Hindawi
Shock and Vibration
Volume 2022, Article ID 9073554, 13 pages
https://doi.org/10.1155/2022/9073554

Research Article

Evaluation of Water Inrush Risk in Deep Mines Based on Variable Weight and Unascertained Measure Theories and GIS

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Received 19 January 2022; Revised 21 February 2022; Accepted 10 March 2022; Published 9 April 2022

Academic Editor: Zhanbo Cheng

Water inrush is a serious geological disaster in deep coal mining and rock engineering in China. The occurrence of water inrush is affected by the interaction of many controlling factors in underground reservoir areas. In order to improve the accuracy of water inrush risk evaluation, the changes in index weights due to the change in influencing factors and the uncertain factors should be both considered. In this study, an evaluation model that integrates variable weight and unascertained measure (VWUM) theories was established. First, a modified credible degree recognition was established to make the evaluation results represent both the evaluation grade and the difference in the degree to which the indexes belong to the same grade. Then, the VWUM model was established by coupling the variable weight, unascertained measure, modified credible degree recognition, and geographic information system (GIS). Last, the VWUM model is applied to a case study to evaluate water inrush risk. Results indicates that more detailed risk grades and their spatial distribution zones can be obtained by the VWUM model compared with those obtained by the water inrush coefficient. The VWUM model can provide a more accurate evaluation result.

1. Introduction

The extraction of energy sources such as coal, oil, and natural gas hydrate is a global concern [1, 2]. China is the largest coal producer and consumer [3]. The complex geological conditions in coal mines can cause many disasters, such as roof accidents, gas accidents, coal dust accidents, water inrush, and fire. Mine water inrush is a major threat to mine production safety [4]. The impacts of high temperature, high groundwater pressure, high ground stress, and complex hydro chemical erosion have a great influence on rock damage [5–7], which increase the possibility of water inrush. The risk of water inrush needs to be evaluated to reduce the water inrush accidents. The risk of water inrush can be evaluated by studying the relationship between the water pressure and the properties of the water-resisting strata. Before the middle of the 20th century, Slesarev's formula was adopted to predict the risk of water inrush from coal seam floor. This period is called Slesarev's formula period [8]. Z. T. Bieniawski and C. F. Santos studied the mechanism of the coal seam floor, and further studied the water-resisting capacity of the coal seam floor by using the modified Hoek-Brown strength criterion combined with the critical energy release point [9]. In 1964, researchers proposed the water inrush coefficient (WIC) based on the statistical analysis of long-term water inrush data. The water inrush coefficient denotes the ratio of the water pressure to the thickness of the water-resisting strata [10]. This period is called the water inrush coefficient period. At the end of the 20th century, based on the rapid development of hydraulics, some researchers focused on the relationship between stress and seepage and tried to establish a relevant risk evaluation system through a finite element calculation program [11]. With the development of modern computer information technology, various scientific systems are integrated to form a new water inrush prediction method, which can be called the pan-decision analysis theory of water inrush forecast [12]. Pan-decision-making method refers to the fields of engineering and natural science, includes information theory, artificial neural network, vulnerability index method, expert system, and so on. It has high accuracy in the prediction and evaluation of water inrush. For example, Wu Qiang proposed the vulnerability index method. This method creatively coupled geographic information system (GIS) with the artificial neural network, the weight of evidence, the logistic regression, or the analytic hierarchy process to evaluate the risk of floor water inrush [13].

Index weights reflect the relative strength or importance of related factors [14]. Constant weights are usually adopted in the pan-decision-making method. However, index weights will change with the change of index values. Constant weights cannot reflect the change of index values. In order to take index weights to respond to the change in the values of controlling factors of water inrush, variable weight theory has been used in the above-mentioned evaluation methods. For example, Qiang Wu et al. used variable weight model to partition and evaluate the risk of floor water inrush [14]. Wenping Li et al. improved the water inrush vulnerability evaluation model of confined aquifers based on the water inrush coefficient method [10].

The prediction of geological disasters and underground engineering accidents are often vague and uncertain because the influencing factors are often difficult to measure accurately and the interaction of the influencing factors is complex. The evaluation of geological disasters and underground engineering accidents usually considers the uncertain factors. Unascertained measure theory can effectively and quantitatively analyze various uncertain factors and has been widely used in many fields [15–17]. It was first proposed by Guangyuan Wang [18]. Kaidi Liu et al. [19] established unascertained mathematical model to quantitatively describe the unascertained state or the unascertained size for unascertained measure theory. Water inrush is affected by many uncertain factors. The unascertained measure theory can be adopted to analyze uncertainty in the evaluation of water inrush risk. In order to consider the variable weights and the uncertain factors at the same time, the models integrating variable weights theory and unascertained measure theory have been proposed and applied to the evaluation of water inrush risk [20]. The water inrush risk grades can be determined by a credible degree recognition of unascertained measure theory. Some indexes belonging to the same risk grades may have a different degree to which these indexes belong to this grade. However, the risk grades determined by the credible degree recognition cannot reflect this difference. Moreover, this grade cannot be processed as zoning risk maps by GIS because it is an integer. The integer only shows the evaluation grade and cannot show the difference in the same evaluation grade. If decimals are added, the difference can be described. Meanwhile, they can be processed as zoning risk maps by GIS to predict the risk grades of all zones. Therefore, the credible degree recognition should be modified to make the evaluation results represent both the evaluation grade and the difference in degree and be coupled with GIS.

In summary, the evaluation of water inrush risk needs to consider the changes in index weights due to the change in the values of controlling factors and the uncertainty in controlling factors. Because of this, an evaluation model that integrates variable weight and unascertained measure (VWUM) theories was established. In which, the credible degree recognition is modified by defining a new parameter to make the evaluation results represent both the evaluation grade and the difference in the degree to which the indexes belong to the same grade. The parameter can be processed as zoning risk maps by GIS. Then, the VWUM model is applied to a case study to evaluate water inrush risk.

2. Methods

2.1. Unascertained Measure Theory. There are m evaluation objects and n evaluation indexes, which can be expressed as an evaluation matrix $R = (x_{ij})_{m\times n}$. x_{ij} denotes the measured value of the i-th evaluation object with respect to the j-th evaluation index. The evaluation grade space is expressed as $C = \{C_1, C_1, \ldots, C_p\}$, where C_k $(k = 1, 2, \ldots, p)$ is the k-th evaluation grade and $C_k > C_{k+1}$.

2.1.1. Single-Index Unascertained Measure. The degree to which the measured value x_{ij} belongs to the k-th evaluation grade C_k is called the unascertained measure, denoted as μ. Then μ should satisfy the following conditions [15]:

$$0 \le \mu\left(x_{ij} \in C_k\right) \le 1, \quad (i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m;\ k = 1, 2, \ldots, p), \tag{1}$$

$$\mu\left(x_{ij} \in C\right) = 1, \quad (i = 1, 2, \ldots, n;\ j = 1, 2, \ldots, m), \tag{2}$$

$$\mu\left|x_{ij} \in \bigcup_{l=1}^{k} C_l\right| = \sum_{l=1}^{k} \mu\left(x_{ij} \in C_l\right), \quad (k = 1, 2, \ldots, p). \tag{3}$$

Equations (2)–(4) are called nonnegative boundedness, normalization, and additivity, respectively. The value of μ is determined by the values of evaluation indexes x and threshold of the grades a. The function to describe the relationship of μ, x, and a is called the single-index unascertained measure function. The construction methods of a single-index unascertained measure function mainly include linear, exponential, parabolic, and sinusoidal methods [15].

The linear unascertained measure function is adopted in this study, and its calculation expression is as follows [15]:

$$\begin{cases} \mu_i(x) = \begin{cases} \dfrac{-x}{a_{i+1}-a_i} + \dfrac{a_{i+1}}{a_{i+1}-a_i}, & a_k < x \le a_{i+1}, \\ 0, & x > a_{i+1}, \end{cases} \\ \mu_{i+1}(x) = \begin{cases} 0, & x \le a_k, \\ \dfrac{x}{a_{i+1}-a_i} - \dfrac{a_i}{a_{i+1}-a_i}, & a_i < x \le a_{i+1}. \end{cases} \end{cases} \tag{4}$$

The evaluation objects, indexes, and grades form the single-index unascertained measure matrix:

$$\left(\mu_{ijk}\right)_{m\times p} = \begin{bmatrix} \mu_{i11} & \mu_{i12} & \cdots & \mu_{i1p} \\ \mu_{i21} & \mu_{i22} & \cdots & \mu_{i2p} \\ \cdots & \cdots & \ddots & \cdots \\ \mu_{im1} & \mu_{im2} & \cdots & \mu_{\text{imp}} \end{bmatrix}. \tag{5}$$

2.1.2. Multi-Index Comprehensive Unascertained Measure. The degree to which the evaluation object belongs to the k-th evaluation grade is determined by the single-index unascertained measure and the index weight w_j, and is calculated by [15]

$$\mu_{ik} = \sum_{j=1}^{n} w_j \mu_{ijk}, \quad (j = 1, 2, \ldots, n; k = 1, 2, \ldots, p),$$
$$0 \le \mu_{ik} \le 1, \tag{6}$$
$$\sum_{k=1}^{p} \mu_{jk} = 1.$$

The vector $\{\mu_{i1}, \mu_{i1}, \ldots, \mu_{ip},\}$ is called the multi-index comprehensive unascertained measure vector. A credible degree recognition is introduced to determine the evaluation grade of the object, which is expressed as [15]

$$k_0 = \min\left\{k\colon \sum_{1}^{k} \mu_{ik} \ge \lambda, \quad k = 1, 2, \ldots, p\right\}. \tag{7}$$

where λ is the credible degree, and is usually set as 0.6 or 0.7. k_0 denotes the evaluation object belonging to the evaluation grades C_{k0}, and it is the minimum of k that satisfies $\sum_1^k \mu_{ik} \ge \lambda$.

2.2. Modified Credible Degree Recognition. The evaluation grade C_{k0} can be obtained by the credible degree recognition. However, the evaluation grade C_{k0} calculated by the credible degree recognition corresponds to different values of cumulative sum term (i.e., $\sum_1^k \mu_{ik}$). The cumulative sum term indicates the degree to which the indexes belong to the same grade. For example, there are two evaluation objects X_1 and X_2, and their multi-index comprehensive unascertained measure vectors are $\mu_{1k} = \{0.3, 0.35, 0.2, 0.15\}$ and $\mu_{2k} = \{0.3, 0.45, 0.15, 0.1\}$, respectively. If λ is set as 0.6, k_0 is 2 and $\sum_1^k \mu_{ik}$ is 0.65 and 0.75, respectively. The degree to which the X_1 belong to C_2 is smaller than the degree to which the X_2 belongs to C_2 since $0.65 < 0.75$. However, k_0 cannot represent the difference in cumulative sum term of evaluation objects that belong to the same evaluation grade. That is, it cannot represent the difference in the degree to which the indexes belong to same grade. Therefore, the credible degree recognition needs to be modified to make the evaluation results represent both the evaluation grade and the difference in cumulative sum term. Because of this, the credible degree recognition is modified by the flowing steps in this study (see Figure 1). First, the value of cumulative sum term and k are calculated by equation (7). Second, a parameter, named the degree parameter, is introduced to represent the difference in cumulative sum term of evaluation objects that belong to the same evaluation grade, defined as

$$D = \frac{\sum_1^k \mu_{ik} - \lambda}{1 - \lambda}, \quad 0 < D \le 1, \tag{8}$$

where D is the degree parameter. Note that $\sum_1^k \mu_{ik} \ge \lambda$ of (7) should be changed to $\sum_1^k \mu_{ik} > \lambda$ to satisfy $D > 0$. Last, a parameter, named the grade and degree parameter is introduced to represent both the evaluation grade and the difference in cumulative sum term, defined as

$$G = k_0 - 1 + D, \tag{9}$$

where G is the grade and degree parameter. The evaluation grade and the difference in cumulative sum term can be obtained by the grade and degree parameter. For example, the grade and degree parameters of the above-mentioned two objects X_1 and X_2 are 1.125 and 1.375, respectively. The evaluation grades of X_1 and X_2 are both C_2. The degree parameters of X_1 and X_2 are 0.125 and 0.375, which indicates that the degree to which the X_1 belongs to C_2 is smaller than the degree to which the X_2 belongs to C_2.

2.3. Determination of Index Variable Weight. The constant weights of major controlling factors should be determined before the determination of index variable weights. The constant weights can be calculated by the entropy weight method [15, 21, 22]:

$$w_j^0 = \frac{1 - H_j}{\sum_{j=1}^{n}\left(1 - H_j\right)}, \tag{10}$$

where H_j is the index entropy value, which denotes the chaos and uncertainty of the evaluation objects. It can be calculated by

$$H_j = -\frac{1}{\ln m} \sum_{i=1}^{m} f_{ij} \cdot \ln f_{ij}, \tag{11}$$

where $f_{ij} = x_{ij}/\sum_{i=1}^{m} x_{ij}$. In order to avoid $f_{ij} = 0$, f_{ij} can be expressed as [23]

$$f_{ij} = \frac{x_{ij} + 1}{\sum_{i=1}^{m}\left(x_{ij} + 1\right)}. \tag{12}$$

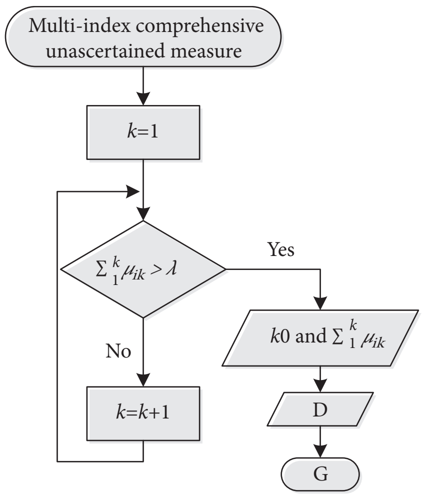


FIGURE 1: The flow-chart of the modified credible degree recognition.

The variable weights of major controlling factors W_j are calculated by [14]

$$W_j = \frac{w_j^0 \cdot S_j(X)}{\sum_{j=1}^{n}\left(w_j^0 S_j(X)\right)}, \quad (13)$$

where $S_j(X)$ is the state variable weight vector, which can be calculated by

$$S_j(X) = \begin{cases} e^{u\left(\beta - x_{ij}\right)}, & x_{ij} \le \beta, \\ 1, & x_{ij} > \beta, \end{cases} \quad (14)$$

where β and u are called punishment level and incentive level, respectively, which values are set as 0.7 and 0.5, respectively [24]. Then, the variable weights can be obtained and expressed as a matrix:

$$(W)_{m\times n} = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \cdots & \cdots & \ddots & \cdots \\ w_{m1} & w_{m2} & \cdots & w_{mn} \end{bmatrix}. \quad (15)$$

2.4. The VWUM Model for the Evaluation of Water Inrush Risk. Through the above analysis, we can see that: the variable weight can respond to the change of index values; the modified credible degree recognition can represent both the evaluation grade and the difference in cumulative sum term; and the grade and degree parameter G can be analyzed by GIS to obtain the risk grade zoning maps because G contains integers and decimals. Combing the variable weight theory, modified credible degree recognition, and unascertained measure theory, the VWUM model is established in this study. The steps of using the VWUM model and GIS to evaluate the water inrush are as follows: (1) the variable weights are determined; (2) a standard is determined to divide index values into different risk grades; (3) the single-index unascertained measure are calculated by equation (4); (4) the multi-index comprehensive unascertained measure are calculated by putting the variable weights and single-index unascertained measure into equation (6); (5) the grade and degree parameter are determined by the modified credible degree recognition; and (6) The grade and degree parameters show the risk grades of discrete points. The risk grades of all other zones are obtained by the interpolation analysis GIS based on the risk grades of discrete points. Then, the water inrush risk grade zoning map and evaluation results are obtained, which can show both the evaluation grade and the difference in degree in all zones.

3. Case Study

3.1. Study Area. Yangcheng coal mine is located about 17 km northwest of Jining City, Shandong Province. The mining area is located in the monsoon climate zone with four distinct seasons. The average annual precipitation is about 600 mm. The precipitation is concentrated from June to September. The faults are relatively developed and cover the whole mining area. There is no collapse column in the mining area. The target coal seam for the risk evaluation of water inrush is the No. 3 coal seam. Ordovician aquifers are a major threat to the mining safety of the No. 3 coal seam.

3.2. Evaluation Factors (Indexes). Five major controlling factors are used in this study to evaluate the floor water inrush risk according to geological and hydrogeological conditions of the Yangcheng coal mine.

3.2.1. Coal Seam Mining Depth. Mine pressure increases with the increase of mining depth. The floor is damaged under the impact of rock pressure, and thus, water inrush channels are formed. Therefore, the increase of mining depth will increase the risk of water inrush, which is a main controlling factor for evaluating the risk of water inrush.

3.2.2. Dip Angle of Coal Seam. Dip angles of coal seam cause a water pressure difference between the upper and lower roadways of the working face. The water pressure difference and mine pressure have an impact on mining-induced damage of coal seam floor, and thus changes the risk of water inrush.

3.2.3. Thickness of Water-resisting Strata. Water-resisting strata can block groundwater from entering the working face and prevent the occurrence of water inrush. Therefore, the increase in the thickness of the water-resisting strata reduces the risk of water inrush.

3.2.4. Water Pressure in Confined Aquifers. Water pressure in confined aquifers is the prerequisite for water inrush. The risk of water inrush increases with increasing water pressure.

3.2.5. The Fault Intensity Index. Faults can connect aquifers and coal seams, and increase the possibility of a water inrush.

The distribution and amounts of faults can be denoted by the fault intensity index [25]:

$$\mathrm{FII} = \frac{\sum_{i=1}^{N} H_i \cdot L_i}{S}, \tag{16}$$

where FII is the fault intensity index, H is the fault throw, L is the corresponding strike length, S is the area of the grid cell; and n is the number of faults encountered in the grid cell. The risk of water inrush increases with increasing FII.

3.3. Geographic Data of Evaluation Factors (Indexes). The borehole data is shown in Table 1. The geographic data of each major controlling factor was first input into GIS and then was output as a zoning map. The zoning maps of major controlling factors are shown in Figure 2.

3.4. The Evaluation of Water Inrush Risk Using VWUM Model. The original data of boreholes should be normalized before the evaluation of water inrush risk using the VWUM model. The original data of boreholes are normalized by

$$X_i = \frac{x_{\max} - x_i}{x_{\max} - x_{\min}}, \tag{17}$$

where X_i is the data after normalization, x_i is the original data, $x_{\max}$ and $x_{\min}$ are the maximum and minimum of each index values, respectively. The normalization results are shown in Table 2.

3.4.1. The Variable Weights. The constant weights are determined by the entropy weight method. f_{ij} can be calculated by putting the normalization data of boreholes to equation (12). H_j can be calculated by putting f_{ij} to equation (11), then, the constant weights w_j^0 can be obtained by equation (10) (see Table 3).

The state variable weight vectors are calculated by putting the punishment level, the incentive level, and the normalization of original data into equation (14). Then, the variable weights can be obtained by putting the state variable weights and constant weights to equation (13) (see Table 4).

3.4.2. The Index Risk Grade Standards. The index risk is divided into four grades. The index risk grade standards are determined by the K-means clustering method. For example, the threshold values of each group for mining depth, obtained by the K-means clustering method are 449.96, 511.39, 701.7, 733.78, 929.44, and 955.74, respectively. Then, the threshold values of index risk grade standards are 480.675, 717.54, and 942.59, respectively. The index risk grade standards are shown in Table 5.

3.4.3. The Single-Index Unascertained Measure. The single-index unascertained measure of evaluation objects can be obtained by putting the original data of boreholes and index risk grade standard to equation (4). The calculation process of the single-index unascertained measure matrix is as follows by taking borehole number 1st as an example. 750 belongs to Index grades 3. Putting the threshold values of the index risk grade standards for mining depth into equation (4) can obtain the single-index unascertained vector for mining depth, i.e., (0, 0.3467, 0.6533, 0). Then, the single-index unascertained measure matrix for all major controlling factors can be obtained as follows:

$$\left(\mu_{1jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0.3467 & 0.6533 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0.5053 & 0.4947 \end{bmatrix},$$

$$\left(\mu_{2jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0.7778 & 0.2222 & 0 & 0 \\ 0 & 0.136 & 0.864 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix},$$

$$\left(\mu_{3jk}\right)_{5\times4} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0.7778 & 0.2222 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.6335 & 0.3665 & 0 & 0 \end{bmatrix},$$

$$\left(\mu_{4jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0.265 & 0.735 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.4036 & 0.5964 & 0 \\ 1 & 0 & 0 & 0 \\ 0.6335 & 0.3665 & 0 & 0 \end{bmatrix},$$

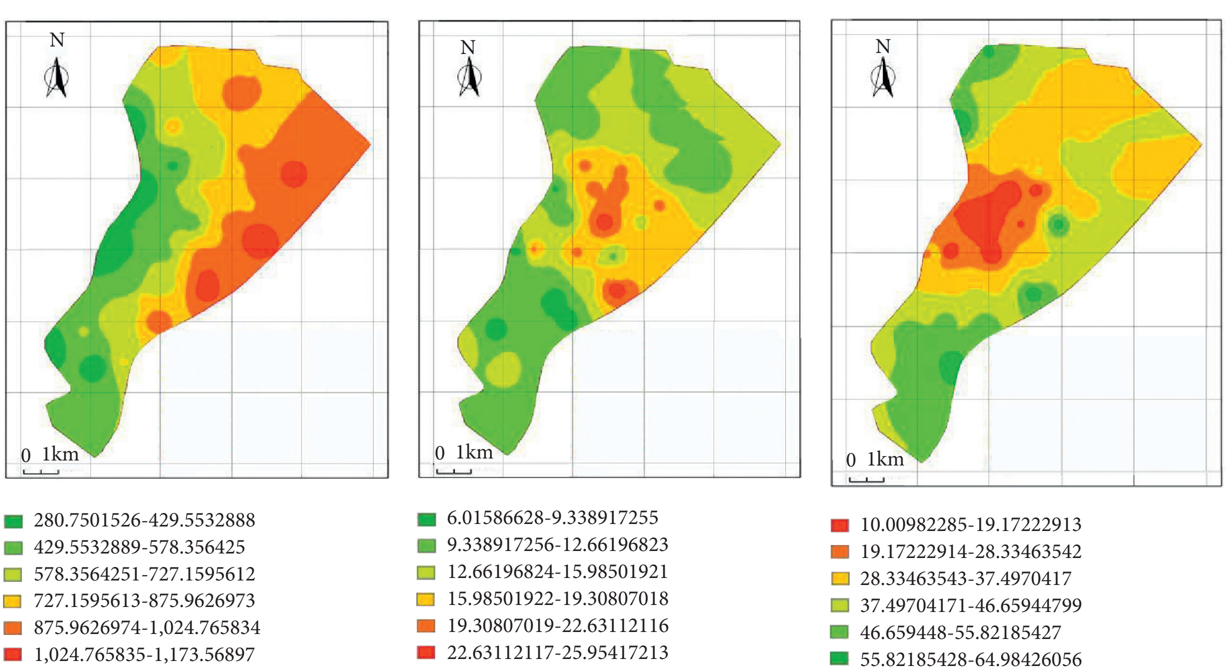
$$\left(\mu_{5jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0.1627 & 0.8373 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.2419 & 0.7581 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.7778 & 0.2222 & 0 \end{bmatrix},$$

$$\left(\mu_{6jk}\right)_{5\times4} = \begin{bmatrix} 0.1896 & 0.8104 & 0 & 0 \\ 0 & 0.7727 & 0.2273 & 0 \\ 0 & 0.1181 & 0.8819 & 0 \\ 1 & 0 & 0 & 0 \\ 0.6353 & 0.3647 & 0 & 0 \end{bmatrix},$$

$$\left(\mu_{7jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0 & 0.1169 & 0.8831 \\ 0 & 0.7727 & 0.2273 & 0 \\ 0 & 0.9342 & 0.0658 & 0 \\ 0.5484 & 0.4516 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

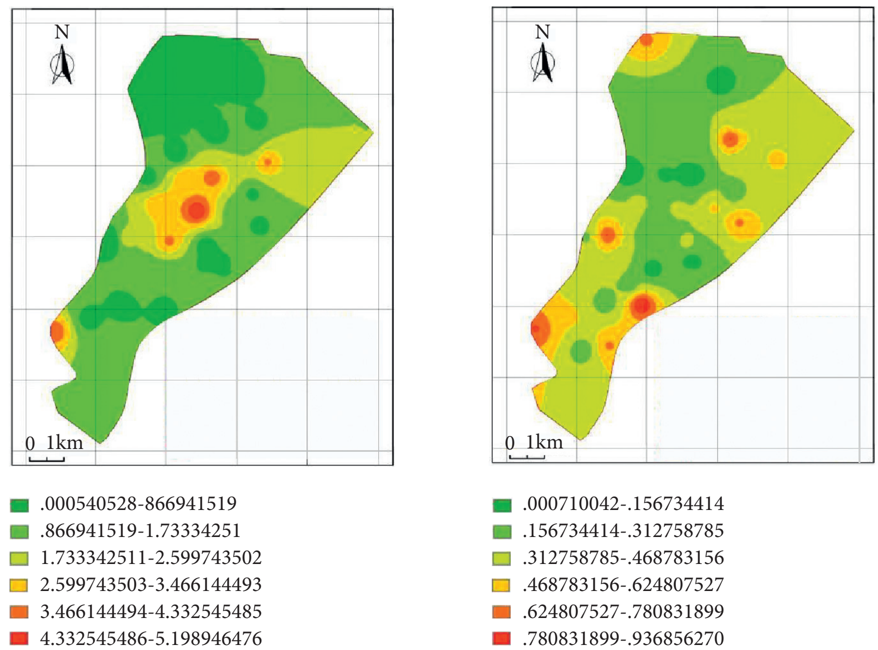
Table 1: Original data of boreholes.

Borehole number	Mining depth (m)	Dip angle of coal seam (°)	Thickness of water-resisting strata (m)	Water pressure (MPa)	Fault intensity index
1	750	10	56.33	0.3	0.422
2	955.74	12	33.12	0.5	0.052
3	280.6	12	65	0	0.14115
4	768.86	10	37.29	0.5	0.14115
5	792.5	10	34.77	0.5	0.235
6	576.66	15	32.84	0	0.141
7	929.44	15	45.56	1.2	0.515
8	405.33	20	33.01	0	0.1355
9	701.7	20	38.56	2.3	0.128
10	968.92	10	45.66	3.6	0.2345
11	1095.9	10	35.5	2.3	0.3285
12	586.79	20	10.5	3.4	0.0995
13	298.03	9	20	0.3	0.04735
14	784.11	20	15	4.2	0.012
15	864.18	20	32	0.6	0.141
16	1173.99	17	40.2	0.6	0.422
17	432.2	10	10	3.3	0.235
18	511.39	25	18.63	5.2	0.235
19	900.12	15	58.89	1.1	0.3285
20	405.8	20	12.81	2.5	0.515
21	537.2	20	12.37	3.7	0.14065
22	922.35	12	33.42	0.3	0.235
23	301.29	9	38.8	0	0.3285
24	290.41	9	25	0	0.14065
25	1080.99	18	44.07	0	0.04921
26	449.96	11	34.57	1.3	0.235
27	691.87	13	36.6	1.2	0.04921
28	1100.82	26	62.3	1.2	0.14065
29	752.72	6	41.66	1.3	0.15
30	633.97	10	48.8	0.5	0.14065
31	1000.03	8	51	0.5	0.6105
32	586.86	8	49	0.5	0.3285
33	304.18	15	44.91	4.1	0.5155
34	733.78	10	64	1.2	0.4215
35	321.18	15	47.51	1.2	0.14065



(a) (b) (c)

Figure 2: Continued.



(d) (e)

Figure 2: The zoning maps of seven major controlling factor. (a) Mining depth. (b) Dip angle of coal seam. (c) Thickness of water-resisting strata. (d) Water pressure. (e) Fault intensity index.

Table 2: The normalization of original data of boreholes.

Borehole number	Mining depth	Dip angle of coal seam	Thickness of water-resisting strata	Water pressure	Fault intensity index
1	0.475	0.800	0.158	0.942	0.315
2	0.244	0.700	0.580	0.904	0.933
3	1.000	0.700	0.000	1.000	0.784
4	0.453	0.800	0.504	0.904	0.784
5	0.427	0.800	0.550	0.904	0.627
6	0.669	0.550	0.585	1.000	0.784
7	0.274	0.550	0.353	0.769	0.160
8	0.860	0.300	0.582	1.000	0.794
9	0.529	0.300	0.481	0.558	0.806
10	0.230	0.800	0.352	0.308	0.628
11	0.087	0.800	0.536	0.558	0.471
12	0.657	0.300	0.991	0.346	0.854
13	0.980	0.850	0.818	0.942	0.941
14	0.436	0.300	0.909	0.192	1.000
15	0.347	0.300	0.600	0.885	0.784
16	0.000	0.450	0.451	0.885	0.315
17	0.830	0.800	1.000	0.365	0.627
18	0.742	0.050	0.843	0.000	0.627
19	0.307	0.550	0.111	0.788	0.471
20	0.860	0.300	0.949	0.519	0.160
21	0.713	0.300	0.957	0.288	0.785
22	0.282	0.700	0.574	0.942	0.627
23	0.977	0.850	0.476	1.000	0.471
24	0.989	0.850	0.727	1.000	0.785
25	0.104	0.400	0.381	1.000	0.938
26	0.810	0.750	0.553	0.750	0.627
27	0.540	0.650	0.516	0.769	0.938
28	0.082	0.000	0.049	0.769	0.785
29	0.472	1.000	0.424	0.750	0.769
30	0.604	0.800	0.295	0.904	0.785
31	0.195	0.900	0.255	0.904	0.000

Table 2: Continued.

Borehole number	Mining depth	Dip angle of coal seam	Thickness of water-resisting strata	Water pressure	Fault intensity index
32	0.657	0.900	0.291	0.904	0.471
33	0.974	0.550	0.365	0.212	0.159
34	0.493	0.800	0.018	0.769	0.316
35	0.955	0.550	0.318	0.769	0.785

Table 3: The constant weights.

Weights	Mining depth	Dip angle of coal seam	Thickness of water-resisting strata	Water pressure	Fault intensity index
Constant weights	0.249	0.176	0.220	0.181	0.174

Table 4: The variable weights.

Borehole number	Mining depth	Dip angle of coal seam	Thickness of water-resisting strata	Water pressure	Fault intensity index
1	0.246	0.155	0.254	0.160	0.186
2	0.290	0.163	0.217	0.168	0.162
3	0.228	0.161	0.286	0.166	0.159
4	0.267	0.166	0.230	0.172	0.165
5	0.269	0.166	0.224	0.171	0.170
6	0.245	0.184	0.226	0.176	0.169
7	0.264	0.162	0.224	0.155	0.195
8	0.237	0.204	0.222	0.172	0.165
9	0.247	0.195	0.223	0.177	0.158
10	0.273	0.152	0.227	0.191	0.156
11	0.296	0.154	0.209	0.170	0.171
12	0.236	0.199	0.204	0.200	0.161
13	0.249	0.176	0.220	0.181	0.174
14	0.252	0.190	0.195	0.207	0.155
15	0.271	0.195	0.211	0.165	0.158
16	0.296	0.167	0.209	0.152	0.177
17	0.240	0.169	0.212	0.206	0.174
18	0.217	0.211	0.191	0.224	0.157
19	0.260	0.163	0.254	0.156	0.168
20	0.224	0.193	0.198	0.179	0.205
21	0.231	0.199	0.204	0.206	0.161
22	0.285	0.163	0.217	0.168	0.167
23	0.238	0.168	0.235	0.173	0.186
24	0.249	0.176	0.220	0.181	0.174
25	0.291	0.177	0.224	0.157	0.151
26	0.243	0.172	0.231	0.177	0.176
27	0.258	0.172	0.230	0.173	0.166
28	0.272	0.200	0.244	0.145	0.139
29	0.263	0.165	0.238	0.170	0.164
30	0.246	0.165	0.254	0.171	0.164
31	0.267	0.146	0.229	0.151	0.206
32	0.236	0.163	0.251	0.168	0.181
33	0.215	0.164	0.225	0.200	0.197
34	0.240	0.152	0.268	0.157	0.183
35	0.235	0.179	0.251	0.171	0.164

Table 5: The index risk grade standards.

Index grades	Mining depth (m)	Dip angle of coal seam (°)	Thickness of water-resisting strata (m)	Water pressure (MPa)	Fault intensity index
1	<480.68	<11.5	>53.67	<0.85	<0.11
2	480.68–717.54	11.5–16	39.50–53.67	0.85–2.40	0.11–0.28
3	717.54–942.59	16–22.5	22.50–39.50	2.40–4.70	0.28–0.47
4	>942.59	>22.5	<22.50	>4.70	>0.47

$$\left(\mu_{8jk}\right)_{5\times4} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0.7692 & 0.2308 \\ 0 & 0.129 & 0.871 & 0 \\ 1 & 0 & 0 & 0 \\ 0.7 & 0.3 & 0 & 0 \end{bmatrix},$$

$$\left(\mu_{9jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0.5558 & 0.4442 & 0 \\ 0 & 0 & 0.7692 & 0.2308 \\ 0 & 0.4851 & 0.5149 & 0 \\ 0 & 0.6494 & 0.3506 & 0 \\ 0.7882 & 0.2118 & 0 & 0 \end{bmatrix},$$

$$\left(\mu_{10jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 0.9406 & 0.0594 & 0 \\ 0 & 0 & 0.9565 & 0.0435 \\ 0 & 0.7806 & 0.2194 & 0 \end{bmatrix},$$

$$\left(\mu_{11jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 0.2887 & 0.7113 & 0 \\ 0 & 0.6494 & 0.3506 & 0 \\ 0 & 0.2583 & 0.7417 & 0 \end{bmatrix},$$

$$\left(\mu_{12jk}\right)_{5\times4} = \begin{bmatrix} 0.104 & 0.896 & 0 & 0 \\ 0 & 0 & 0.7692 & 0.2308 \\ 0 & 0 & 0 & 1 \\ 0 & 0.0779 & 0.9221 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix},$$

$$\left(\mu_{13jk}\right)_{5\times4} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix},$$

$$\left(\mu_{14jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0.199 & 0.801 & 0 \\ 0 & 0 & 0.7692 & 0.2308 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0.4348 & 0.5652 \\ 1 & 0 & 0 & 0 \end{bmatrix},$$

$$\left(\mu_{15jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0 & 0.6968 & 0.3032 \\ 0 & 0 & 0.7692 & 0.2308 \\ 0 & 0.0642 & 0.9358 & 0 \\ 1 & 0 & 0 & 0 \\ 0.6353 & 0.3647 & 0 & 0 \end{bmatrix},$$

$$\left(\mu_{16jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0.4091 & 0.5909 & 0 \\ 0 & 0.5903 & 0.4097 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0.5053 & 0.4947 \end{bmatrix},$$

$$\left(\mu_{17jk}\right)_{5\times4} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0.1299 & 0.8701 & 0 \\ 0 & 0.7778 & 0.2222 & 0 \end{bmatrix},$$

$$\left(\mu_{18jk}\right)_{5\times4} = \begin{bmatrix} 0.7407 & 0.2593 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 0 & 0.7778 & 0.2222 & 0 \end{bmatrix},$$

$$\left(\mu_{19jk}\right)_{5\times4} = \begin{bmatrix} 0 & 0 & 0.3774 & 0.6226 \\ 0 & 0.7727 & 0.2273 & 0 \\ 1 & 0 & 0 & 0 \\ 0.6774 & 0.3226 & 0 & 0 \\ 0 & 0.2583 & 0.7417 & 0 \end{bmatrix},$$

$$
\begin{aligned}
\left(\mu_{20jk}\right)_{5\times 4} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0.7692 & 0.2308 \\ 0 & 0 & 0 & 1 \\ 0 & 0.5455 & 0.4545 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, &
\left(\mu_{28jk}\right)_{5\times 4} &= \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0.5484 & 0.4516 & 0 & 0 \\ 0.6394 & 0.3606 & 0 & 0 \end{bmatrix}, \\
\left(\mu_{21jk}\right)_{5\times 4} &= \begin{bmatrix} 0.5228 & 0.4772 & 0 & 0 \\ 0 & 0 & 0.7692 & 0.2308 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0.8696 & 0.1304 \\ 0.6394 & 0.3606 & 0 & 0 \end{bmatrix} &
\left(\mu_{29jk}\right)_{5\times 4} &= \begin{bmatrix} 0 & 0.3349 & 0.6651 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.684 & 0.316 & 0 \\ 0.4194 & 0.5806 & 0 & 0 \\ 0.5294 & 0.4706 & 0 & 0 \end{bmatrix}, \\
\left(\mu_{22jk}\right)_{5\times 4} &= \begin{bmatrix} 0 & 0 & 0.1799 & 0.8201 \\ 0.7778 & 0.2222 & 0 & 0 \\ 0 & 0.1553 & 0.8447 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.7778 & 0.2222 & 0 \end{bmatrix}, &
\left(\mu_{30jk}\right)_{5\times 4} &= \begin{bmatrix} 0 & 0.8491 & 0.1509 & 0 \\ 1 & 0 & 0 & 0 \\ 0.3126 & 0.6874 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.6394 & 0.3606 & 0 & 0 \end{bmatrix}, \\
\left(\mu_{23jk}\right)_{5\times 4} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.5005 & 0.4995 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.2583 & 0.7417 & 0 \end{bmatrix}, &
\left(\mu_{31jk}\right)_{5\times 4} &= \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0.6231 & 0.3769 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \\
\left(\mu_{24jk}\right)_{5\times 4} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0.2941 & 0.7059 \\ 1 & 0 & 0 & 0 \\ 0.6394 & 0.3606 & 0 & 0 \end{bmatrix}, &
\left(\mu_{32jk}\right)_{5\times 4} &= \begin{bmatrix} 0.1034 & 0.8966 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.3409 & 0.6591 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.2583 & 0.7417 & 0 \end{bmatrix}, \\
\left(\mu_{25jk}\right)_{5\times 4} &= \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0.2273 & 0.7727 & 0 \\ 0 & 0.8386 & 0.1614 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, &
\left(\mu_{33jk}\right)_{5\times 4} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.7727 & 0.2273 & 0 \\ 0 & 0.8925 & 0.1075 & 0 \\ 0 & 0 & 0.5217 & 0.4783 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \\
\left(\mu_{26jk}\right)_{5\times 4} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0.2291 & 0.7709 & 0 \\ 0.4194 & 0.5806 & 0 & 0 \\ 0 & 0.7778 & 0.2222 & 0 \end{bmatrix}, &
\left(\mu_{34jk}\right)_{5\times 4} &= \begin{bmatrix} 0 & 0.4169 & 0.5831 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.5484 & 0.4516 & 0 & 0 \\ 0 & 0 & 0.5105 & 0.4895 \end{bmatrix}, \\
\left(\mu_{27jk}\right)_{5\times 4} &= \begin{bmatrix} 0 & 0.5984 & 0.4016 & 0 \\ 0.3333 & 0.6667 & 0 & 0 \\ 0 & 0.3593 & 0.6407 & 0 \\ 0.5484 & 0.4516 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, &
\left(\mu_{35jk}\right)_{5\times 4} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.7727 & 0.2273 & 0 \\ 0.1306 & 0.8694 & 0 & 0 \\ 0.5484 & 0.4516 & 0 & 0 \\ 0.6394 & 0.3606 & 0 & 0 \end{bmatrix}.
\end{aligned} \tag{18}
$$

Table 6: The multi-index comprehensive unascertained measure.

Borehole number	Index grades				Borehole number	Index grades			
	1	2	3	4		1	2	3	4
1	0.569	0.085	0.254	0.092	19	0.359	0.219	0.260	0.162
2	0.457	0.066	0.187	0.290	20	0.224	0.097	0.230	0.448
3	0.906	0.094	0.000	0.000	21	0.224	0.168	0.332	0.276
4	0.443	0.224	0.333	0.000	22	0.295	0.200	0.272	0.233
5	0.337	0.230	0.433	0.000	23	0.579	0.166	0.256	0.000
6	0.330	0.429	0.241	0.000	24	0.717	0.063	0.065	0.155
7	0.085	0.404	0.082	0.428	25	0.308	0.228	0.173	0.291
8	0.525	0.078	0.350	0.047	26	0.489	0.293	0.218	0.000
9	0.125	0.394	0.437	0.045	27	0.319	0.430	0.251	0.000
10	0.152	0.336	0.231	0.282	28	0.413	0.116	0.000	0.471
11	0.154	0.215	0.335	0.296	29	0.324	0.427	0.250	0.000
12	0.186	0.227	0.338	0.250	30	0.520	0.443	0.037	0.000
13	0.780	0.000	0.000	0.220	31	0.440	0.086	0.000	0.473
14	0.155	0.050	0.439	0.356	32	0.441	0.424	0.134	0.000
15	0.266	0.071	0.536	0.127	33	0.215	0.327	0.166	0.293
16	0.152	0.191	0.273	0.384	34	0.507	0.171	0.233	0.090
17	0.409	0.162	0.218	0.212	35	0.467	0.493	0.041	0.000
18	0.160	0.178	0.035	0.626	—	—	—	—	—

Table 7: The grade and degree parameter.

Borehole number	Grade index	Borehole number	Grade index	Borehole number	Grade index	Borehole number	Grade index	Borehole number	Grade index
1	1.134	8	1.007	15	2.682	22	2.416	29	1.375
2	2.274	9	2.887	16	2.041	23	1.361	30	1.907
3	0.765	10	2.296	17	2.471	24	0.293	31	3.527
4	1.167	11	2.260	18	3.374	25	2.272	32	1.664
5	3.000	12	2.376	19	2.595	26	1.456	33	2.269
6	1.397	13	0.450	20	3.552	27	1.372	34	1.194
7	3.572	14	2.109	21	2.309	28	3.529	35	1.899

3.4.4. The Multi-Index Comprehensive Unascertained Measure. The multi-index comprehensive unascertained measure can be obtained by putting single-index unascertained measure and variable weights to (6) as shown in Table 6.

4. Results and Discussion

The grade and degree parameter can be determined by the modified credible degree recognition (see Table 7).

The grade and degree parameters are put into GIS and processed as a risk grade zoning map (see Figure 3(a)). We can see that water inrush risk is divided into four levels. Risk grades 0-1, 1-2, 2-3, and 3-4 denote extremely safe zone, safe zone, dangerous zone, and extremely dangerous zone, respectively.

The water inrush coefficient (WIC) is an important value and can be used to predict the occurrence of water inrush. It was proposed based on the statistical analysis of long-term water inrush data and was defined in the Detailed Regulations for Coal Mine Water Prevention and Control as an empirical formula [10]:

$$K = \frac{P}{M}, \tag{19}$$

where K is the WIC (MPa/m), P is the water pressure (MPa), and M is the thickness of the water-resisting strata (m). The critical water inrush coefficient is 0.1 MPa/m, i.e., water inrush will occur when the coefficient is greater than 0.1 MPa/m, and will not occur when it is smaller than or equal to 0.1 MPa/m. The zoning maps of water inrush risk obtained by the WIS method is shown in Figure 3(b). We can see that the water inrush risk is only divided into two levels, i.e., safety and danger. The results obtained by the WIC method cannot show the degree of safety and danger.

Comparing the evaluation results obtained by the VWUM model and the WIC method, it can be seen that there is the same part in the dangerous zone of the two results, which can validate the evaluation results obtained by the VWUM model. In addition, the more detailed risk grades and their distribution zones can be obtained by the VWUM model compared with those obtained by the WIC method. The more dangerous zones are found by the VWUM model. This is because the VWUM model considers five controlling factors, while the WIC method only

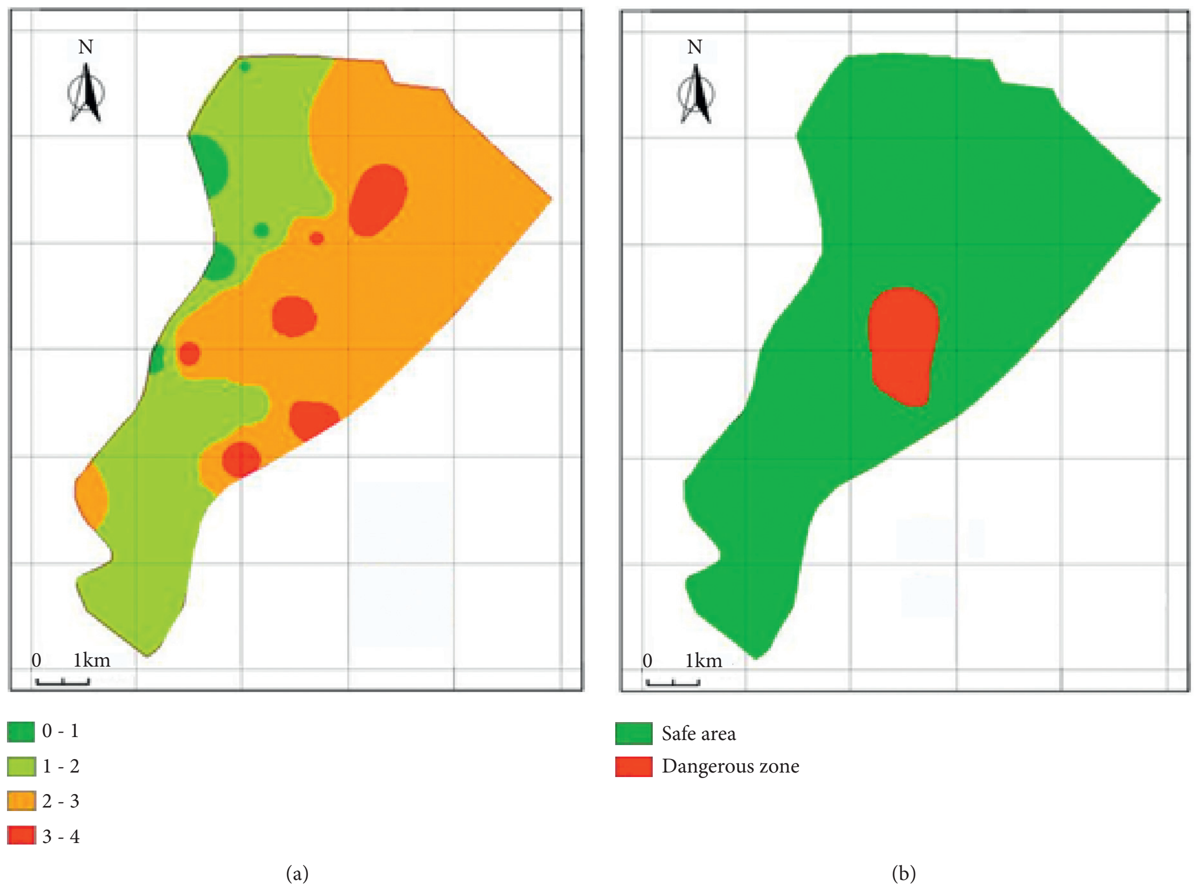


Figure 3: The zoning maps of water inrush risk. (a) By the VWUM model. (b) By the WIC method.

considers two factors, i.e., the thickness of water-resisting strata and water pressure. The evaluation results obtained by the VWUM model can show more detailed risk grades and the difference in the degree. Therefore, the VWUM model can improve the accuracy of water inrush risk evaluation.

There might be a better method to modify the credible degree recognition to represent both the evaluation grade and the difference in degree. In addition, the constant weights only consider the objective weights. In some cases, the subjective weights should be also considered.

5. Conclusions

The VWUM model was established to evaluate water inrush risk caused by deep coal mining and rock engineering by coupling the variable weight, unascertained measure, modified credible degree recognition, and GIS in this study. The VWUM model can consider the changes in index weights due to the change in controlling factors and the uncertain factors. The main conclusions are as follows:

(1) Compared with the evaluation results obtained by the credible degree recognition, the grade and degree parameter obtained by the modified credible degree recognition can represent both the evaluation grade and the difference in the degree to which the indexes belong to the same grade

(2) Compared with the traditional method, WIC, the VWUM model can consider more controlling factors, and the modified credible degree recognition can make the VWUM model be coupled with GIS

(3) Compared with the evaluation results obtained by WIC, the water inrush risk obtained by the VWUM model can be divided into more levels

The VWUM model can provide more comprehensive and accurate evaluation results, and thereby help reduce water inrush and increase mining safety.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

Acknowledgments

This research was funded by the Shandong Higher Education Teaching Reform Research Project of China (2015M138), the National Natural Science Foundation of

China (41807211), and Ministry of Education, Higher Education Department, Industry, Education and Research Collaborative Education Project of China (201802197019).

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