

Mine Water Inrush Risk Assessment Evaluation Based on the GIS and Combination Weight-Cloud Model: A Case Study

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Cite This: *ACS Omega* 2021, 6, 32671–32681

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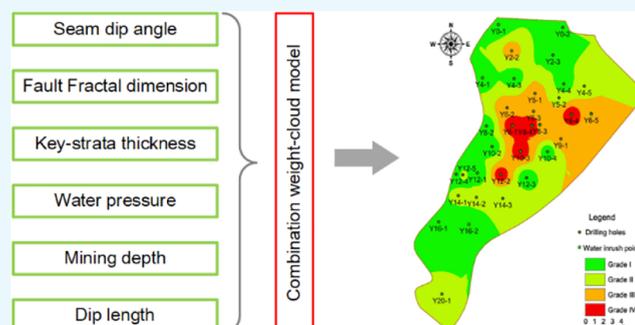
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ABSTRACT: With the increase in mining depth, the hydrogeological conditions of mines become more complex, which leads to higher possibility and harmfulness of water inrush accidents and brings great challenges to mine safety. It is particularly important to accurately evaluate the risk of mine water inrush. In order to study and prevent the floor water disaster of coal mines, it is necessary to correctly evaluate the risk of water inrush according to the limited borehole data. Based on the six main factors affecting water inrush, such as the seam dip angle, fault fractal dimension, key-strata thickness, water pressure, mining depth, and dip length, a comprehensive evaluation index system of floor water inrush risk is established in this paper. In the first step, we combine the combination weight method based on game theory with the cloud model to calculate the risk level of water inrush at each borehole location. In the second step, the risk level is displayed in a geographic information system, and the single index and comprehensive zoning map of water inrush risk in the study area are established to provide scientific guidance for mine water disaster prevention and control in this area. Through the case study of the Yangcheng Coal Mine, the whole process is further expounded. The results show that the five actual water inrush points in the Yangcheng Coal Mine are located in the dangerous area (grade IV) and the relatively dangerous area (grade III), which verifies the effectiveness of this method. At the same time, the evaluation results show that water pressure has great influence on floor water inrush.



1. INTRODUCTION

The mining industry has always been considered as an inherently high-risk profession worldwide.^{1,2} In China, with the increasing mine mining depth, a series of engineering disasters and accidents have increased, especially the increase in water inrush disasters from coal seam floor.³ Therefore, mine water risk has always been one of the important factors restricting coal mining in China, and it is of great application value to carry out research on mine water inrush risk assessment evaluation.⁴

Water inrush risk assessment refers to the comprehensive evaluation of potential impacts of uncertain accidents or disasters. The increase in mine mining depth leads to the complexity of hydrogeology, so the influencing factors and influencing mechanism of mine water inrush are also complex and variable.^{5–8} At present, scholars at home and abroad have done a lot of research on the risk assessment of floor water inrush. On the basis of establishing the main control index system of floor water inrush, Wu et al.⁹ put forward an artificial neural network (ANN) vulnerability index method based on a geographic information system (GIS) to evaluate the risk of water inrush. Zhang and Wang¹⁰ used fisher discriminant analysis (FDA) and three classification algorithms to process the limited borehole data and predicted the water abundance level at different locations in the study area. Wang et al.¹¹

developed a new type of similar material for similar simulation experiments in the laboratory to predict separation water inrush accidents. Zhao et al.¹² refined the crack evaluation process based on the deep learning method to improve the accuracy of subsequent water inrush evaluation. Dai et al.¹³ analyzed the water inrush risk of the 11th coal seam in the Hancheng mining area using GIS and the analytic hierarchy process (AHP). Qu et al.¹⁴ conducted gray evaluation of water inrush risk. Zhang et al.¹⁵ established a multiple logistic regression model to identify the water inrush source and predict the risk of floor water inrush. Hu et al.¹⁶ obtained the weights of the evaluation factors through AHP and the entropy weight method (EWM) and further determined water inrush risk zonation using the GIS technology. Qiu et al.¹⁷ adopted the fuzzy AHP based on geology, hydrogeology, floor permeability, and other factors to construct the water inrush index of coal seam floor. Similar studies also include the studies

Received: August 12, 2021

Accepted: November 10, 2021

Published: November 19, 2021



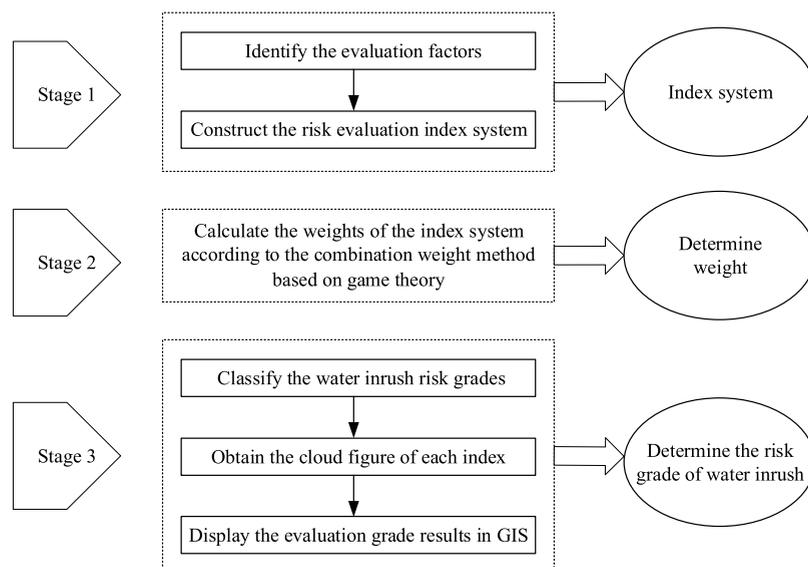


Figure 1. Evaluation process of water inrush risk in coal mine.

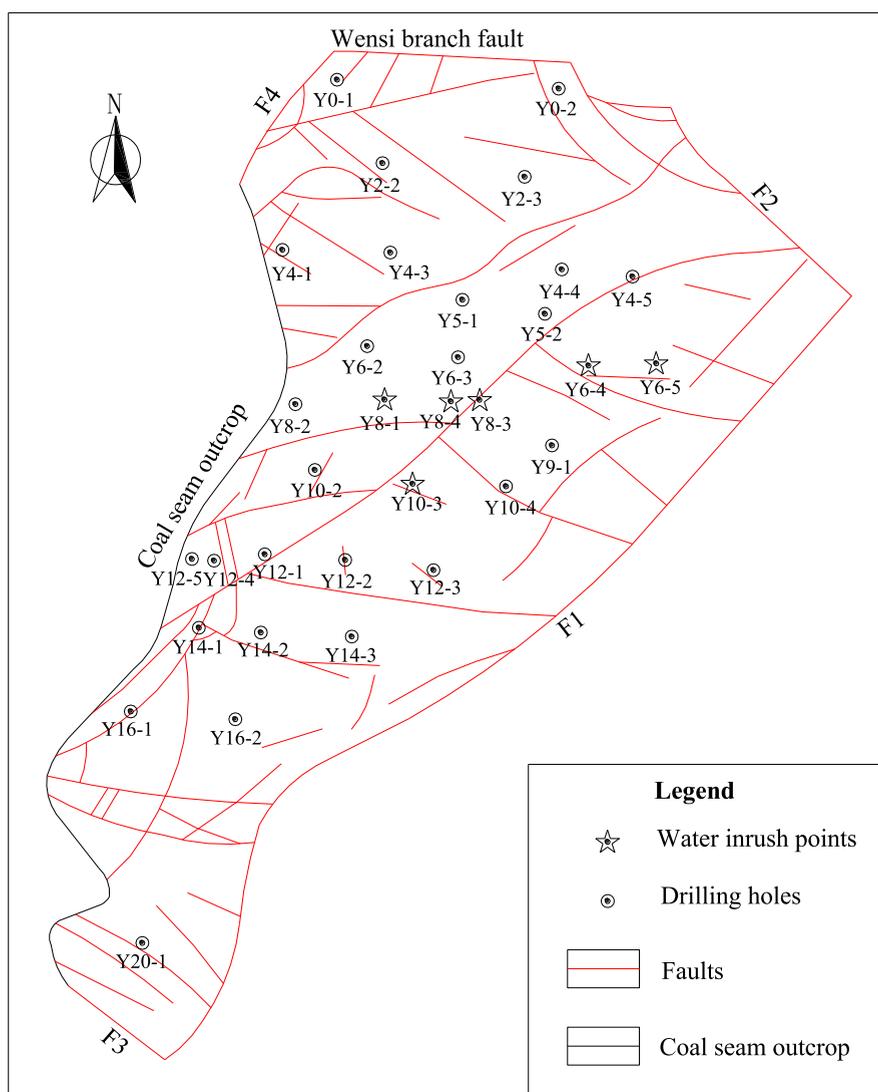


Figure 2. Drilling holes and geological structure of Yangcheng Coal Mine.

by Nie et al.¹⁸ and Shi et al.¹⁹ These methods have the limitation of randomness and fuzziness due to their strong subjectivity, so the evaluation results are often inaccurate.²⁰ The combination weighting method based on game theory²¹ and the cloud model can solve the above limitations. The cloud model can realize the bidirectional uncertainty mapping from the evaluation value to the evaluation domain and measure the fuzziness and randomness of the evaluation index.²² The cloud model has been widely used in urban rail transit operation safety evaluation,²³ heavy metal pollution assessment in Farmland soils of mining areas,²⁴ tunnel safety construction,²⁵ and has achieved very good results.

In this study, we propose a new combined evaluation method for water inrush risk-level prediction and further apply it to Yangcheng Coal Mine. In this method, a comprehensive index evaluation system with combination weights and cloud model to evaluate the risk of the water inrush in coal mine was established. The GIS is combined with the combination weighting-cloud model to analyze the risk status of floor water inrush and provide early warning of floor water inrush. The flow chart of research methods is shown in Figure 1. Stage 1: Construct the evaluation index system of water inrush risk. In this paper, by summarizing the previous research results on water inrush risk assessment, six evaluation factors are screened out. On the basis of in-depth analysis and excavation, the index system of water inrush risk is constructed. Stage 2: Determine the weight of each evaluation index, according to the combination weight method based on game theory. It calculates subjective and objective weights by the AHP and the EWM, respectively, and then combines them based on game theory. Stage 3: Evaluate the risk of water inrush in Yangcheng Coal Mine on the basis of the cloud model. In this stage, the first step is to classify the water inrush risk grades. Next, based on the theory of the cloud model, three eigenvalues of the cloud model are used to reflect the membership relationship between evaluation indexes and risk grades, and the cloud droplet distribution of each evaluation index is obtained, that is., cloud figure. According to the cloud figure and the actual data of each index, the risk grade of each evaluation index is obtained and displayed intuitively in GIS. Finally, the risk grade of each evaluation index at each borehole is combined with the weight of the evaluation index, and the comprehensive water inrush evaluation grade result is obtained, which is displayed intuitively in GIS. The advantages of this evaluation model are three-fold: (1) the method of calculating weights based on game theory combines subjective and objective weights and is more accurate than a single weight calculation method. (2) Using a cloud model combined with the combined empowerment method to determine the risk grade is more objective and accurate than a normal cloud model. (3) Instead of a direct superposition of thematic layers of each indicator with specific weights, the resulting zoning map is calculated by the evaluation process, which will make the evaluation results more accurate, but the process will also be more complicated.

The rest of this paper is organized as follows. The basic information of our study area is first presented, and the influencing factors of the water inrush risk are then selected. Subsequently, the evaluation procedures are described in detail and validated on the available data set. Finally, the application results are discussed.

2. STUDY BACKGROUND

2.1. Study Area. The south, north, and east boundaries of Yangcheng Coal Mine are large faults with a drop of more than 800 m, and the west is coal seam outcrop. The number and character of faults are with average thickness of 250 m, buried depth of 250–1350 m, and drop greater than 50 m in the quaternary system; 46 large- and medium-sized faults in this area are normal faults, among which nine faults with drop greater than 200 m, eight faults with drop greater than 200 m, 16 faults with drop greater than 50–100 m, and seven faults with drop greater than 30–50 m are observed. Three aquifers in the study area affect the mining of coal seams. The actual water inrush at 33 drilling holes in Yangcheng Coal Mine was Y6-4, Y6-5, Y8-1, Y8-3, Y8-4, and Y10-3 (Figure 2). These six drilling holes can be called water inrush points.

2.2. Evaluation Index System. Floor water inrush of coal mine is a phenomenon that the water inflow increases abruptly in a short period of time, which is caused by a series of complex factors. In the aspect of influencing factors, based on the “China provisions on prevention and control of water in coal mines,” though summarizing the previous research on the water inrush risk evaluation, we think that the main influencing factors are the seam dip angle (C1), fault fractal dimension (C2), key-strata thickness (C3), water pressure (C4), mining depth (C5), and dip length (C6), where C1 and C2 belong to the geological condition, C3 and C4 belong to the hydro-geological condition, and C5 and C6 belong to the mining condition. Therefore, the structure model of AHP is shown in Figure 2. The supporting evidence are provided below.

Seam dip angle (C1): The dip angle of coal seam determines the stress difference between mining pressure and water pressure on both sides of the panel during mining, which changes the failure depth of the floor and the location of water inrush.

Fault fractal dimension (C2): Because of the complexity of fracture structure, the prediction model of floor water inrush has the characteristics of difficult quantification and low accuracy. Through the study of the well field, this paper selected the fault fractal dimension for the quantitative evaluation of the complexity of the fracture structure. It can reflect the complexity of the fracture structure more accurately and objectively than other indicators (such as fault density) and improve the accuracy of water inrush prediction.

Key-strata thickness (C3): The aquitard rock layers of floor can inhibit the floor water inrush and block the water flow from entering the working face. According to the key-strata theory, the key layer of water resistance is composed of one or more aquifers, which controls the movement of rock mass and prevents the confined water from entering underground panels. The thicker the water-resistant key strata, the lower the risk of water inrush.

Water pressure (C4): Water pressure affects the floor water inrush. On the one hand, water can soften the rock of aquitard rock layers and reduces its strength; on the other hand, water will fill the cracks of aquitard rock layer rock mass under the action of water pressure, and the pore water pressure will reduce the overall strength of rock mass. These conditions will lead to the continuous expansion of the water inrush channel and increase the water inflow of floor water inrush. The greater the water pressure, the easier it is to expand the water inrush channel, and the higher the possibility of water inrush.

Table 1. Normalized Values of Evaluation Indexes for Water Inrush

drilling holes	mining depth	fault fractal dimension	key-strata thickness	water pressure	dip length	seam dip angle
Y0-1	0.6494	0.2050	0.1576	0.0577	0.3282	0.0625
Y0-2	0.6129	0.2668	0.1627	0.0577	0.6200	0.0625
Y2-2	0.9621	0.3168	0.6311	0.0962	0.4248	0.1875
Y2-3	0.9425	0.5907	0.5796	0.0962	0.4264	0.1875
Y4-1	0.0000	0.4008	0.0000	0.0000	0.0278	0.1875
Y4-3	0.6774	0.4341	0.5038	0.0962	0.3541	0.0625
Y4-4	0.7111	0.4055	0.5496	0.0962	0.3959	0.0625
Y4-5	0.6971	0.5833	0.4545	0.0962	0.3952	0.0625
Y5-1	0.4586	0.6027	0.5847	0.0000	0.2034	0.3750
Y5-2	0.9032	0.6991	0.3535	0.2308	0.4142	0.3750
Y6-2	0.1837	0.3087	0.5816	0.0000	0.3077	0.6875
Y6-3	0.5989	0.6027	0.4807	0.4423	0.4161	0.6875
Y6-4	0.9565	0.6991	0.3516	0.6923	0.2658	0.0625
Y6-5	1.0000	0.2820	0.5364	0.4423	0.4604	0.0625
Y8-1	0.4264	0.6712	0.9909	0.6538	0.7180	0.6875
Y8-2	0.0266	0.0946	0.8182	0.0577	0.2286	0.0000
Y8-3	0.7251	0.2235	0.6618	0.4038	0.3610	0.6875
Y8-4	0.7377	0.8137	0.9091	0.8077	0.7183	0.6875
Y9-1	0.8822	0.2197	0.6000	0.1154	0.3457	0.6875
Y10-2	0.2090	0.3165	1.0000	0.6346	0.4238	0.0625
Y10-3	0.3871	0.2315	0.8431	1.0000	0.4238	1.0000
Y10-4	0.8808	0.2875	0.1111	0.2115	0.0682	0.3750
Y12-1	0.2062	1.0000	0.9489	0.4808	0.1134	0.6875
Y12-2	0.4011	0.7963	0.9569	0.7115	0.4242	0.6875
Y12-3	0.9229	0.1474	0.5742	0.0577	0.0000	0.1875
Y12-4	0.0337	0.1809	0.4764	0.0000	0.3841	0.0000
Y12-5	0.0126	0.1809	0.7273	0.0000	0.3841	0.0000
Y14-1	0.2328	0.2304	0.6909	0.2500	0.3850	0.1250
Y14-2	0.2637	0.3950	0.5533	0.2500	0.8168	0.1250
Y14-3	0.6396	0.0000	0.5164	0.2308	0.3280	0.2500
Y16-1	0.1501	0.6627	0.5455	0.0385	1.0000	0.0625
Y16-2	0.6003	0.4843	0.2945	0.0962	0.5021	0.0625
Y20-1	0.7055	0.5710	0.0182	0.2308	0.6196	0.0625

Mining depth (C5): With the continuous increase in mining depth, the floor strata are more likely to produce cracks, which provides a good water inrush channel from the floor, and the deepening of mining depth increases the risk of floor water inrush.

Dip length (C6): The dip length of the working face is one of the factors that determine the mining space of coal seam. Under certain other mining conditions, the mining space of coal seam determines whether water inrush occurs in the floor. With the increase in the dip length of the working face, the stress around the working face is also increasing, and the deformation and failure degree of the water-resistant key strata are more serious, and the probability of floor water inrush is also greater.

In the following paragraphs, we name above factors as the evaluation indexes. Then, we quoted the original data of drilling holes about six indexes from Li and Sui.²⁶ In order to avoid the dimension difference of each factor, it is necessary to normalize the original data of each factor, in which eq 1 is used to calculate seam dip angle (C1), fault fractal dimension (C2), water pressure (C4), mining depth (C5), and dip length (C6), which are positively related to floor water inrush, and eq 2 is used to calculate key-strata thickness (C3), which are negatively related to floor water inrush. The normalized results are shown in Table 1.

$$x_i = \frac{X_i - \min(X)}{\max(X) - \min(X)} \quad (1)$$

$$x_i = \frac{\max(X) - X_i}{\max(X) - \min(X)} \quad (2)$$

where x_i is the normalized data, X is the original data, and $\min(X)$ and $\max(X)$ are the minimum and maximum values of each evaluation index, respectively.

3. THEORY AND METHODS

After establishing the index system and obtaining the index data, each index is weighted by the principle and steps of the combined weighting method, and then the risk of water inrush from the floor of Yangcheng Coal Mine is evaluated using the cloud model.

3.1. Grade Division. In order to use the cloud model for evaluation, it is necessary to divide the data into water inrush risk grades. The risk grade division of evaluation indexes affects the reliability of evaluation results. The Jenks²⁷ can classify the data, maximize the differences between the classes, and set their boundaries at the positions where the differences are the greatest. This difference is just what we need. In this paper, we use Jenks built in GIS to directly divide the normalized data into four categories, corresponding to four water inrush evaluation grades, which are I (safety), II (relative safety), III

Table 2. Division of the Evaluation Levels of Water Inrush Risk

evaluation index	I (safety)	II (relative safety)	III (relative danger)	IV (danger)
seam dip angle	0–0.20	0.20–0.36	0.36–0.54	0.54–1
fault fractal dimension	0–0.31	0.31–0.43	0.43–0.54	0.54–1
key-strata thickness	0–0.32	0.32–0.53	0.53–0.71	0.71–1
water pressure	0–0.17	0.17–0.31	0.31–0.50	0.50–1
mining depth	0–0.33	0.33–0.55	0.55–0.73	0.73–1
dip length	0–0.31	0.31–0.48	0.48–0.69	0.69–1

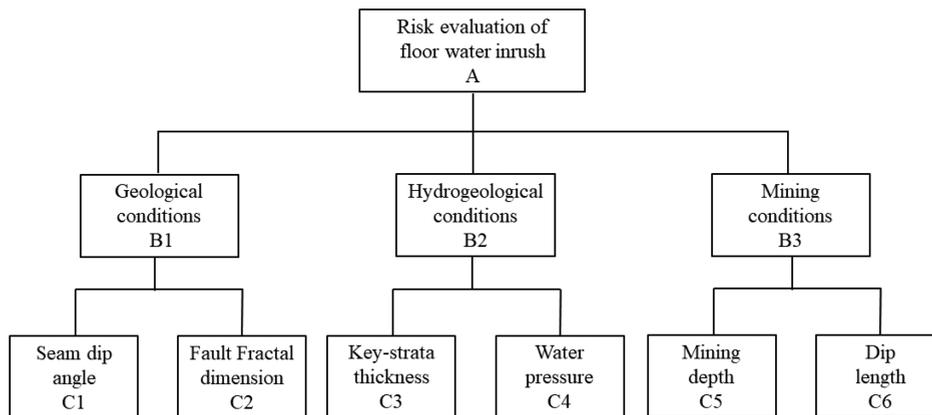


Figure 3. Evaluation index system of the water inrush risk.

(relative danger), and IV (danger). The specific division is shown in Table 2.

3.2. Combination Weight-Cloud Model. AHP and EWM are subjective weight calculation methods and objective weight calculation methods, respectively, which have strong subjective and objective defects, respectively. The combination of subjective and objective weights based on game theory can coordinate the conflict and consistency of subjective and objective weights so as to get the optimal combination weight, which can reflect the subjective and objective influence of each index on the evaluation object, and is more accurate and realistic than the single weight calculation method. The cloud model can weaken the influence of fuzziness and randomness in the evaluation process. Combining the advantages of the combined weight calculation method based on game theory and the cloud model, the obtained weighted cloud model can get more accurate evaluation results when evaluating water inrush risk.

3.2.1. Combination Weight. Different evaluation indexes have different importance to evaluation objects, and a single weight method can easily lead to one-sidedness and limitation of index weights, thus affecting the reliability of evaluation results. Therefore, the combination weighting method based on game theory can be used to determine the combination weights of the evaluation indexes of floor water inrush. The combination weighting method of game theory is to minimize the deviation of subjective and objective weights and find out the consistency and compromise between different weights. The process of determining the combination weights by this method is as follows.²⁸

Step 1: Using N different methods to calculate the weight of each water inrush evaluation index, respectively.

Step 2: The weights calculated by N different methods are recombined into a basic weight set $W = \{w_1, w_2, \dots, w_N\}$. Let w_k be a row vector, after any combination, $w = \sum_{k=1}^N \alpha_k w_k^T$, where α_k is a linear combination coefficient.

The combination weighting method of game theory is to solve the optimal weight linear combination coefficient, minimize the deviation of weights of different methods, and find out the optimal weight w^* . The gaming model is obtained as follows

$$\min \left\| \sum_{k=1}^N \alpha_k w_k^T - w_j^T \right\|^2, \quad j = (1, 2, \dots, N) \tag{3}$$

Step 3: According to the condition that the optimal first derivative is 0, eq 4 can be obtained.

$$\begin{bmatrix} w_1 w_1^T & \dots & w_1 w_N^T \\ \vdots & \ddots & \vdots \\ w_N w_1^T & \dots & w_N w_N^T \end{bmatrix} \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_N \end{pmatrix} = \begin{bmatrix} w_1 w_1^T \\ \vdots \\ w_N w_N^T \end{bmatrix} \tag{4}$$

Step 4: After the coefficient $(\alpha_1, \alpha_2, \dots, \alpha_N)$ is normalized with eq 6 and the optimal weight coefficient is obtained, the comprehensive weight is

$$w^* = \sum_{k=1}^N \alpha_k^* w_k^T \tag{5}$$

$$\alpha_k^* = \frac{\alpha_k}{\alpha_1 + \alpha_2 + \dots + \alpha_N} \tag{6}$$

In this paper, $N = 2$, and w_k is a vector with six columns in one row. The AHP²⁹ of the subjective weighting method and the EWM³⁰ of the objective weighting method are selected for combination calculation in order to ensure the rationality and balance of combination weights.

3.2.2. Cloud Model. Cloud model is not only the concrete implementation method of cloud but also the foundation of cloud-based operation, reasoning, and control. This model was put forward by Li et al.,³¹ academician of Chinese Academy of Engineering in 1995, aiming at the deficiency of probability

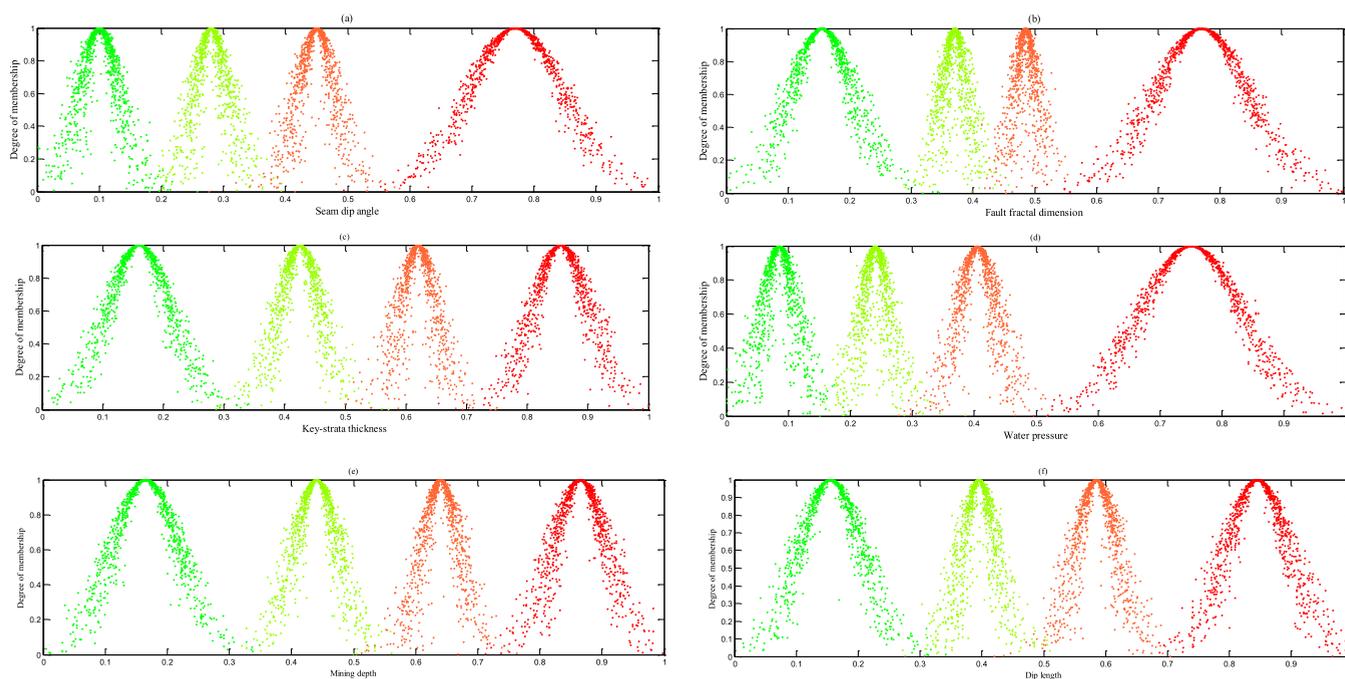


Figure 4. Cloud figure of (a) C1, (b) C2, (c) C3, (d) C4, (e) C5, and (f) C6.

Table 3. Weight of Evaluation Indexes of Water Inrush

evaluation index	seam dip angle	fault fractal dimension	key-strata thickness	water pressure	mining depth	dip length
subjective weight	0.033	0.167	0.400	0.200	0.067	0.133
objective weight	0.288	0.098	0.087	0.307	0.129	0.091
combination weight	0.146	0.136	0.260	0.247	0.095	0.116

theory and fuzzy mathematics in dealing with uncertainty. It is an uncertain transformation model dealing with qualitative concepts and quantitative descriptions. It has great advantages in security evaluation and data mining and provides a scientific and convenient theoretical model for solving random and fuzzy problems. Therefore, the cloud model can be used to measure the risk of water inrush. It includes the following four steps.³²

Step 1: The cloud characteristic numbers (Ex , En , and He), according to the evaluation grade, are determined. Ex is the expectation, which is the central point reflecting the qualitative concept and represents the overall characteristics of the qualitative concept; En is the entropy, which can reflect the fuzziness and randomness of qualitative concepts and their relevance; and He is the entropy of entropy, that is, super entropy, which represents the randomness of membership degree. (Ex , En , and He) can be calculated, according to the following equations.³³

$$Ex = (I_{\max} + I_{\min})/2 \quad (7)$$

$$En = (I_{\max} - I_{\min})/6 \quad (8)$$

$$He = k \quad (9)$$

where I_{\max} and I_{\min} are, respectively, represented as the upper and lower boundary values of each evaluation grade interval. k is a constant reflecting the threshold value of fuzzy evaluation. Normally, k is 0.01.

Step 2: The corresponding cloud figure is generated to represent the grade of each index, according to the evaluation grade divided by water inrush risk. The cloud figure of each grade is shown in Figure 4, the abscissa represents the

normalized value of borehole data in Yangcheng Coal Mine, and the ordinate represents the membership degree corresponding to each evaluation grade, and I (safety) is indicated in green, II (relative safety) is indicated in cyan, III (relative danger) is indicated in orange, and IV (danger) is indicated in red.

Step 3: According to (Ex , En , and He) and the actual data of each index, the membership degree of each evaluation index corresponding to each grade is calculated, and the membership matrix $U = [u_{ij}]_{33 \times 4}$ is formed. The membership degree u_{ij} of different indexes belonging to each grade j is calculated, according to the actual data x_i using eq 10. Taking index C1 as an example, the degree of membership of C1 in each drilling hole is shown in Table S1.

$$u_{ij}(x_i) = \exp(-(x_i - Ex_{ij})^2 / 2(En'_{ij})^2), \quad (10)$$

$$(i = 1, 2, \dots, n; j = 1, 2, \dots, m)$$

where n is the number of evaluation indexes and m is the number of risk grades; $En' = \text{randn}(1) \times He + En$, $En' \sim N(En, He^2)$.

Step 4: Fuzzy transforms the combination weight vector matrix w^* and the membership matrix U

$$T = W^* \otimes U = (t_1, t_2, \dots, t_j) \quad (11)$$

$$t_j = \sum_{i=1}^{33} \omega_i^* u_{ij}, \quad j = 1, \dots, 4 \quad (12)$$

where t_j is the evaluation degree, in which one drilling hole belongs to the grade j .

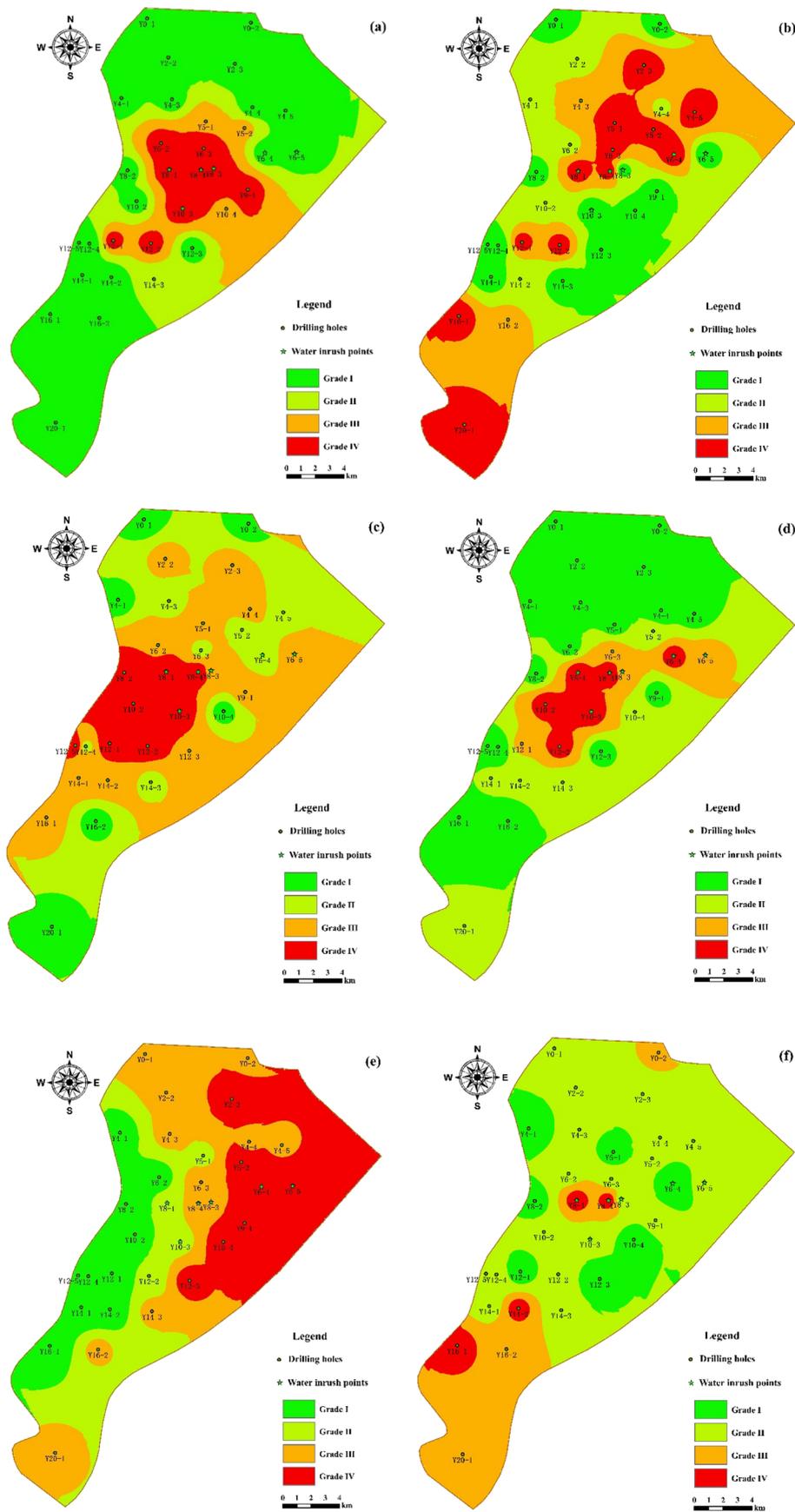


Figure 5. Thematic maps of evaluation results of (a) C1, (b) C2, (c) C3, (d) C4, (e) C5, and (f) C6.

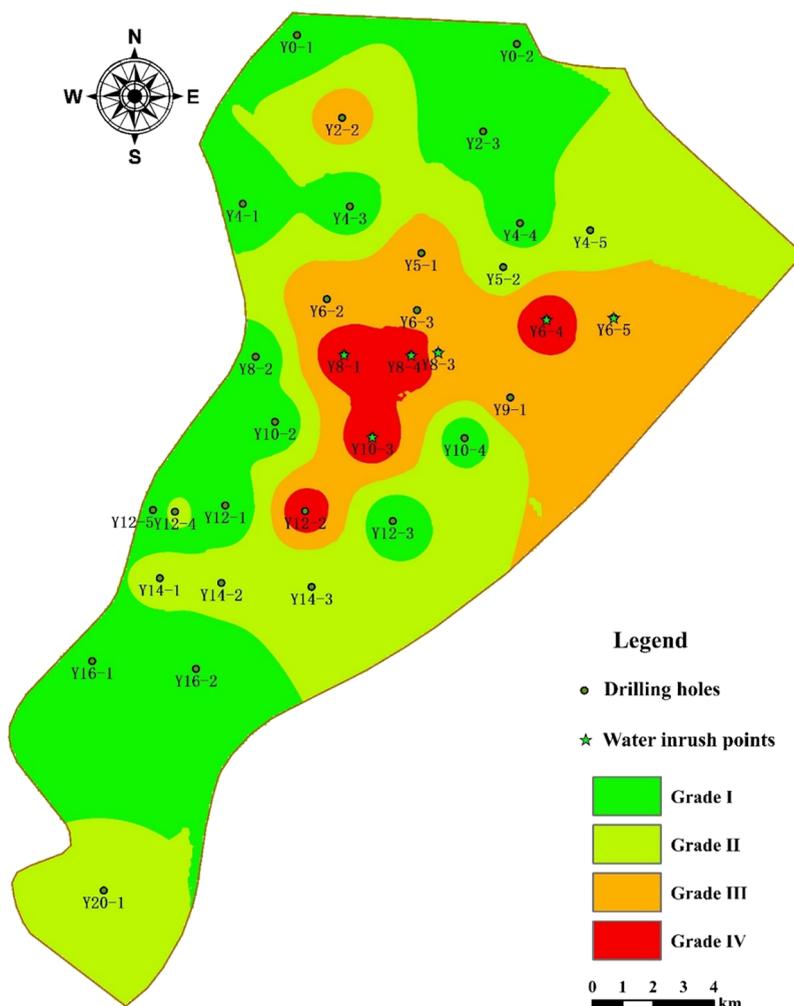


Figure 6. Evaluation results of the risk of water inrush in 33 drilling holes.

According to the maximum membership degree principle, the grade with the highest degree of membership is the grade of this drilling hole.

4. RESULTS

4.1. Calculation of Combination Weight of Indexes.

As shown in Figure 3, the first-grade evaluation indexes: $A = (B1, B2, B3)$, the second-grade evaluation indexes: $B1 = \{C1, C2\}$, $B2 = \{C3, C4\}$, $B3 = \{C5, C6\}$. According to the subjective scoring method of experts, the judgment matrix R of each level index based on relative importance was constructed

$$R_{A(B1,B2,B3)} = \begin{pmatrix} 1 & 1/3 & 1 \\ 3 & 1 & 3 \\ 1 & 1/3 & 1 \end{pmatrix}$$

$$R_{B1(C1,C2)} = \begin{pmatrix} 1 & 1/5 \\ 5 & 1 \end{pmatrix} \quad R_{B2(C3,C4)} = \begin{pmatrix} 1 & 2 \\ 1/2 & 1 \end{pmatrix}$$

$$R_{B3(C5,C6)} = \begin{pmatrix} 1 & 1/2 \\ 2 & 1 \end{pmatrix}$$

By calculating the subjective weight and testing the consistency of the two levels of evaluation index sets, we can get that the consistency ratio (CR) values of the first-grade index set and the second-grade index set were all 0, so all the

CR values were less than 0.1, which showed that the judgment matrix has passed the consistency test, and the weight is reasonable. Based on this, the index weights of each secondary index set were normalized in combination with the first-grade index weights, and the subjective weights of each index can be obtained, as shown in Table 3.

According to the normalized values of 33 groups of drilling hole data in Yangcheng Coal Mine, the objective weights of each index were obtained using EWM.

It can be seen from Table 3 that there were some differences and conflicts between the subjective weight of AHP and the objective weight of EMW, such as the weight of seam dip angle was larger in objective weight, while the weight of subjective weight was smaller. At the same time, the subjective weights of key-strata thickness, fault fractal dimension, and dip length were higher, but the objective weights of the three were lower. This showed that it was difficult to synthetically embody the importance of each index by a single weighting method, so it was necessary to find an equilibrium point to synthetically determine the weight of an evaluation index based on subjective and objective weights using game theory.

From the four steps of calculating the combination weight, the combination weight coefficient can be obtained: $\alpha_k^* = (0.553, 0.447)^T$. Substituting the results into formula 3, the combined weights of each evaluation index are obtained, as shown in Table 3.



Figure 7. Influence degree of each index of water inrush for (a) Y6-4, (b) Y6-5, (c) Y8-1, (d) Y8-3, (e) Y8-4, and (f) Y10-3.

4.2. Evaluation Index Cloud. According to the evaluation procedure, we can get the degree of membership of the risk of water inrush in each drilling hole (as seen in Table S2). Because the evaluation results obtained directly from cloud figures are mainly in the numerical form (as seen in Tables S1 and S2), which lack spatial characteristics, GIS and other spatial tools can be used to visually display the water inrush risk in the study area. Combining GIS with the cloud model,

we can show the thematic maps of the influence grade of a single evaluation index on water inrush (as seen in Figure 5) and further combine the risk grade of each evaluation index at each borehole with the weight of an evaluation index to obtain the comprehensive water inrush evaluation grade result, which is visually displayed in GIS (as seen in Figure 6).

Figure 5 shows that there are significant differences in the influence level of each index on water inrush risk at different

positions. C1 and C4 have great influence on the middle part of coal mine, C2 has great influence on the north and south end of coal mine, C3 has great influence on the middle and west part of coal mine, C5 has great influence on the northeast part of coal mine, and C6 has little influence on water inrush in coal mine. As we know, the weights of C3 and C4 are relatively large, so the possibility of water inrush is the highest in the middle part of the study area which is greatly affected by water inrush by these two factors.

4.3. Risk of Water Inrush. Based on the evaluation of six single indexes of seam dip angle (C1), fault fractal dimension (C2), key-strata thickness (C3), water pressure (C4), mining depth (C5), and dip length (C6), we evaluated the risk of water inrush in each drilling hole from a comprehensive index system. The results are shown in Figure 6. In general, the risk of water inrush in the middle and east of coal mine is relatively large. Specifically, five actual water inrush points were located in the dangerous area (grade IV) and relatively dangerous areas (grade III). The maximum probability principle shows that the ratio of water inrush points in the dangerous area to water inrush point in relatively dangerous area was more than 90%, and the fitting effect of the model was good. According to this principle, the location distribution of water inrush points verifies the high accuracy of the water inrush evaluation model.

4.4. Evaluation Index Comparison. In the evaluation process, it was found that the influence of each evaluation index was different for the water inrush points Y6-4, Y6-5, Y8-1, Y8-3, Y8-4, and Y10-3 predicted by the evaluation model. Therefore, we analyzed the influence of each index on water inrush. The influence degree of each evaluation index was expressed by the product of membership degree to the grade IV and combination weight of each evaluation index. The results are shown in Figure 7.

As can be seen from Figure 7, for these six water inrush points, the influence degree of each evaluation index is different. Y6-4 and Y6-5 were mainly affected by water pressure and faults; Y8-1 was mainly affected by water pressure, faults, and seam dip angle; Y8-3 was mainly affected by water pressure, key-strata thickness, and seam dip angle; Y8-4 was mainly affected by water pressure, key-strata thickness, and seam dip angle; and Y10-3 was mainly affected by water pressure, seam dip angle, and faults. On the whole, water pressure had a great influence on water inrush of Yangcheng Coal Mine, and the focus of preventing water inrush should be on drainage and depressurization.

5. CONCLUSIONS

To evaluate the risk of mine water inrush, this study constructs a risk assessment index system of water inrush with the combination weight method based on game theory and the cloud model to evaluate the risk of the water inrush in study area. The results are visualized by combining the evaluation grade results of each borehole with GIS. By evaluating the risk of water inrush in the study area, conclusive warning information is obtained to clarify an effective risk management system.

The evaluation results of water inrush risk in Yangcheng Coal Mine show that the five actual water inrush points in Yangcheng Coal Mine are located in the dangerous area (grade IV) and the relatively dangerous area (grade III), and the fitting results with the actual water inrush points verified the high fitting accuracy of the evaluation model.

The early warning results of the evaluation model show that water pressure has great influence on floor water inrush. This has important guiding significance for water disaster control in Yangcheng Coal Mine.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsomega.1c04357>.

Degree of membership of C1 (seam dip angle) in each drilling hole and degree of membership of the risk of water inrush in each drilling hole (PDF)

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the SDUST Research Fund (grant 2018TDJH102), the National Natural Science Foundation of China (grant 42007172 and 51874192), and the Natural Science Foundation of Shandong Province (grant ZR2019MEE084 and ZR2020QE126).

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