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Risk Assessment of Water Inrush from the Floor of No. 15 Coal Seam in Yuecheng Mine

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ABSTRACT: Based on the analysis of hydrogeological data and drilling data of Yuecheng Mine, six main controlling factors affecting the water inrush of main coal seam floor are determined as Aohui water level elevation, 15 coal seam floor elevation, water pressure of aquifer, thickness of water-barrier layer, water inrush coefficient and structure distribution. The CRITIC method and interval variable weight theory are used to determine the variable weight of the index, and the spatial processing function of Arcgis is combined to obtain the assessment zone of water inburst vulnerability in the study area. The areas of safe zone, safe zone, transition zone and dangerous zone within the well field are 11.15%, 36.16%, 32%, 17.28% and 3.37%, respectively. The dangerous areas of floor water inrush are generally weak, and the dangerous areas and more dangerous areas are mainly concentrated in the areas where the subsidence column develops and the water inrush coefficient is large.

KEYWORDS: floor water inrush; CRITIC method; Interval variable weight; Vulnerability assessment

1. INTRODUCTION

The hydrogeological conditions of coal mines in China are complicated. With the deep mining of coal mines, the water pressure borne by the bottom plate of working face gradually increases, and the risk of water inrush also increases. For a long time, water inrush accidents in coal mines have caused great losses to the lives and property of the country and people (Liu et al 2021，Chen et al 2024，Zeng et al 2023).At present, many scholars have done a lot of work in the field of coal seam floor water inrush risk prediction and evaluation. (Sang et al 2019)used the combination of AHP method and entropy weight method to assign weights to determine the weights of each index, and calculated the water inrush risk level of a mine working face in Jining City based on TOPSIS approximation ideal ranking method, and the results were basically consistent with the actual working face situation.（ Wang et al ，2024） established the critical-AHP comprehensive weighting method to evaluate the roof mining cracking risk and the water-rich grade of aquifer in mining area respectively, and obtained the comprehensive zoning map of roof water inrush risk of coal seam No. 9 by Arcgis geographic information processing technology. （Liu et al，2024)improved and optimized the variable weight model of water inburst region based on Arcgis spatial analysis technology and entropy weight method. The conservative zonal variable weight function is used to modify the variable weight model. The results show that the improved zonal variable weight model has better evaluation effect and higher precision, and has guiding significance for the prediction and prevention of mine water damage.(Sun et al，2023）used the five-figure double coefficient method, with water inrush coefficient as the main factor and pressure coefficient as the auxiliary factor, to evaluate the risk of water inrush from floor of coal seam mining with pressure, and divided the three-level evaluation area. The results show that most of the areas are areas with high safety of mining under pressure. (Zhao et al， 2023)predicted the water inrush risk of coal seam floor based on deep learning theory, used the evaluation results of mining areas to build data sets, trained the convolutional neural network model, and compared it with the BP neural network model. Finally, CNN model was used to evaluate the water inrush risk of coal seam floor in the mining area.

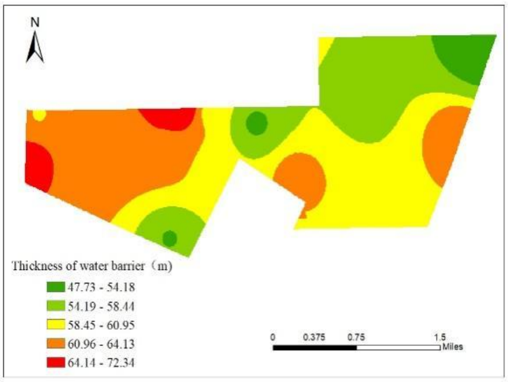
The above research introduced a variety of theories and techniques into the risk assessment of coal seam floor water inrush, and provided support for the development of mine water damage prediction technology. However, these evaluation and prediction methods also have some problems. They are relatively fixed in the determination of index weights, and most of them do not consider the relative importance of various control factors in different combination states. Based on the above background, this paper takes the water inburst risk of No. 15 coal seam floor in Yuecheng Mine as an example, introduces the CRITIC evaluation method, and combines the method with the zoning variable weight theory. At the same time, Arcgis spatial analysis function is used to establish a regional variable weight evaluation model combining geological structure, aquifer and aquifer. The evaluation results of this method are compared with the evaluation model constructed by the constant weight. The rationality and accuracy of the model are confirmed, which can provide reference for the prevention and control of water inrush in coal mine floor.

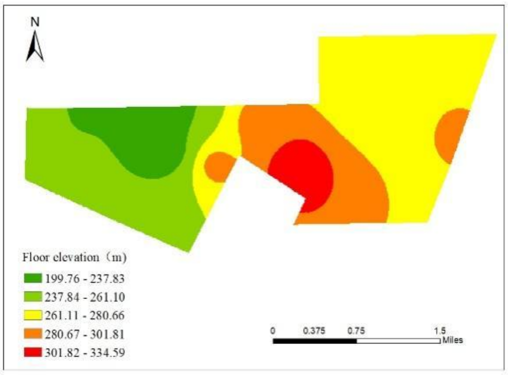
2. GELOGICIAL BACKGROUND OF THE STUDY AREA

The karst fissure of Ordovician limestone aquifer in Yuecheng Coal Mine is relatively developed, and No. 15 coal seam is threatened by the karst fissure aquifer of the underlying Ordovician limestone, and the Ordovician limestone water level is higher than the mining level of No. 15 coal seam. Between the floor of No. 15 coal seam and the Ordovician strata, the relative water-insulating layer composed of mudstone, sandstone and aluminous mudstone at the bottom of Taiyuan Formation is mainly developed. The thickness is 8.61~39.92m, with an average thickness of 25.95m, and the thickness varies greatly. Therefore, the Ordovician aquifer is taken as the target aquifer to study.

3. MAIN CONTROL FACTOR SELECTION AND DATA NORMALIZATION

The selection of main control factors plays a key role in the construction of the zonal variable weight evaluation model and the accuracy of the vulnerability index evaluation results (Li et al，2023). In this paper, based on the previous research results of Yuecheng Coal Mine and the actual production data, the influence of aquifer, water-barrier layer and structure on water inrush in coal mine is fully considered. Six factors, namely Aohui water level elevation, floor elevation of No. 15 coal seam, water pressure of aquifer, thickness of water-barrier layer, water inrush coefficient and structure distribution, are selected as the main control factors of water inrush of No. 15 coal seam floor.The main controlling factors of No. 15 coal seam floor are quantified by using the borehole data collected. Arcgis software was used to map the water level elevation, floor elevation of No. 15 coal seam, water pressure of aquifer, thickness of aquifer layer, water inrush coefficient, and structure distribution grid distribution.





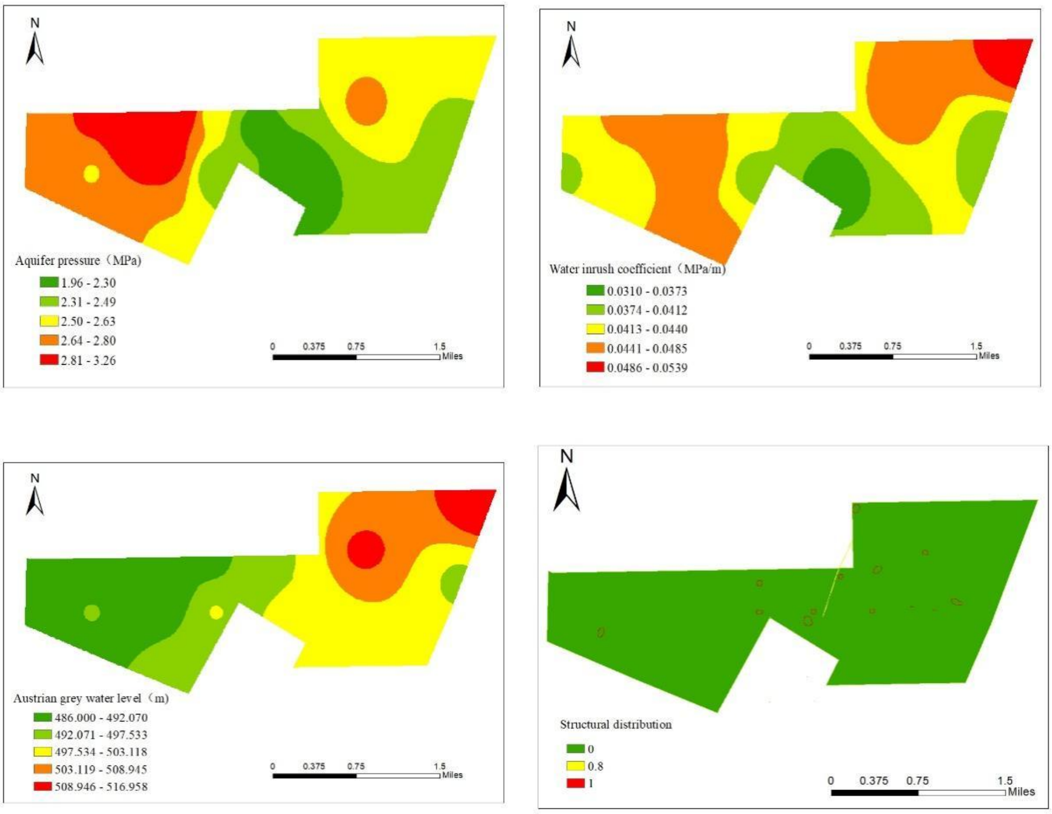


FIG. 1 Grid diagram of the numerical distribution of different controlling factors

Because the main control factors belong to different categories, it is necessary to normalize the magnitude of each factor. Each index can be divided into forward index and reverse index according to the difference in the control effect of coal seam water inrush. The positive index is positively correlated with water inrush, that is, the larger the quantization value is, the more water inrush is likely. On the contrary, the reverse index mainly inhibits the water inrush of coal seam.

The normalization formula of the forward index is as follows:

$$y_j = \frac{(x_j - x_{jmin})}{(x_{jmax} - x_{jmin})} \qquad (1)$$

The normalization formula of reverse index is as follows:

$$y_j = \frac{(x_{jmax} - x_j)}{(x_{jmax} - x_{jmin})} \qquad (2)$$

Where: y_j is the data after normalization; X_j is the magnitude value of each main control factor before normalization. X_{jmax} and X_{jmin} are the maximum and minimum quantized values of each main control factor respectively. j indicates the sample number. The linear function classification function of fuzzy membership degree tool in ArcGIS is used to normalize the thematic map of main control factors, and the thematic process map of main control factors is obtained. The process diagram is the basis of building the variable weight model of the partition.

4. CONSTRUCTION OF PARTITION VARIABLE WEIGHT MODEL

4.1CRITIC WEIGHT METHOD TO DETERMINE THE CONSTANT WEIGHT VECTOR

The weight of CRITIC is calculated based on the variability of evaluation indicators and the conflict among evaluation indicators（He et al，2019，Wang er al，2023）. When the

CRTIC weight method is used to determine the weight of each main control factor, the mean value and standard deviation of the evaluation index of the main control factor of water inrush on the floor should be calculated first, and then the correlation coefficient should be calculated to calculate the mean value and standard deviation:

$$\bar{x}_j = \frac{1}{n}\sum_{i=1}^{n} X_{ij} \qquad (3)$$

X_j is the average value of the data. n is the number of data in the main control factor. S_j is the standard deviation of the JTH data.

$$r_{ij} = \frac{\sum_{i=1}^{n}(x_i - \bar{x}_i)(x_j - \bar{x}_j)}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x}_i)^2}\sqrt{\sum_{i=1}^{n}(x_j - \bar{x}_j)^2}} \qquad (5)$$

Where, r_{ij} is the correlation coefficient between indicators xi and x_j.

The standard deviation and correlation coefficient are used to obtain the information contained in the indicators of the main control factors, and the weight of each indicator is calculated using formula 7:

$$C_j = S_j \sum_{j=1}^{m}(1 - r_{ij}) \qquad (6)$$

$$w_j = \frac{c_j}{\sum_{j=1}^{m} c_j} \qquad (7)$$

Where, c_j is the amount of information contained by the influencing factor index; w_j is the index weight of influencing factors.

The calculated main control factors of water inrush are shown in Table 1.

Table 1 Weight of main control factors of water inrush in floor plate

Main control factor	w_j
Elevation of coal seam floor	17.41%
Austrian ash water level high	17.59%
Aquifer pressure	13.99%
Water inrush coefficient	13.15%
Thickness of water barrier	15.09%
Structural distribution	22.77%

4.2CONSTRUCT PARTITION STATE VARIABLE WEIGHT VECTOR

When applying the vulnerability index method to evaluate the danger of groundwater inrush at the coal seam bottom, the fixed weight of the principal control factor weights is often used, which cannot reflect the change in the contribution of each main control factor index value to the groundwater inrush threat when it undergoes a sudden change. Therefore, a variable weight evaluation model is introduced, which can better highlight the impact of the main control factor on coal seam groundwater inrush when it undergoes a sudden change. Setting reasonable "punishment" and "incentive" mechanisms can adjust the original weight of the principal control factor, so that the high or low value of the principal control factor index can obtain a greater weight, thereby improving the accuracy of the evaluation results （ Zhang et al ，2019 ，Wu et al ，2013 ，Niu er al，2018）. The weight of the "punishment" interval factors decreases as the quantitative value increases, while the weight of the "incentive" interval factors increases as the quantitative value increases. In addition, the bottom water inrush change law needs to be analyzed, and the state variable weight function needs to be improved, and the variable weight interval needs to be adjusted to "punishment interval", "no punishment and no incentive interval", "initial incentive interval", and "strong incentive interval". The mathematical model of the state variable weight vector is as shown in Equation 8

$$\mathbf{S}_{\mathrm{i}}(X)=\begin{cases} e^{a_1(d_{i1}-X)}+c-1, X\in[0,d_{i1}) \\ c, X\in[d_{i1},d_{i2}) \\ e^{a_2(X-d_{i2})}+c-1, X\in[d_{i2},d_{i3}) \\ e^{a_3(X-d_{i3})}+e^{a_2(d_{i3}-d_{i2})}+c-2, X\in[d_{i3},1] \end{cases} \tag{8}$$

In the formula, c, a_1, a_2, and a_3 are weighting parameters, and d_{i1}, d_{i2}, and di_3 are threshold values for the weighting intervals of the individual factors. For the state weighting vector $Si_{(X)}$, the [0, d_{i1}] interval is the punishment interval, the [d_{i1}, d_{i2}] interval is the non-punishment and non-reward interval, the [d_{i2}, d_{i3}] interval is the initial reward interval, and the [d_{i3}, 1] interval is the strong reward interval.

4.3 CLUSTERING ANALYSIS BASED ON CIS ANG DETERMINATION OF VARIABLE WEIGJT INTERVALS

When adjusting the constant weight of the main control factors using the partition weighting model, the main control factor indicators need to be partitioned for processing (Wu et al ,2016).

Using the grouping analysis tool in GIS's clustering analysis, the K-Means algorithm is used to classify the main control factors and obtain the classification critical value of the indicator values when the main control factors are divided into 4 categories. Based on the classification critical value, the threshold value of the weighting interval is determined according to the following formula:

$$d_{i1}=(f_{i1}+f_{i2})/2 \tag{9}$$

$$d_{i2}=(f_{i3}+f_{i4})/2 \tag{10}$$

$$d_{i3}=(f_{i5}+f_{i6})/2 \tag{11}$$

Where, d_{i1} is the variable weight interval threshold of the i index; fi is the classification critical value of the index value of the I-th factor in the clustering classification.

Table 2 Categorical critical values of each controlling factor

Main control factor	f_1	f_2	f_3	f_4	f_5	f_6
Austrian ash water level high	0.134	0.2099	0.3246	0.3876	0.5329	0.8104
Floor elevation	0	0.1798	0.2664	0.3531	0.5415	0.6416
Thickness of water baffle plate	0	0.1913	0.3494	0.4257	0.6158	0.7287
Aquifer pressure	0.2571	0.3286	0.5214	0.6357	0.7286	1

Water inrush coefficient	0.3913	0.4348	0.6087	0.6957	0.7391	1
Structural distribution	0	0	0	0.8	0.8	1

On the basis of determining the classification critical value, the threshold value of each variable weight interval is determined according to formulas 9 to 11, and the variable weight interval of each main control factor is obtained.

Table 3 Variable weight intervals of each main control factor

Main control factor	Penalty interval	No penalty and no incentive interval	Initial excitation interval	Strong excitation interval
Austrian ash water level high	0≦X<0.17	0.17≦X<0.35	0.35≦X<0.67	0.67≦X≦1
Floor elevation	0≦X<0.09	0.09≦X<0.31	0.31≦X<0.59	0.59≦X≦1
Thickness of water baffle plate	0≦X<0.09	0.09≦X<0.39	0.39≦X<0.67	0.67≦X≦1
Aquifer pressure	0≦X<0.29	0.29≦X<0.58	0.58≦X<0.86	0.86≦X≦1
Water inrush coefficient	0≦X<0.41	0.41≦X<0.65	0.65≦X<0.87	0.87≦X≦1
Structural distribution		0≦X<0.40	0.40≦X<0.90	0.90≦X≦1

4.4 DETERMINNATION OF VARIABLE WEIGHT MODEL PARAMENTS

Based on the determined weighting interval thresholds, the weighting parameters c, a_1, a_2, a_3 also need to be determined (Fu et al，2022). The specific method is as follows: First, select or construct an evaluation unit that satisfies the conditions, which requires that the four main control factor indicators in the evaluation unit are located in different weighting intervals, and one indicator is located in the punishment interval. Set the indicator value X1 in the punishment interval, X2 in the non-punishment and non-incentive interval, X3 in the initial incentive interval, X4 in the strong incentive interval, X5 in the punishment interval, and other factors in the non-punishment and non-incentive interval. According to the state weighting vector, the following equation can be derived:

$$W_1 = \frac{W_1^0\left[e^{a_1(d_{11}-X_1)} + c - 1\right]}{\sum_{i=1}^{6} W_i^0\, S_i(X)} \qquad (12)$$

$$W_2 = \frac{W_2^0 c}{\sum_{i=1}^{6} W_i^0 S_i(X)} \qquad (13)$$

$$W_3 = \frac{W_3^0\left[e^{a_2(X_3-d_{32})} + c - 1\right]}{\sum_{i=1}^{6} W_i^0 S_i(X)} \qquad (14)$$

$$W_4 = \frac{W_4^0\left[e^{a_3(X_4-d_{43})} + e^{a_2(d_{43}-d_{42})} + c - 2\right]}{\sum_{i=1}^{6} W_i^0 S_i(X)} \qquad (15)$$

W1/W2 can derive the a2 expression for the parameter:

$$a_1 = \frac{1}{d_{11} - X_1} \ln(\frac{W_1 W_2^0 c}{W_2 W_1^0} - c + 1) \qquad \text{（16）}$$

W3/W2 can derive parameter a2 expression:

$$a_2 = \frac{1}{X_3 - d_{32}} \ln(\frac{W_3 W_2^0 c}{W_2 W_3^0} - c + 1) \qquad \text{（17）}$$

W4/W2 can derive parameter a3 expression:

$$a_3 = \frac{1}{X_4 - d_{43}} \ln\left[\frac{W_4 W_2^0 - W_2 W_4^0}{W_2 W_4^0} c + 2 - \left(\frac{W_3 W_2^0 - W_2 W_3^0}{W_2 W_3^0} c + 1\right)^{\frac{d_{43} - d_{42}}{X_3 - d_{32}}}\right]$$

According to the index value and constant weight of each controlling factor in the study area, the following formula is obtained.

$$k_1 c = (k_2 c + 1)^{k_3} - 1 \qquad \text{（19）}$$

$$k_1 = \frac{W_2^0 - W_2^0(W_1 + \ldots + W_4) - W_2(W_5^0 + W_6^0)}{W_2 W_5^0} \qquad \text{（20）}$$

$$k_2 = \frac{W_1 W_2^0 - W_2 W_1^0}{W_2 W_1^0} \qquad \text{（21）}$$

$$k_3 = \frac{d_{51} - X_5}{d_{11} - X_1} \qquad \text{（22）}$$

The values of a1, a2 and a3 can be obtained according to formulas 16 to 18. After calculating the values of the adjusting weight parameters c, a1, a2 and a3, the state vector is calculated according to formula 8, and then the variable weight weight W(X) of the index is calculated. Using the entropy method and related formulas to solve the weight adjustment parameters, the calculation results are as follows: a1=0.609, a2=0.112, a3=0.029, c=0.09. On the basis of known weight adjustment parameters, the state vector formula can be obtained by substituting the weight adjustment parameters into formula 8:

$$\mathcal{S}_{\mathrm{i}}(X) = \begin{cases} e^{0.012((d_{i1} - X)} + 0.009 - 1, X \in [0, d_{i1}) \\ 0.009, X \in [d_{i1}, d_{i2}) \\ e^{0.007(X - d_{i2})} + 0.009 - 1, X \in [d_{i2}, d_{i3}) \\ e^{0.0179(X - d_{i3})} + e^{0.007(d_{i3} - d_{i2})} + 0.009 - 2, X \in [d_{i3}, 1] \end{cases} \qquad \text{（23）}$$

The variable weight model of water inrush risk of No. 15 coal seam floor is established based on the established state vector formula and the obtained variable weight interval and adjusting weight parameters. Based on the constructed variable weight model, the variable weight vector S(X) and variable weight weight can be solved according to the formula, and the variable weight weight value that changes with the change of the state value of the factors is obtained on the basis of considering the combined state level of different factors.

Table 4 Borehole weight change

Hole number	Austrian grey water level high	Elevation of coal seam floor	Thickness of water baffle plate	Aquifer pressure	Water inrush coefficient	Structural distribution
ZK-1	0.1522	0.2449	0.1113	0.1735	0.1501	0.1679
ZK-2	0.1741	0.2092	0.1408	0.1305	0.1329	0.2125
ZK-3	0.1719	0.1849	0.1475	0.1446	0.1285	0.2225
CG-1	0.2692	0.1503	0.1573	0.1106	0.1413	0.1711
CG-2	0.1691	0.1799	0.1568	0.1401	0.1352	0.2190
CG-3	0.1575	0.1668	0.1508	0.1367	0.1207	0.2675
319	0.1672	0.2007	0.1457	0.1315	0.1410	0.2139
318	0.2522	0.1697	0.1305	0.1327	0.1178	0.1970
9-5	0.2076	0.1595	0.1687	0.1960	0.0982	0.1700
9-6	0.1524	0.1661	0.1307	0.1235	0.1139	0.3134
9-7	0.0728	0.0994	0.0707	0.5790	0.0544	0.1236
101	0.2247	0.1419	0.1230	0.1522	0.1147	0.2435
10-2	0.2462	0.1502	0.1304	0.1593	0.1175	0.1964
324	0.2567	0.1530	0.1331	0.1414	0.1156	0.2002
10-1	0.2608	0.1538	0.1330	0.1359	0.1159	0.2007

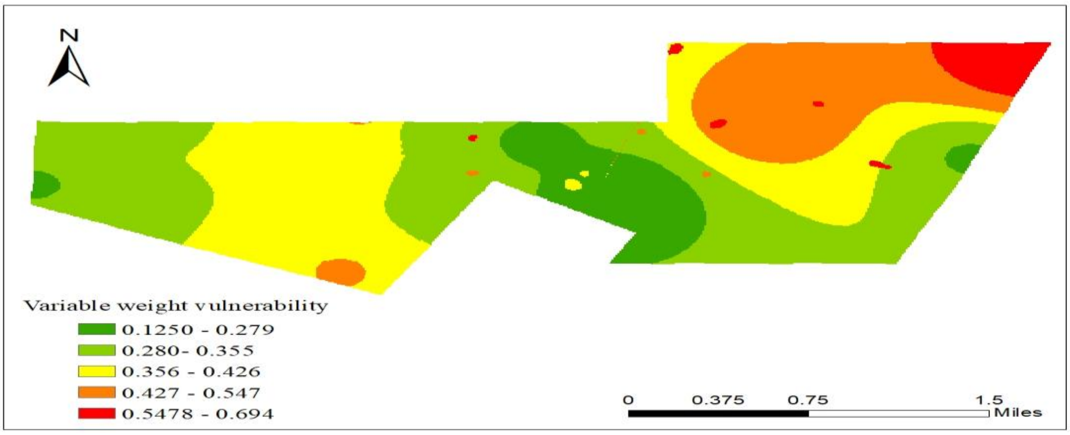
The vulnerability model based on the variable weight theory of No. 15 coal seam floor water inrush risk is established as follows:

$$\mathrm{VI}=\sum_{i=1}^{m}W_i f_i(x,y)=\sum_{i=1}^{m}\frac{W_i^0 S_i(X)}{\sum_{j=1}^{m}W_j^0 S_j(X)}f_i(x,y)=\frac{W_1^0 S_1(X)}{\sum_{j=1}^{1}W_j^0 S_j(X)}f_1(x,y)+\frac{W_2^0 S_2(X)}{\sum_{j=1}^{2}W_j^0 S_j(X)}f_2(x,y)+\ldots\ldots+\frac{W_m^0 S_m(X)}{\sum_{j=1}^{6}W_j^0 S_j(X)}f_m(x,y) \tag{24}$$

In the formula, VI is the vulnerability index, m is the number of influencing factors, Wi is the variable weight vector of influencing factors, fi(x, y) is the influence value function, (x, y) is the geographical coordinate, Wi0 is any constant weight vector, Si(X) is the M-dimensional partition state variable weight vector, and X is the state value of factors after normalization.

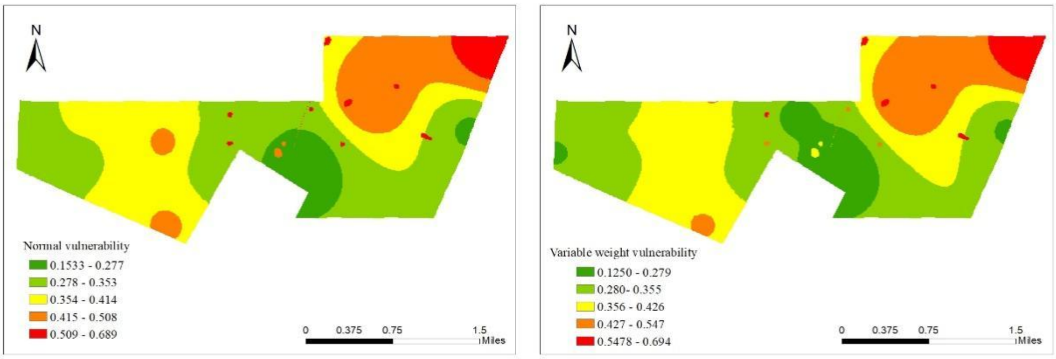
According to formula 24, the vulnerability index (VI) corresponding to each evaluation cell was calculated. GIS spatial information processing technology and natural break point classification method were used to obtain the partition thresholds of the vulnerability index evaluation model, which were 0.279, 0.355, 0.427 and 0.549, respectively. According to the above four thresholds, the risk zones of Ordovician limestone water inrush on the floor of No. 15 coal seam are divided into five evaluation areas:

VI≧0.549	dangerous areas
0.427≦VI<0.549	More dangerous area
0.355≦VI<0.427	Transition region
0.279≦VI<0.355	Relatively safe zone
VI≦0.279	Safe zone



As can be seen from Figure 3, the red and orange areas are the dangerous and relatively dangerous areas, accounting for 3.37% and 17.2% respectively, which are mainly located in the northeast of the study area and the collapse column development area. In the eastern region, the thickness of the water barrier layer is thin and the water pressure of the Ordovician limestone water in the bottom floor is large. The subsidence column will cause serious damage to coal seam and surrounding rocks, and may communicate with aquifer and fissure water to form water channel, leading to water inrush in coal mine floor. Therefore, in the production process, attention should be paid to the actual situation of the region. The yellow area is the transition area of water inrush, which is mainly distributed in the periphery of the more dangerous area, accounting for 32%. The water barrier layer in this area is thin, the water pressure and water inrush coefficient are relatively large, and the threat of water inrush in this area should be further considered. Light green area and green area are relatively safe areas and safe areas, accounting for 36.16% and 11.15% respectively, mainly located in the western and central regions. The water pressure and water inrush coefficient of aquifer in most areas of the area are relatively small, and the thickness of aquifer layer is medium and thick, so water inrush is not easy to occur in this area.

4.5 VULNERABILITY ANALYSIS OF PERMANENT AND VARIABLE RIGHTS



(a) Normal vulnerability **(b) Variable weight vulnerability**

FIG. 4 Evaluation results of constant weight model and variable weight model

By comparing the vulnerability assessment zones of variable weight and constant weight, it can be seen that the overall distribution trend is basically the same, and the water inrush of coal seam floor is greatly affected by the collapse column, the thickness of water-retaining layer and the water pressure of aquifer. However, the zoning map of the variable weight evaluation model is more detailed in the classification of water inrush risk in the study area. Compared with the normal weight vulnerability model, the variable weight vulnerability model expands the scope of the safe zone and the relatively safe zone. The reason for this difference is that the degree of "punishment" is greater than that of "incentive" in constructing state variable weight vector. Indicators in the "punishment" range are given a higher weight than those in the "incentive" range. In both the constant weight vulnerability model and the variable weight vulnerability model, the safety zone is concentrated in the central region, mainly because the coal seam floor elevation is higher and the water inrush coefficient is smaller in the central region. The elevation of coal seam floor changes from 0.1741 (normal weight) to 0.0994, and the water inrush coefficient changes from 0.1315 (normal weight) to 0.0544, which effectively highlights the inhibitory effect of coal seam floor elevation and water inrush coefficient on vulnerability assessment in this region, and the evaluation results are more accurate than the traditional normal weight model.

5. CONCLUSION

(1) Using the CRITIC method and the interval variable weight model based on incentive and punishment mechanism to determine the main control factors of constant weight and variable weight, calculate the Aoshi water level elevation, No. 15 coal seam floor elevation, aquifer water pressure, waterproof layer thickness, water inrush coefficient. The constant weight of the main controlling factors of water inrush is 0.1759, 0.1741, 0.1399, 0.1509, 0.1315, 0.2277; The weights were 0.078-0.2692, 0.0994-0.2449, 0.1235-0.5790, 0.0707-0.1687, 0.0544-0.1501, 0.1679-0.3134. Compared with the two evaluation, it is found that the variable weight model can make the weight of each main control factor give different degrees of punishment or incentive with the change of index value, and more effectively reflect the regional differences of the main control factors on the water inrush of coal seam floor.

(2) Based on Arcgis spatial analysis and data processing functions, the variable weight model for assessment of water inrush vulnerability of coal seam floor No. 15 was obtained. According to the provisions of critical threshold, the risk of water inrush of coal seam floor was divided into five regions, namely safe zone, safer zone, transition zone, more dangerous zone and dangerous zone. The area accounted for 11.15%, 36.16%, 32%, 17.28% and 3.37%, respectively. The safe zone and relatively safe zone are mainly concentrated in the central and western regions, the transition zone is mainly concentrated in the periphery of the more vulnerable zone, the more vulnerable zone is in the subsidence column development area, and the danger zone is concentrated in the northeast region.

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