Multi-source information fusion technology for risk assessment of water inrush from coal floor karst aquifer

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ABSTRACT

In order to effectively solve the technical problem of the prediction of coal floor water inrush, according to the spatial distribution differences of geological conditions, combined with the typical coal mine, a partition calculation map of the development depth of the mineral pressure failure zone was made, and the mining process under different geological conditions has been numerically simulated and analyzed. And the empirical formula is modified by the numerical simulation calculation results, the calculation formula of the development depth of the mineral pressure failure zone of a typical coal mine was established, which effectively improves the accuracy of the calculation of the depth of the mineral pressure failure zone and lays the foundation for the quantification of evaluation indicators related to the aquifuge. According to the hydrogeological characteristics of southwest mines in China, 12 evaluation indicators determined from the three aspects of aquifer, aquifuge and geological structure, and an evaluation index system of water inrush risk of the karst aquifer in the coal floor has been constructed. On this basis, further using GIS technology and entropy weight theory, a multi-source information evaluation method for the risk of water inrush from coal floor was proposed, and verified the evaluation results.

1. Introduction

Coal is the world’s most abundant and widely distributed conventional energy, and it is also the cheapest energy. It accounts for 25% of the world’s primary energy consumption and is widely used in steel, electric power, chemical and other fields.
With the gradual depletion of shallow coal resources, the mining depth of mines continues to increase, and the geological conditions of coal mining are gradually becoming more complicated. The harm of karst water inrush from the coal seam floor is becoming more serious. If reasonable water prevention and control measures are not taken, not only will water inrush accidents continue to increase, but a large number of mines threatened by water damage will be scrapped ahead of schedule (Howladar 2013; Li et al. 2020; Newman et al. 2017).

Southwest China is an important coal production base, and this area is also the world’s largest contiguous bare carbonate distribution area (He et al. 2011; Yang et al. 2016). Under the long-term karst action, the hydrogeological conditions of the mines in this area are extremely complex, and water richness of karst confined aquifer in coal seam floor has obvious spatial distribution unevenness and anisotropy (Ding et al. 2021; Wu et al. 2016; Ma et al. 2022). The redistribution of stress generated by coal seam mining will inevitably cause the destruction of the coal seam floor. The confined water of the aquifer breaks through the barrier of the aquifuge and inrush into the working face in the weak zone of the aquifuge, resulting in a rapid increase in mine water inflow and even flooding the entire mine (Li et al. 2013; Zhang and Yang 2021; Chen et al. 2017). The process mechanism of water inrush from coal seam floor is extremely complex, involving disciplines such as hydrogeology, engineering geology, and rock mechanics (Rui et al. 2018; Wang et al. 2012). For a long time, many scholars have studied water inrush from coal seam floor from different perspectives. Representative examples are: The Hungarian scholar Weg Florence first proposed the concept of relative aquifers and realized that water inrush from the coal seam floor is not only related to the thickness of the aquifer but related to water pressure (Dong et al. 2020); Based on the theory of statics, the Soviet scholar B.U. Sreshalev studied the failure mechanism of coal seam floor under the action of confined water (Hu et al. 2019). Santos and Bieniawski (1989) introduced the concept of critical energy release point based on the improved Hoek-Brown rock mass strength rule and analyzed the bearing capacity of the floor aquifuge.

In China, the research on water inrush from coal seam floor has a history of more than 40 years (Zeng et al. 2018; Li et al. 2022). The Xi’an Branch of China Coal Research Institute, Shandong University of Science and Technology, and China University of Mining and Technology have done a lot of detection, analysis and experimental research work, and have put forward the thin plate structure, zero damage, and in-situ tensile cracking, strong seepage channel, rock-water stress relationship, key layer, lower three zones theory, etc. (Yang and Luo 2021; Shi et al. 2020; Li et al. 2017). These important research works have laid the foundation for solving the problem of coal seam floor water inrush, but most of the existing theories are still in the theoretical research stage, and many key technical problems have not yet been solved and are difficult to be applied in practice. In the early 1960s, coal mine areas such as Jiaozuo, Fengfeng and Zibo in China summarized the empirical formula for predicting floor water inrush based on the actual data of floor water inrush, was the water inrush coefficient method (The ratio of the water pressure to the thickness of the aquifuge) (Qiao et al. 2019; Li and Sui 2021), has been used until now. However, there are many factors affecting water inrush from the coal seam floor, and the water
The inrush process shows a very complex nonlinear dynamic characteristic. The traditional water inrush coefficient method only considers the water pressure and the thickness of the aquifuge, cannot describe the situation that the water inrush is controlled by multiple factors and has a complicated formation mechanism, and it has been unable to meet the need of water inrush risk assessment under new mining methods and new hydrogeological conditions. Therefore, applying contemporary multi-source information integration theory to predict water inrush from coal seam floor has become a popular research area in recent years due to a large number of complex and variable water inrush influencing factors. Researchers like Wu et al. (2015), Wang et al. (2012), Li et al. (2021), Liu and Wang (2012), etc. have all proposed some water inrush evaluation methods that can take a variety of factors into account. However, the existing research has the following problems: (1) The calculation of the depth of the fracture zone often relies on empirical formulas, and the geological conditions of each coal mine are different. Therefore, the error of the depth of the fracture zone is frequently significant. (2) How to quantify and integrate various factors affecting water inrush, factor weights determine how to eliminate human interference and other essential technical issues still need to be improved.

In view of the above reasons, combined with the typical coal mine, according to the differences in geological conditions, made a partition calculation map of the depth of mineral pressure failure zone, numerical simulation calculations are carried out on the mining process under different geological conditions, and a correction calculation formula for the depth of mineral pressure failure zone is established, which makes up for the error caused by insufficient consideration of its influencing factors when directly adopting the empirical formula, and laid the foundation for the quantification of the relevant factors of the aquifuge. At the same time, 12 evaluation indexes were determined according to the hydrogeological characteristics of mines in southwest China, constructed a system of evaluation indexes for the risk of water breakout in karst aquifers at the bottom of coal seams in southwest China. On this basis, and further combining GIS technology and entropy weight method, a multi-source information evaluation method for the risk of water inrush from coal seam floor was proposed, and the evaluation results were verified. The multi-source information assessment approach based on GIS and entropy weight method can completely and objectively describe the features of coal seam floor water inrush regulated by a number of parameters and has a highly complicated creation process, which provides a definite reference for study in related disciplines.

2. Overview of the research area

2.1. Physical geography

Longfeng Coal Mine is located in the southwest of Jinsha County in Guizhou Province, China, with the east longitude 106°07′30″~106°15′00″ and the north latitude 27°14′45″~27°24′45″. With an irregular strip shape, the coal mine spreads in the NE-SW direction, as shown in Figure 1. With an elevation of 1100~1350 m and a relative height difference of 100~300 m, Longfeng Coal Mine is generally affected by the geological structure and lithology. The terrain is generally high in the northwest and low in the southeast in the coal mine, where the maximum monthly average
precipitation is 169.2 mm, the minimum monthly average precipitation is 20.2 mm, and the annual average precipitation is 1050 mm.

2.2. Hydrological geology

The atmospheric precipitation is an important source of regional underground water. The deep underground water mainly exists in the form of confined water, and the flow direction of underground water is mainly controlled by stratum and structure, which is consistent with the trend of the stratum. The aquifuge of the coal seam floor consists of mudstone, silty mudstone, fine sandstone, and siliceous limestone. According to the hydrogeological investigation data of the coal mine, the distance between the karst fracture aquifer in the Maokou formation of the Permian Middle System and the 11th coal seam is 14.06~29.25m and the mean distance is 19.76 m. It is the direct aquifer of the 11th coal seam. The grey to light grey powder limestones with thickness above 60 m can be found in the Maokou formation of the Permian Middle System. The aquifer in Maokou formation is featured with developed karst fractures and channels, the non-uniform height of water-rich stratum, static water level elevation 1076.799~1151.883m, specific capacity 0.0054192 ~ 0.017010 L/s.m, and hydraulic conductivity 0.0000004 m~0.04153 m/d. Figure 2 shows the hydrogeological structure.

3. Determination of depth of mineral pressure failure zone in the coal seam floor

3.1. Calculation of empirical value of the depth of mineral pressure failure zone

The mineral pressure failure zone in the coal seam floor refers to the stratum zone with a significant change in hydraulic conductivity where vertical fractures can be
found due to damage in the continuity of the floor stratum under the effect of the dynamic pressure of mining. The accurate calculation of the depth of the mineral pressure failure zone can help determine the thickness of the complete aquifuge. The empirical value of the depth of the mineral pressure failure zone in the drilling coal seam floor of the research area is calculated with the calculation formula in the Regulations of water prevention and control for coal mine (Formula 1) (National Coal Mine Safety Supervision Bureau 2018), as shown in Table 1. Figure 3 shows the drilling distribution.

\[ h = 0.0085T + 0.1665a + 0.1079L - 4.3579 \]  

where \( a \) is the dip angle of coal seam; \( T \) is the mining depth; \( L \) is the dip length of working face; \( h \) is the depth of mineral pressure failure zone. The dip length of the working face is 100 m, and mining depth is the depth of the coal seam floor.

### 3.2. Division of differentiation zones by geological conditions

The depth of the mineral pressure failure zone is calculated with the empirical formula to simply obtain parameters. Although it is widely used, there are some limitations as below: First, the empirical formula for the depth of the mineral pressure

| Stratigraphic System | Aquifer | Lithology | Thickness m | Lithology Characterization |
|----------------------|---------|-----------|-------------|---------------------------|
| Permian Upper System Longtan Formation | Aquifer | Sandstone | 14.06-29.25 | Sandstone Coal seams |
| Permian Middle System Maokou Formation | Aquifer | Mudstone Sand and Mud | >50 m | Limestone |

![Figure 2. Hydrogeological structure.](image)
failure zone in the Regulations of water prevention and control for coal mine is based on the statistical analysis of the measured data of the shallow burial depth working face. There is often a large deviation between the calculated results and the actual; second, the empirical formula takes into account the three factors of coal seam dip angle, mining depth, and working face slanting length, but the mineral pressure failure zone of the floor is also related to mining pressure, rock formation damage resistance, geological structure and other factors, the empirical formula is not comprehensive enough to consider the influencing factors.

Numerical simulation technology has been widely used to solve various geological problems in the field of mine engineering. It is possible to effectively simulate the development depth of the mineral pressure failure zone under different geological conditions, consider various factors completely, and achieve higher accuracy through calculating the depth of the mineral pressure failure zone with numerical simulation technology. However, it may be time-consuming and infeasible to perform numerical simulation calculations for each geological drill. As a result, this study creates a map of geological zones that are differentiated from one another based on variations in the spatial distribution of geological conditions in the research region. Next, it generalizes the geological conditions of various zones, calculates the depth of each zone’s mineral pressure failure zone in the coal seam floor, and adjusts the empirical formula using simulation values to produce the modified depth of each zone’s mineral pressure failure zone.

The depth of the mineral pressure failure zone in the coal seam floor is mainly related to the lithological composition of the aquifuge, mining depth, dip length of working face, dip angle and thickness of coal seam, original stress, etc. According to the statistical analysis for geological data of Longfeng Coal Mine, the thickness of coal seams in the mine area can be divided into thin, medium-thick, and thick seams, and the depth of coal seam burial is between 180 m~490m, and the number of lithological combination layers is 3~15. The above factors vary widely within the mine area, while the slope length of the working face (100 m) and the dip angle of the coal

| Drilling number | Mining depth (m) | Dip angle of coal seam (°) | The depth of mineral pressure failure zone (m) | Drilling number | Mining depth (m) | Dip angle of coal seam (°) | The depth of mineral pressure failure zone (m) |
|-----------------|------------------|----------------------------|-----------------------------------------------|-----------------|------------------|----------------------------|-----------------------------------------------|
| zk1             | 370.93           | 3.72                       | 15.85                                         | zk17            | 386.93           | 8.72                       | 16.52                                         |
| zk2             | 371.93           | 5.71                       | 16.07                                         | zk18            | 387.93           | 8.72                       | 16.53                                         |
| zk3             | 372.93           | 5.71                       | 16.08                                         | zk19            | 388.93           | 8.72                       | 16.54                                         |
| zk4             | 373.93           | 5.71                       | 16.09                                         | zk20            | 389.93           | 8.72                       | 16.55                                         |
| zk5             | 374.93           | 9.06                       | 16.46                                         | zk21            | 390.93           | 8.72                       | 16.56                                         |
| zk6             | 375.93           | 9.06                       | 16.47                                         | zk22            | 391.93           | 3.72                       | 16.02                                         |
| zk7             | 376.93           | 9.06                       | 16.47                                         | zk23            | 392.93           | 6.71                       | 16.36                                         |
| zk8             | 377.93           | 5.71                       | 16.12                                         | zk24            | 393.93           | 6.71                       | 16.36                                         |
| zk9             | 378.93           | 9.06                       | 16.49                                         | zk25            | 394.93           | 5.72                       | 16.27                                         |
| zk10            | 379.93           | 9.06                       | 16.5                                          | zk26            | 395.93           | 8.72                       | 16.6                                          |
| zk11            | 380.93           | 9.06                       | 16.51                                         | zk27            | 396.93           | 8.72                       | 16.61                                         |
| zk12            | 381.93           | 2.98                       | 15.86                                         | zk28            | 397.93           | 5.72                       | 16.29                                         |
| zk13            | 382.93           | 3.72                       | 15.95                                         | zk29            | 398.93           | 5.72                       | 16.3                                          |
| zk14            | 383.93           | 6.56                       | 16.26                                         | zk30            | 399.93           | 6.71                       | 16.42                                         |
| zk15            | 384.93           | 6.56                       | 16.27                                         | zk31            | 400.93           | 5.72                       | 16.32                                         |
| zk16            | 385.93           | 8.72                       | 16.51                                         | zk32            | 401.93           | 5.72                       | 16.33                                         |
seam (about 5 degrees) do not differ significantly within the mine area, so the study area was partitioned according to the variability in the spatial distribution of the coal seam depth, the number of layers of the lithological combination and the thickness of the coal seam, as shown in Figure 4.

3.3. Simulated calculation of the depth of mineral pressure failure zone

Using the numerical simulation method to calculate the development depth of the mineral pressure failure zone, it is necessary to obtain accurate physical and mechanical parameters of the rock formation, and the generalization of the geological conditions must be consistent with the actual situation. Otherwise, the calculated results are often inaccurate. In this article, the measured rock physics and mechanics indexes are as simulation parameters, as shown in Table 2. And the strata are divided into the lower Triassic Yulongshan Member ($T_1y^2$), the Permian Upper Changxing Formation ($P_{3c}$), the Permian the strata of the Upper Longtan Formation ($P_{3l}$) and the Middle Permian Maokou Formation ($P_{2m}$) are divided into 10 units layers according to the difference in lithology. The coal seams are located in the Upper Permian Longtan Formation. Based on the Mohr-Coulomb failure criterion, a UDEC triangular mesh finite element is used to divide the computational grid, and a two-dimensional geological generalization model for different geological conditions is
established. The simulation analysis is made for the mining process of a coal seam in each zone. The simulation process includes two steps. First, the equilibrium state of the stratum is simulated under initial geological conditions. Second, excavate in 10 m steps along the coal seam until the depth of vertical fissure development tends to be the same as the previous step, then stop excavation. The excavation is made by steps along the trend of the coal seam, and the failure depth of the aquifuge in the coal seam floor due to mining is determined based on formation rules of fracture. The numerical simulation results show that the fissures develop along vertical and horizontal in the aquifuge, the development height of vertical fractures gradually stabilizes with the increase of excavation length, and the horizontal fractures keep the expansion trend with the boost of excavation length. Figure 5 shows simulation results of the depth of the mineral pressure failure zone in a different zone with various geological conditions.

3.4. Correction for the depth of mineral pressure failure zone

The correction coefficient of the empirical formula for the mineral pressure failure zone is calculated based on average method, and the correction coefficient for each zone is calculated with Formula 2 based on the calculation value of the depth of
Where \( \theta_j \) is the correction coefficient of empirical formula for the jth zone; \( H_{ij} \) is the calculation value of the mineral pressure failure zone for the ith drill in the jth zone from the empirical formula; \( h_j \) is the simulation value of the depth of mineral pressure failure zone in the jth zone; \( n \) is the total number of drills in the jth zone.

The correction coefficient in Table 3 multiplies by calculation value of the mineral pressure failure zone for drills in corresponding zones from empirical formula to obtain correction value of the depth of mineral pressure failure zone for each drill, as shown in Table 4.

### Table 2. Rock physical and mechanical parameters of different formations.

| Stratigraphic code | Lithology       | Density Kg/m³ | Tensile strength Mpa | Internal friction angle | Cohesiveness Mpa | Elastic modulus x10⁵Mpa | Poisson ratio | Bulk modulus 10⁴Mpa | Shear modulus x10³Mpa |
|--------------------|----------------|----------------|----------------------|------------------------|-----------------|------------------------|--------------|---------------------|----------------------|
| T₁jy²               | Siltstone      | 2425.00        | 1.36                 | 31.20                  | 2.50            | 0.44                   | 0.12         | 1.93                | 19.60                |
| T₁jy³               | Limestone      | 2730.00        | 2.89                 | 37.90                  | 4.93            | 0.20                   | 0.27         | 1.43                | 7.76                 |
| T₁jy⁴               | Mudstone       | 2760.00        | 1.79                 | 36.90                  | 1.80            | 0.24                   | 0.28         | 1.82                | 9.38                 |
| P₂c                 | Limestone      | 2780.33        | 7.98                 | 35.69                  | 6.63            | 0.57                   | 0.14         | 2.64                | 25.00                |
| P₁j                 | Muddy Sandstone| 2942.71        | 6.32                 | 33.76                  | 3.60            | 0.17                   | 0.18         | 0.87                | 7.03                 |
|                   | Coal           | 2770.11        | 1.59                 | 35.90                  | 1.60            | 0.22                   | 0.18         | 1.15                | 9.32                 |
|                   | Muddy Limestone| 2753.20        | 4.92                 | 39.40                  | 4.73            | 0.14                   | 0.26         | 0.94                | 5.36                 |
|                   | Sandstone      | 2905.69        | 5.21                 | 36.57                  | 7.15            | 0.44                   | 0.18         | 2.29                | 18.60                |
|                   | Mudstone       | 2782.75        | 1.79                 | 35.92                  | 1.80            | 0.24                   | 0.28         | 1.82                | 9.38                 |
| P₂m                 | Limestone      | 2823.98        | 3.38                 | 37.95                  | 4.40            | 0.16                   | 0.18         | 0.81                | 6.57                 |

### 4. Risk evaluation for water inrush from karst confined aquifer in the coal seam floor

#### 4.1. Creation of evaluation indicator system for water inrush from coal seam floor

Many studies have been made for the field of control factors for water inrush from coal seam floor, for example, such as: Wu et al. (2018), Greassidis et al. (2020), Bozau et al. (2017), Lin et al. (2020). The control factors for water inrush have been recognized in the field to a certain extent. The confined aquifer is a precondition and material foundation for causing water inrush from coal seam floor; the aquifuge plays a significant control effect on the water inrush, and geological structure is a prominent favourable factor for causing water inrush. Therefore, this article constructs an index system for evaluating the risk of water inrush in karst confined aquifers at the coal seam floor from the perspective of aquifers, aquifuge and geological structures, taking into full consideration the hydrogeological characteristics of coal mines in the southwest China. The selected evaluation indicators reflect the controlling effect of aquifers, aquifuge, and geological structures on water inrush from different angles, and the indicators are independent of each other and have little correlation.
4.1.1. Aquifuge

(1) Aquifuge thickness under mineral pressure failure zone (ATMPFZ)

The stratum with water-proof capacity in the aquifuge mainly refers to the rock member that was not damaged during mining. ATMPFZ reflects the overall water-proof ability of the aquifuge. The strength of the water-proofing and anti-damage capabilities increase with the aquifuge thickness.

Hard rock thickness under mineral pressure failure zone (HRTMPFZ)

Hard rocks in the aquifuge that haven’t been damaged by mining have good mechanical and pressure-resistant qualities and can successfully withstand both rock pressure and water pressure. The larger the hard rock thickness in aquifuge is, the stronger the water-proof capacity will be.

Number of layers of lithology combination of aquifuge (NLLCA)

Figure 5. Simulation results for the depth of mineral pressure failure zone in differentiation zones with various geological conditions.
NLLCA is the number of different lithologic interfaces between the coal seam and the floor aquifer. During hydraulic fracturing, the fracture will extend along the direction with minimum resistance. If the rock is isotropic and uniform, the fracture will continue development until it reaches the stratum interface, the fracture will determine extension based on interfacial property. Therefore, the bigger the NLLCA, the less likely a fracture will emerge and the more stable the aquifuge will be.

Rock quality designation (RQD)

Rock quality designation is defined as the specific value between the length of the rock core section larger than 10cm from round trip drilling and the footage per round trip (Haftani et al. 2016). RQD can reflect the degree of completeness of aquifuge rock. The greater the RQD, the more complete the rock and the greater the aquifuge’s water-proof capability.

Drilling rinse fluid consumption (DRFC)

Drilling rinses fluid consumption can reflect the rock fracture degree and development of joint fissure in aquifuge. The completeness of the rock seam will be poorer, and the aquifuge’s ability to withstand water will be less effective, the bigger the DRFC.

Aquifuge mudstone ratio (AMR)

The water-proof capacity of aquifuge has a close relationship with the lithology. Generally, the hard rock can maintain the stability of the aquifuge. The fracture cannot occur on the mudstone due to its better shape. Therefore, the water-proof effect increases with the proportion of mudstone in the aquifuge.

4.1.2. Geological structure

(1) Fault and fold distribution (FFD)

The faults and folds are the stress concentration distribution areas, the rock mass is broken and the mechanical strength is low. Under the action of mining disturbance and water pressure, water inrush channels are often formed, and more than 60% of water inrush disasters occur in geological structure distribution areas. It should be noted that this indicator does not include small geological structures such as karst collapse columns and volcanic intrusions.

Fractal dimension of geological structure (FDGS)
The fractal dimension of the geological structure is used to quantitatively describe the development degree of regional structure by collecting spatial distribution characteristics of geological structure (Feranie et al. 2011; Zhang et al. 2021). First, the research area is divided into several square meshes with side length \( r \) and the number of structural trace lines through mesh \( N(r) \) is collected. Second, the side length of the mesh is decreased to \( r/2 \) and then the number of structural trace lines through mesh \( N(r/2) \) is collected again, and so on. The number of trace lines \( N(r_i) \) through mesh with side length \( r, r/2, \ldots, r/i \) is collected, and the statistical number is input into the coordinate system of \( \lg N(r_i)/\lg r \) to get FDGS of the mesh through data fitting (formula 3). Finally, the interpolation analysis is made with centre coordinates of mesh and FDGS value to obtain the thematic map.

\[
D_r = \dim F(r) = \lim_{r \to 0} \frac{\lg N(r_i)}{\lg r}
\]  

(3)

4.1.3. Aquifer

(1) Water pressure of aquifer (WPA)

The water pressure of the aquifer refers to water pressure in the coal seam floor. As the power source of water inrush from the coal seam floor, WPA can promote the potential energy into kinetic energy for the confined water. The probability of water inrush increases with WPA value.

(2) Specific capacity (SC)

The specific capacity is the water inflow when the water level in the well decreases one metre during the pumping test. It is an important indicator for evaluating the water yield property of the aquifer. The larger the SC is, the better the water yield property of the aquifer will be.

(3) Hydraulic conductivity (HC)

The hydraulic conductivity is the discharge under the unit hydraulic gradient and can reflect the difficulty level of fluid through pore structure. Generally, the larger the HC is, the water yield property of the aquifer will be better.
Karst rate (KR)
The difference in value between certain rocks with karst and the other rocks in a particular location is known as the karst rate. It might be a reflection of the carbonatite aquifer’s degree of karst development. It may be categorized as linear karst rate, facial karst rate, and volumetric karst rate using various statistical approaches (Frumkin et al. 2015). This article uses the linear karst rate as an evaluation indicator, as shown in Formula 4.

\[ Z = \sum v/V \]  

where \( Z \) is the linear karst rate; \( \sum v \) is the sum of drilling footage of miarolitic; \( V \) is the total drilling footage.

4.2. Establishment of thematic map of evaluation indicators

Through collecting geological drills, hydrogeological tests, and the geological structure of the Longfeng Coal Mine, this article extracts evaluation indicators, creates the original database, conducts interpolation calculations, and plots a thematic map of each evaluation indicator with GIS. Figure 6 shows the thematic map of aquifuge thickness under the mineral pressure failure zone, and Figure 7 shows the thematic map of the water pressure of the aquifer. Due to limited space, Figures S1–S10 show other thematic maps in the supplementary material.

4.3. Distribution of indicator weight based on entropy weight method

4.3.1. Fundamental theory of the entropy weight method

The entropy weight method is an objective weighting method, which calculates the entropy weight of the indicator with information entropy based on the degree of variation of each index, then corrects the weight based on the entropy weight, and finally obtains the objective weight value (Alipour et al. 2021; Liu et al. 2021; Zhou et al. 2013). The entropy weight method can avoid the influence of decision-maker on indicator weight and obtain more objective results, with the calculation process as below:

(1) Calculate the proportion \( P_{ij} \) of the ith standard value of the jth indicator:

\[ P_{ij} = \frac{U_{ij}}{\sum_{i=1}^{m} U_{ij}} \]  

(5)

(2) Calculate the entropy \( e_j \) of the jth indicator \((0 \leq e_j \leq 1)\):

\[ e_j = -k \sum_{i=1}^{m} (p_{ij} \ln p_{ij}) \]  

(6)

(3) Calculate the utility value \( d_j \) of the jth indicator. The larger the \( d_j \) is, the larger the indicator value will be, and the larger the weight will be.
Calculate the entropy weight $W_j$ of the $j$th indicator:

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, \text{ satisfy: } \sum_{j=1}^{n} W_j = 1$$  \tag{8}

where $x_{ij}$ and $U_{ij}$ are the value of the $j$th evaluation indicator in the $i$th evaluation unit and its standard value; $k$ is the accommodation coefficient, $k = 1/\ln m$; $m$ is the number of evaluation units.

### 4.3.2. Determination of weight of evaluation indicator

This article calculates the proportion $P_{ij}$ of each indicator with Formula 5 and then calculates the entropy value $e_j$ and utility value $d_j$ with Formula 6 & 7, as shown in Table 5. The smaller the entropy value is, the larger the data size of the indicator will be, and the larger the effect in the evaluation and the weight will be. Finally, the weight value of each indicator is calculated with Formula 8, as shown in Table 5.

$$d_j = 1 - e_j \quad \tag{7}$$
4.4. Risk evaluation for water inrush from coal seam floor

Before the multi-factor comprehensive analysis, the information overlay function of GIS technology was used to fuse and overlay each evaluation indicator thematic map to form an overlay layer containing all indicator information. Then, according to the evaluation model of water inrush risk of coal seam floor (Formula 9), the water inrush risk index of coal seam floor of each superimposed unit is calculated, and finally the water inrush risk assessment partition map is made (Figure 8).

\[
RI = \sum_{i=1}^{n} W_i \cdot f_i(x, y)
\]

where \(RI\) is the risk indicator; \(W_i\) is the weight of indicator; \(f_i(x, y)\) is the influence function of a single indicator; \(x\) & \(y\) are geographical coordinates; \(n\) is the number of indicators; \(f_i(x, y)\) is the standard value of the \(i\)th evaluation indicator.

It can be seen from Figure 8 that the risk of water inrush from the coal seam floor in the research area tends to be large in the south and small in the north. From the weight value of each evaluation indicator in Table 4, according to its influence on the risk of water inrush, the more important factors are the thickness of the aquifer under the mine pressure failure zone, water pressure, and the hard rock layer under...
the mine pressure failure zone, thickness, number of lithological assemblages, distribution of faults and folds. The red region represents the risky zone, which is mostly found in the southwest and southeast of the study area and fault distribution area. With deep development and strong water yield property of aquifer, the mineral pressure failure zone in the southwest is a complete failure area. In the southeast, with high-water pressure (4.29–4.42 Mpa), the number of layers of lithology combination of aquifuge is small, and the hard rock thickness under the mineral pressure failure zone is thin. The orange area is the danger zone which is located in the southwest and southeast of the research area and fault distribution area. In this area, the weak water-proof capacity of the aquifuge, high-water pressure (4.26–4.35 Mpa), and strong water yield properties of the aquifer can be observed. The green and light green areas

Table 5. Evaluation indicator weight.

| Evaluation indicator | ATMPFZ | HRTMPFZ | NLLCA | RQD | DRFC | AMR |
|----------------------|--------|---------|-------|-----|------|-----|
| Entropy value        | 0.8042 | 0.8363  | 0.8545 | 0.9361 | 0.9554 | 0.9431 |
| Utility value        | 0.1958 | 0.1637  | 0.1455 | 0.0639 | 0.0446 | 0.0569 |
| Weight value         | 0.1581 | 0.1322  | 0.1175 | 0.0516 | 0.0360 | 0.0459 |
| Evaluation indicator | FDGS   | SC      | HC    | KR  | GSD  | WPA |
| Entropy value        | 0.9560 | 0.9225  | 0.9276 | 0.9362 | 0.8729 | 0.8169 |
| Utility value        | 0.0440 | 0.0775  | 0.0724 | 0.0638 | 0.1271 | 0.1831 |
| Weight value         | 0.0355 | 0.0626  | 0.0585 | 0.0515 | 0.1026 | 0.1479 |

Figure 8. Partition map of risk evaluation for water inrush from coal seam floor.
are safe and slightly safe zone, located in the north and middle of the research area. In these zones, the strong water-proof capacity of aquifuge, low water pressure, and weak water yield property of aquifer can be observed. The yellow area is the dangerous transition zone between the dangerous zone and the slightly safe zone.

4.5. Verification of evaluation results

Introduction of risk fit percentage (RFP) to validate the accuracy of the assessment model. The geological drilling points are selected in the water inrush risk zone and safe zone to input into the model for fitting analysis. When $RFP$ is greater than 90%, the model meets related requirements; otherwise, the parameters need to be adjusted and refitted.

The concept of RFP is expressed as below:

$$RFP = \frac{DF}{DS} \times 100\%$$  \hspace{1cm} (10)

$DF$ is the number of fitting points where evaluation results are consistent with actual conditions; $DS$ is the total number of fitting points.

Figure 9. Distribution diagram of fitted geological drilling positions.
The geological drilling positions (zk5, zk7, zk12, zk19, zk22, zk25, and zk27) are selected in the dangerous and safe zone to recognize the water inrush risk (Figure 9). If the weak water-proof capacity of aquifuge, strong water yield property of aquifer, and concentrated geological structure exist, the water inrush disaster may occur easily; otherwise, there is a less possibility of water inrush disaster. If the aquifuge thickness at the drilling position zk5 is 18.60 m and lower than the development depth of the mineral pressure failure zone, it is a complete failure zone where a high degree of karst development, good water yield property, large water pressure of aquifer and high-water inrush risk can be observed. Similarly, the water inrush risk is recognized for the rest of the four drilling positions to obtain consistent evaluation results. Therefore, the model can meet the accuracy requirement.

5. Conclusions

1. According to the spatial distribution of coal seam depth, coal seam thickness and the number of layers of lithology combination of aquifuge, a depth partition calculation diagram of mineral pressure failure zone was made, and the numerical simulation calculations were carried out on the mining process of working face in different zones, the depth distribution law of mineral pressure failure zone was obtained. On this basis, the empirical formula was corrected according to the depth simulation value, and the correction calculation formulas for the depth of mineral pressure failure zone with different geological conditions were established, which makes up for the error caused by insufficient consideration of the influencing factors when directly using the empirical formula, effectively improving the accuracy of the calculation of the mine pressure failure, and can provide a certain basis for future research.

2. For the risk evaluation of water inrush, it is significant to accurately understand evaluation indicators of the water inrush from the coal seam floor. Due to the strong karst effect, hydrogeological conditions of mines in southwest China have significant regional characteristics. This article develops a comprehensive risk evaluation indicator system for water inrush from the karst aquifer in the coal seam floor in southwest China by determining 12 evaluation indicators from the viewpoint of an aquifer, aquifuge, and geological structure. This system can be a theoretical reference for risk evaluation indicators of water inrush from coal seam floors in similar karst areas.

3. This article selects a typical coal mine to determine risk evaluation indicators of water inrush and creates a comprehensive risk evaluation model for water inrush from the coal seam floor with the nonlinear mathematical method (i.e. entropy weight method). Compared to the subjective weighting method, the entropy weight method has a more objective process of determining weight. On this basis, this article processes evaluation indicators with GIS technology, plots a thematic map of evaluation indicators, implements superposition and evaluation grading for the thematic map, obtains the partition map of risk evaluation for water inrush from coal seam floor, and verifies the accuracy of evaluation results. The multi-source information evaluation technology for water inrush from coal seam
floor based on GIS and entropy weight method can comprehensively and objectively reflect that the water inrush is influenced by many factors and has a very complex formation mechanism. Besides, the intuitive evaluation results can provide a reference for the research of related fields to a certain extent.

4. The following steps need to be paid attention to in the risk assessment process of water inrush from the coal seam floor: The numerical simulation method to calculate the depth of the mineral pressure failure zone requires accurate and detailed geological exploration data. The selection of water inrush risk assessment indicators should conform to the geological conditions of the mining area, and the data of the indicators should be able to be quantified. The weight determination process needs to be objective, and the influence of human subjective factors on the weight should be minimized.

Disclosure statement
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Data availability statement
The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

References
Alipour M, Hafezi R, Rani P, Hafezi M, Mardani A. 2021. A new Pythagorean fuzzy-based decision-making method through entropy measure for fuel cell and hydrogen components supplier selection. Energy. 234:121208.
Bozau E, Licha T, Ließmann W. 2017. Hydrogeochemical characteristics of mine water in the Harz Mountains, Germany. Chemie Der Erde-Geochemistry. 77(4):614–624.
Chen LW, Feng XQ, Xie WP, Zeng W, Zheng ZY. 2017. Using a fluid-solid coupled numerical simulation to determine a suitable size for barrier pillars when mining shallow coal seams beneath an unconsolidated. Mine Water Environ. 36(1):67–77.
Ding Z, Liu Y, Wang LC, Chen YA, Yu PJ, Ma MG, Tang XG. 2021. Effects and implications of ecological restoration projects on ecosystem water use efficiency in the karst region of Southwest China. Ecol Eng. 170:106356.

Dong SN, Zheng LW, Tang SL, Shi PZ. 2020. A scientometric analysis of trends in coal mine water inrush prevention and control for the period 2000–2019. Mine Water Environ. 39(1): 3–12.

Feranie S, Fauzi U, Bijaksana S. 2011. 3D fractal dimension and flow properties in the pore structure of geological rocks. Fractals-Complex Geometry Patterns and Scaling in Nature and Society. 19(3):291–297.

Frumkin A, Zaidner Y, Na’aman I, Tsatskin A, Porat N, Vulfson L. 2015. Sagging and collapse sinkholes over hypogenic hydrothermal karst in a carbonate terrain. Geomorphology. 229: 45–57.

Greassidis S, Quoc VT, Bromme K, Stolpe H. 2020. Waterminer—a regional spatio-temporal approach to water reuse management in mining areas in Vietnam. J Water Reuse Desalin. 10(4):527–534.

Haftani M, Chehreh HA, Meinrad A, Binazadeh K. 2016. Practical investigations on use of weighted joint density to decrease the limitations of rqd measurements. Rock Mech Rock Eng. 49(4):1551–1558.

He KQ, Jia YY, Wang F, Lu YR. 2011. Overview of karst geo-environments and karst water resources in north and south China. Environ Earth Sci. 64(7):1865–1873.

Howladar MF. 2013. Coal mining impacts on water environs around the Barapukuria coal mining area, Dinajpur, Bangladesh. Environ Earth Sci. 70(1):215–226.

Hu YB, Li WP, Wang QQ, Liu SL, Wang ZK. 2019. Study on failure depth of coal seam floor in deep mining. Environ Earth Sci. 78(24):697.

Li B, Wu Q, Liu ZJ. 2020. Identification of mine water inrush source based on PCA-FDA: Xianedewang coal mine case. Geofluids. 2020:1–8.

Li B, Zhang HL, Luo YL, Liu L, Li T. 2022. Mine inflow prediction model based on unbiased Grey-Markov theory and its application. Earth Sci Inform. 15(2):855–862.

Li MK, Ni HJ, Wang G, Wang RH. 2017. Simulation of thermal stress effects in submerged continuous water jets on the optimal standoff distance during rock breaking. Powder Technol. 320:445–456.

Li Q, Sui WH. 2021. Risk evaluation of mine-water inrush based on principal component logistic regression analysis and an improved analytic hierarchy process. Hydrogeol J. 29(3): 1299–1311.

Li T, Mei TT, Sun XH, Lv YG, Sheng JQ, Cai M. 2013. A study on a water-inrush incident at Laohutai coalmine. Int J Rock Mech Min Sci. 59:151–159.

Li YH, Bai JB, Yan W, Wang XY, Wu BW, Liu SG, Xu J, Sun JX. 2021. Risk early warning evaluation of coal mine water inrush based on complex network and its application. Adv Civ Eng. 2021:9980948.

Lin G, Dong DL, Li X, Fan PW. 2020. Accounting for mine water in coal mining activities and its spatial characteristics in China. Mine Water Environ. 39(1):150–156.

Liu W, Dincer H, Eti S, Yuksel S. 2021. Gaussian-based hybrid approach to entropy for analyzing energy efficiency of emerging economies. Energy Reports. 7:2501–2511.

Liu XL, Wang SY. 2012. Mine water inrush forecasting during the mining under waters. Disaster Advances. 5(4):876–881. [Mismatch ]

Ma D, Duan HY, Zhang JX, Liu XW, Li ZH. 2022. Numerical simulation of water-silt inrush hazard of fault rock: a three-phase flow model. Rock Mech Rock Eng. 55(8):5163–5182.

National Coal Mine Safety Supervision Bureau. 2018. Rules for coal water prevention and control. Beijing: China Coal Industry Publishing House.

Newman C, Agioutantis Z, Leon GBJ. 2017. Assessment of potential impacts to surface and subsurface water bodies due to longwall mining. International Journal of Mining Science and Technology. 27(1):57–64.

Qiao W, Li WP, Zhang X, Niu YF, Chen YK, Wang YZ, Xing T. 2019. Prediction of floor water disasters based on fractal analysis of geologic structure and vulnerability index method
for deep coal mining in the Yanzhou mining area. Geomatics Natural Hazards & Risk. 10(1):1306–1326.

Rui G, Hao Y, Feng J, Mei XC, Wang XL. 2018. Influential factors and control of water inrush in a coal seam as the main aquifer. Int J Min Sci Technol. 28(2):187–193.

Santos CF, Bieniawski ZT. 1989. Floor design in underground coal mines. Rock Mech Rock Engng. 22(4):249–271.

Shi LQ, Qu XY, Yu XG, Li Y, Pei FH, Qiu M, Gao WF. 2020. Theory and practice on the division of the "water pressure-free zone" in a mining coal seam floor. Arab J Geosci. 13(20):1079.

Sovacool BK, Cooper C, Parenteau P. 2011. From a hard place to a rock: questioning the energy security of a coal-based economy. Energy Policy. 39(8):4664–4670.

Wang N, Wen ZG, Liu MQ, Guo J. 2016. Constructing an energy efficiency benchmarking system for coal production. Applied Energy. 169:301–308.

Wang Y, Yang WF, Li M, Liu X. 2012. Risk assessment of floor water inrush in coal mines based on secondary fuzzy comprehensive evaluation. Int J Rock Mech Min Sci. 52:50–55.

Wu JH, Yu JC, Wang ZF, Fu XH, Su WW. 2018. Experimental investigation on spontaneous imbibition of water in coal: Implications for methane desorption and diffusion. Fuel. 231:427–437.

Wu JS, Xu SD, Zhou R, Qin YP. 2016. Scenario analysis of mine water inrush hazard using Bayesian networks. Safety Science. 89:231–239.

Wu Q, Liu YZ, Zhou WF, Li BY, Zhao B, Liu SQ, Sun WJ, Zeng YF. 2015. Evaluation of water inrush vulnerability from aquifers overlying coal seams in the Menkeqing Coal Mine, China. Mine Water Environ. 34(3):258–269.

Yang J, Luo Y. 2021. Enhanced subsurface subsidence prediction model incorporating key Strata theory. Min Metall Explor. 38(2):995–1008.

Yang QY, Zhang FW, Jiang ZC, Yuan DX, Jiang YJ. 2016. Assessment of water resource carrying capacity in Karst area of Southwest China. Environ Earth Sci. 75(1):37.

Zeng YF, Wu Q, Liu SQ, Zhai YL, Lian HQ, Zhang W. 2018. Evaluation of a coal seam roof water inrush: case study in the Wangjialing coal mine, China. Mine Water Environ. 37(1):174–184.

Zhang GZ, Guo JZ, Xu B, Xu LL, Dai ZX, Yin SX, Soltanian MR. 2021. Quantitative analysis and evaluation of coal mine geological structures based on fractal theory. Energies. 14(7):1925.

Zhang YG, Yang LN. 2021. A novel dynamic predictive method of water inrush from coal floor based on gated recurrent unit model. Nat Hazards. 105(2):2027–2043.

Zhou Y, Xing XP, Fang KN, Liang DP, Xu CL. 2013. Environmental efficiency analysis of power industry in China based on an entropy SBM model. Energy Policy. 57:68–75.