and the elevation is -452.3~-507.9 m; the cut length is 215.6 m. The thickness of coal seam 3 is 0.5-8.0 m, with an average thickness of 4.5 m, and the dip angle of coal seam 3 is -22° with an average of 10°. The thickness of the underlying coal seam 1 is 0-3.9 m, with an average thickness of 3.0 m, and the distance between coal seam 3 and coal seam 1 is about 1.5 m, as shown in Figure 3.

According to the comprehensive analysis of the actual data of the overlying *14124*, *12224*, and *12124* working faces, the adjacent *12223* working face, and the upper and lower bottom drainage roadway of *12123*, it is estimated that the geological structure of the *12123* working face is complex, and 27 faults will be exposed during the excavation, including the normal faults f12223-10, f12224-10, F203, f12223-x4, and f12224-6 which have great influence on the normal driving of the working face; the fall of faults f12223-10, f12224-10, and F203 is large, and coal 3 will be exposed again during driving through the fault. The pseudoroof of coal 3 is carbonaceous mudstone~mudstone; the direct roof is silty fine~medium fine sandstone, with an average thickness of about 20 m; the main roof is dark grey mudstone, with a thickness of about 4.0 m; and the floor of coal 3 is 1.2~1.0 m thick 8 m, with an average of 1.5 m. According to the surface drilling and 3D seismic data, there is no geological abnormal body such as magmatic rock intrusion into the coal seam and collapse column in the 12123 working face, as shown in Figure 4, which is the 3D seismic map of the working face.

4.2. Division of Grade Interval. A total of 8 industry experts and coal mine personnel were invited to form an evaluation expert group. The importance evaluation matrix is obtained by using the analytic hierarchy process (AHP), and the weight value of each index is obtained according to formula (2)~(4), as shown in Table 1.

For qualitative indicators, according to the classification of water inrush risk grade, the indicator score is divided into five grades I~V. The lower the score, the greater the risk of water inrush. Qualitative indicators include coal seam conditions (C11), mining methods (C12), structural properties (C21), geological anomaly body (C22), personnel refuge awareness (C51), personnel safety skills (C52), integrity of waterproof and drainage equipment (C61), availability of waterproof and drainage equipment (C62), perfection of water prevention and control system (C71), and implementation of water prevention and control measures (C72).

For quantitative indicators, the corresponding indicator value is obtained by conversion of borehole measurement

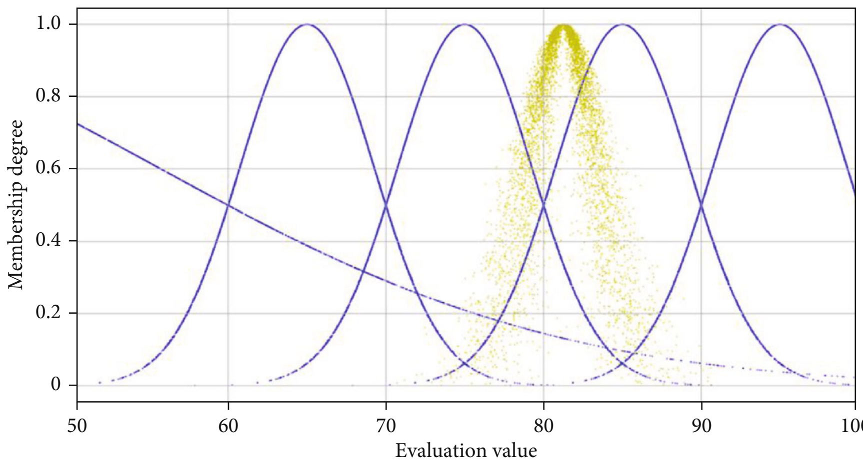

Figure 5: Assessment cloud of coal seam conditions (C11).

Table 3: Three-level indicators and membership degree of evaluation grade.

Indicator name	Cloud eigenvalues of evaluation results			Membership degree value				
	Ex	En	He	I	II	III	IV	V
C11	81.250	2.193	0.739	0.0585	0.0118	0.3245	0.5730	0.0323
C12	82.750	5.170	2.402	0.0488	0.0399	0.2531	0.5377	0.1205
C21	83.250	2.193	0.511	0.0423	0.0038	0.1626	0.7366	0.0547
C22	82.625	3.094	1.355	0.0477	0.0144	0.2338	0.6304	0.0737
C31	0.019	0.026	0.022	0.0000	0.0004	0.0661	0.2300	0.7035
C32	1.701	0.146	0.065	0.0000	0.0000	0.0229	0.9368	0.0403
C41	36.125	15.862	3.594	0.1399	0.4480	0.2967	0.0802	0.0351
C42	3.108	0.304	0.107	0.0003	0.0223	0.3206	0.4853	0.1715
C43	0.077	0.090	0.028	0.0068	0.1174	0.1289	0.3321	0.4147
C51	79.375	3.172	0.699	0.0662	0.0424	0.4830	0.3800	0.0284
C52	79.125	6.149	0.737	0.0647	0.0955	0.4288	0.3421	0.0689
C61	83.500	3.133	0.427	0.0413	0.0083	0.1750	0.6936	0.0818
C62	83.750	3.212	0.870	0.0398	0.0085	0.1655	0.6966	0.0897
C71	85.625	3.486	0.830	0.0329	0.0049	0.1061	0.7140	0.1420
C72	85.500	3.917	2.468	0.0349	0.0111	0.1314	0.6630	0.1595

data. Among them, aquifer water yield property (C31) is characterized by unit water inflow; effective aquifuge thickness (C41) can be converted according to the empirical formula, combined with drilling geological data, coal seam dip angle, mining depth, working face length, and other data, and aquifuge integrity is represented by the permeability coefficient [24]. Combined with the actual situation and common practice of the coal mine, the grade of each indicator is divided.

5. Result and Discussion

Taking the indicator of *coal seam conditions* (*C11*) as an example, the expert scoring is shown in Table 2.

According to equations (8)~(11), calculate the cloud eigenvalue of the index evaluation result, and use the cloud forward generator to get the cloud image of the index evaluation result, as shown in Figure 5. It can be seen from the figure that the evaluation of *coal seam conditions* (*C11*) by the expert group is between *III* and *IV* and is more inclined to *IV*, so the evaluation of this index is more concentrated.

By analogy, the cloud eigenvalues of all three-level indicator evaluation results can be obtained. According to equation (12), the similarity between all three-level index evaluation results and evaluation grades can be obtained. After normalization, the membership degree can be obtained. According to the principle of the maximum membership degree, the grade can be judged. The principle of the maximum membership degree means that if the membership degree of a comprehensive indicator is higher than that of an evaluation grade, then we will set the evaluation target as the evaluation grade. The results are shown in Table 3. The indicator of

Table 4: Secondary indicators and membership degree of evaluation grade.

Indicator name	Membership degree value I	II	III	IV	V
B1	0.0527	0.0286	0.2818	0.5519	0.0850
B2	0.0448	0.0089	0.1966	0.6859	0.0638
B3	0.0000	0.0002	0.0431	0.6060	0.3507
B4	0.0592	0.2291	0.2415	0.2658	0.2043
B5	0.0655	0.0666	0.4583	0.3627	0.0469
B6	0.0404	0.0084	0.1691	0.6954	0.0866
B7	0.0342	0.0089	0.1221	0.6817	0.1531

grade II is thickness of effective aquiclude (41). The indicators of grade III are personnel refuge awareness (C51) and personnel safety skills (C52). The indicators of grade IV are coal seam conditions (C11), mining methods (C12), structural properties (C21), geological anomaly body (C22), aquifer water pressure (C32), aquiclude average tensile strength (C42), integrity of waterproof and drainage equipment (C61), availability of waterproof and drainage equipment (C62), perfection of water prevention and control system (C71), and implementation of water prevention and control measures (C72). The indicators of grade V are aquifer water yield property (C31) and integrity of aquiclude (C43).

The correlation matrix $I_{15\times5}$ of all three-level indicators can be obtained from Table 3, and the weight matrix $W_{1\times15}$ of all three-level indicators can be obtained from Table 1. Then, the evaluation result matrix of floor water inrush risk is $G = W_{1\times15} \cdot I_{15\times5} = (0.03990.06120.19500.53870.1652)$.

According to the weight value of each three-level indicator relative to each secondary indicator, combined with the evaluation value of the corresponding three-level indicator, the evaluation results of each secondary indicator are obtained, as shown in Table 4. According to the principle of maximum membership, the evaluation level of each secondary indicator is judged.

6. Conclusion

(1) Based on the PSR model, the assessment indicator system of coal seam floor water inrush risk is established, which is composed of 7 secondary indicators and 15 three-level indicators, including mining factors, geological structure factors, aquifer factors, aquifuge factors, personnel factors, equipment factors, and management factors, making the assessment indicator system more theoretical and complete

(2) Based on the extension cloud theory and the assessment indicator system, the risk assessment model of water inrush from coal floor is constructed, which solves the fuzziness and randomness in the evaluation process and improves the accuracy of the evaluation

(3) The model is applied to the *12123* working face of *Pan Er coal mine* of *Huainan Mining Group*, and the water inrush risk level is grade IV. Among the secondary indicators, the mining factors (B1), geological structure (B2), aquifer factors (B3), aquiclude factors (B4), equipment factors (B6), and management factors (B7) are grade IV, and the evaluation grade of personnel factors (B5) is grade III

These evaluation results are consistent with the actual situation, which shows that the model is feasible and scientific.

Data Availability

Data will be provided upon request to the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

This work is financially supported by the National Natural Science Foundation of China (Nos. 51874009 and 52074012), the opening project of the State Key Laboratory of Explosion Science and Technology (Beijing Institute of Technology) (No. KFJJ20-11M), the Young Elite Scientists Sponsorship Program by China Association for Science and Technology (No. 2018QNRC001), and the Postdoctoral Fund of Anhui Province (No. 2017B212).

References

[1] G. Tian, "Analysis on theoretical defects of water inrush coefficient in coal mining under safe water pressure," *Applied Mechanics and Materials*, vol. 448, pp. 3825–3829, 2013.

[2] Y. Wang, W. Yang, M. Li, and X. Liu, "Risk assessment of floor water inrush in coal mines based on secondary fuzzy comprehensive evaluation," *International Journal of Rock Mechanics and Mining Sciences*, vol. 52, pp. 50–55, 2012.

[3] Z. Meng, G. Li, and X. Xie, "A geological assessment method of floor water inrush risk and its application," *Engineering Geology*, vol. 143-144, pp. 51–60, 2012.

[4] W. Li, Y. Liu, W. Qiao, C. Zhao, D. Yang, and Q. Guo, "An improved vulnerability assessment model for floor water bursting from a confined aquifer based on the water inrush coefficient method," *Mine Water and the Environment*, vol. 37, no. 1, pp. 196–204, 2018.

[5] K. Fan, W. Li, Q. Wang et al., "Formation mechanism and prediction method of water inrush from separated layers within coal seam mining: a case study in the Shilawusu mining area, China," *Engineering Failure Analysis*, vol. 103, pp. 158–172, 2019.

[6] Q. Wu, H. Xu, and W. Pang, "GIS and ANN coupling model: an innovative approach to evaluate vulnerability of karst water inrush in coalmines of north China," *Environmental Geology*, vol. 54, no. 5, pp. 937–943, 2008.

[7] Z. Liu, D. Jin, and Q. Liu, "Prediction of water inrush through coal floors based on data mining classification technique," *Procedia Earth and Planetary Science*, vol. 3, pp. 166–174, 2011.

[8] L. Shi, M. Qiu, W. Wei, D. Xu, and J. Han, "Water inrush evaluation of coal seam floor by integrating the water inrush

coefficient and the information of water abundance," *International Journal of Mining Science and Technology*, vol. 24, no. 5, pp. 677–681, 2014.

[9] L. P. Li, Z. Q. Zhou, S. C. Li, Y. G. Xue, Z. H. Xu, and S. S. Shi, "An attribute synthetic evaluation system for risk assessment of floor water inrush in coal mines," *Mine Water and the Environment*, vol. 34, no. 3, pp. 288–294, 2015.

[10] J. Wu, S. Xu, R. Zhou, and Y. Qin, "Scenario analysis of mine water inrush hazard using Bayesian networks," *Safety Science*, vol. 89, pp. 231–239, 2016.

[11] M. Qiu, L. Shi, C. Teng, and Y. Zhou, "Assessment of water inrush risk using the fuzzy delphi analytic hierarchy process and grey relational analysis in the Liangzhuang Coal Mine, China," *Mine Water and the Environment*, vol. 36, no. 1, pp. 39–50, 2017.

[12] B. Li, Q. Wu, and Z. Liu, "Identification of mine water inrush source based on PCA-FDA: Xiandewang coal mine case," *Geofluids*, vol. 2020, Article ID 2584094, 8 pages, 2020.

[13] A. Adriaanse, *Environmental Policy Performance Indicators: A Study on the Development of Indicators for Environmental Policy inthe Netherlands*, Uitgeverij, The Hague, 1993.

[14] Q. Wang, S. Li, and R. Li, "Evaluating sustainability of water-energy-food (WEF) nexus using an improved matter-element extension model: a case study of China," *Journal of Cleaner Production*, vol. 202, pp. 1097–1106, 2018.

[15] D. Wang, Y. Shen, Y. Zhao et al., "Integrated assessment and obstacle factor diagnosis of China's scientific coal production capacity based on the PSR sustainability framework," *Resources Policy*, vol. 68, article 101794, 2020.

[16] K. Baert, X. Van Huffel, L. Jacxsens et al., "Measuring the perceived pressure and stakeholders' response that may impact the status of the safety of the food chain in Belgium," *Food Research International*, vol. 48, no. 1, pp. 257–264, 2012.

[17] E. G. B. Xu, K. M. Y. Leung, B. Morton, and J. H. W. Lee, "An integrated environmental risk assessment and management framework for enhancing the sustainability of marine protected areas: the Cape d'Aguilar Marine Reserve case study in Hong Kong," *Science of the Total Environment*, vol. 505, pp. 269–281, 2015.

[18] D. Y. Li and Y. Du, *Artificial Intelligence with Uncertainty*, National Defense Industry Press, Beijing, 2005.

[19] W. Cai, *The Matter-Element Model and Its Application*, Scientific and Technical Documentation Press, Beijing, 1994.

[20] D. Y. Li, C. Y. Liu, and L. Y. Liu, "Study on the universality of the normal cloud model," *Engineering Science*, vol. 6, no. 8, pp. 28–34, 2004.

[21] Y. J. Song, D. Y. Li, X. Z. Yang, and D. H. Cui, "Reliability evaluation of electronic products based on cloud models," *Acta Electronica Sinica*, vol. 28, no. 12, pp. 74–76, 2000.

[22] H. J. Lu, Y. Wang, D. Y. Li, and C. Y. Liu, "The application of backward cloud in qualitative evaluation," *Chinese Journal of Computers*, vol. 26, no. 8, pp. 1009–1014, 2003.

[23] Y. B. Gong, Y. D. Jiang, and X. C. Liang, "Similarity measurement for normal cloud models based on fuzzy similarity measure," *Systems Engineering*, vol. 33, no. 9, pp. 133–137, 2015.

[24] C. L. Liu, Z. X. Tan, P. X. Li, L. G. Bai, and K. Z. Deng, "Calculation methods for depth of floor water-conductive fissure zone induced by mining," *Coal Mining Technology*, vol. 15, no. 5, pp. 38–41, 2010.