A Multifactor Quantitative Assessment Model for Safe Mining after Roof Drainage in the Liangshuijing Coal Mine

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ABSTRACT: To prevent coal mine roof water damage, the water generally needs to be evacuated in advance. It can be mined with the water inrush risk assessed as safe. However, a single index is often employed in the water safety evaluation after the roof drainage, which causes a large gap between the evaluation results and the actual situation. Therefore, the evaluation cannot be effectively used to guide the safety mining in the working face. In this paper, based on the hydrogeological data of the Liangshuijing coal mine, a multifactor water inrush risk assessment model (IAHP-EWM) and multifactor index system are established for assessing the water inrush risk before and after the roof drainage. The improved AHP method and the entropy weight method are adopted in the model to determine the index weight. This combined way avoids the excessive subjectivity and objectivity of the index weight. A fold undulation degree (Fud) is innovatively proposed to quantify the impact of the spatial relief of folds on water inrush in the multifactor index system. The IAHP-EWM model is applied to evaluate the risk of roof water inrush in the 42205 working face of the Liangshuijing coal mine. The evaluation results show that the water inrush risk is "high" when the water is not dredged, and the water inrush risk is "low" after the water is dredged, which are consistent with the actual water inflow data and evaluation results, which verifies the accuracy of the model. The application results of the IAHP-EWM model in the 42202, 42203, and 42204 working faces verify its universal applicability in the Liangshuijing mining area. It can provide a reference for the evaluation of the roof water damage control effect during coal seam mining.

1. INTRODUCTION

The Jurassic coalfield in northern Shaanxi, China is one of the 1.4-billion-ton coal bases in China. It has the advantages of high coal resource enrichment, best coal quality, and good development prospects. With the increase of the development scale and mining intensity of the Jurassic coalfield, the water inrush accidents from the working face roofs become more and more serious. For a long time, people have had insufficient understanding of the severity of roof water damage during the development of the Jurassic coalfield. In addition, the focus of the previous mine-water-control research has been on North China coalfields threatened by floor ash water, resulting in a weak research foundation for roof water hazards in the Jurassic coalfield. The reason for the formation of the water damage from the roof is still unclear, leading to a lack of effective prediction, prevention technology, etc. Therefore, it is of great practical significance to study the risk of water inrush in the roof aquifer and make an accurate evaluation and then propose effective water prevention measures for guiding the safe production of the coal mine.

Many types of roof water disasters are recognized in Jurassic coalfields, such as separated strata water disasters, water inrush, and sand inrush, roof thick sandstone water disasters, burning rock water disasters, etc. The mechanisms for roof water inrush are different case to case. One main mechanism for the water inrush is the roof failure after coal seam mining, which is thoroughly explored by scholars. The major research method is conducting a similar model test. However, the experimental conditions are way different from the actual conditions in the mine, which makes the results less convincing. What is more, the geological conditions, hydrogeological conditions, lithology, and mining conditions are different from one mining area to another mining area, the research results cannot be widely applied, and the existing conclusions are not suitable for the Liangshuijing coal mine. Therefore, the formation of the water damage from the roof is still unclear, leading to a lack of effective prediction and prevention technology.

In terms of risk prediction of the water inrush in working faces in coal mines, the ‘three maps and two predictions method’ and the ‘water-richness index method’ are commonly used for the evaluation of the risk of roof water inrush. For the evaluation of the risk of water inrush from the floor, a vulnerable index method is often used. On this basis, Chinese scholars have proposed a large number of evaluation...
methods and established corresponding engineering geological models and hydrogeological models to assess the risk of water inrush before the drainage. However, in some cases, water inrush occurred after the drainage. To our best knowledge, few studies on the multifactor evaluation of the risk of water inrush from the roof after drainage have been conducted. The research in this paper aims to fill this research gap.

The evaluation of water inrush risk after roof drainage is mainly based on a single factor (drilling site flow attenuation curve) during practical production. The evaluation results are inconsistent with the actual situations of the mining areas. The following problems exist: (1) There is a lack of clear quantitative evaluation thresholds, resulting in serious water inrush accidents even with an evaluation result marked as "low". For example, in September 2020, a single index evaluation system was used in the 1012001 working face of the Yuanzigou coal mine. Serious roof inrush occurred during mining even with the evaluation result of the risk of roof water inrush as "safe". The maximum water inflow amounted to 570 m³/h, submerging the working face of the well and roadway. In October 2020, a roof water inrush accident occurred during mining after the 1309 working face of the Guojiahe coal mine used a single index to evaluate the risk of roof water inrush as "safe". Three water inrush phenomena occurred in this working face. The maximum instantaneous water inrush volumes are 200, 1200, are 500 m³/h, resulting in the shutdown of the working face. (2) There is no clear definition of the state of the flow attenuation curve of the drilling site where the working face can be safely recovered, and it mainly depends on the subjective experience of water prevention and control staffs. (3) The roof water inrush is the result of the combined results of a variety of complex factors such as water inrush sources, water inrush channels, mining, etc. A single index cannot reflect the combined results of multiple factors. Therefore, the multifactor evaluation model for assessing the risk of water inrush at the working face after roof water evacuation is established, which has important guiding significance for guiding the production of the mining areas.

Based on the geological and hydrogeological conditions of the Liangshuijing coal mine, a roof water inrush risk assessment index system before and after drainage is proposed and established in this paper. A "Fold undulation degree (F)" index is included in the system to quantify the impact of the fold spatial relief on water inrush. Based on GIS, improved analytic hierarchy process theory, entropy weight method, and fuzzy mathematics method, a mathematical model of roof water inrush risk assessment is established. The 42202, 42203, and 42204 working faces of the Liangshuijing coal mine are employed to verify the practicability and generality of the model.

2. STUDY AREA

The Liangshuijing coal mine is located about 16 km west of Shenmu County, Shaanxi Province, with a mining area of 68.9 km². The mine has an approved production capacity of 8 million tons/a and service life of 46.8 years. It is mined with longwall fully mechanized mining. The mining area is in the northwest inland with a temperate semi-arid continental climate. The average annual precipitation is 435.7 mm, the average annual evaporation is 1774.1 mm, and the coal seam mining elevation is 1120–1080 m. Coal 4−2 is the main mining seam in the mining area. The coal seam is shallowly buried with a burial depth of 13.45–160.92 m. It is located at the top of the second section of the Jurassic Yan'an Formation. The geographic location of the mining area is shown in Figure 1.

The strata of the mining area from old to new are Upper Triassic Yongping Formation (T₃y), Middle Jurassic Yan'an Formation (J₂y), Zhiluo Formation (J₁z), Neogene Pliocene Baode Formation (N₃b), Quaternary Middle Pleistocene Lishi Formation (Q₃l), Upper Pleistocene Salawusu Formation (Q₃s), and Holocene Aeolian Sand (Q₄s). The mine geological structure is simple, the stratum is gentle, and the dip angle is less than 1°. Only the wavy undulating anticline structure with an extremely wide amplitude is developed, and there is no large fold, fault, and magmatic activity. The bedrock of the coal seam 4−2 roof is thin, and the weathered bedrock develops on the top of the bedrock. The aquifer in the study area is the weathered bedrock aquifer of Yan'an Formation (J₂y) and the Quaternary phreatic aquifer (Q₄eol). The weathered bedrock aquifer is highly water-rich and is the main aquifer in the mining area.
The weathered bedrock fissure water is the main factor affecting the safe production of the mine. This paper uses the 42205 working face as an example to establish a roof water inrush risk assessment model before and after drainage. In the 42205 working face, 66 water exploration and drainage holes were constructed to drain the water in the aquifer. All the holes penetrated the weathered bedrock fissure aquifer, and the final hole was within 1 m of the laterite layer. The lithological columnar shape of the working face and the borehole profile are shown in Figure 2.

### 3. METHODS

Coal seam roof water inrush is affected by a variety of complex factors. These factors have the characteristics of uncertainty, randomness, and ambiguity, which are difficult to be evaluated with classical mathematical models. Therefore, based on GIS, this paper constructs the membership degree of each assessment factor using fuzzy mathematical theory, determines the weight of influencing factors by coupling the improved analytic hierarchy process and the entropy weight method, and establishes a GIS-based multifactor coal seam roof water inrush risk assessment model (IAHP-EWM). The steps are as follows:

**Step 1:** Determine the set of assessment factors and comments.

The assessment factor set is a set composed of various factors that affect the assessment object. It is \( U = \{ u_1, u_2, ..., u_n \} \). \( U \) is the assessment factor set; \( u_1, u_2, ..., u_n \) are the various factors.

The comment set is a set composed of possible results from assessment objects and assessment indicators. It is \( V = \{ v_1, v_2, v_3, ..., v_n \} \). \( V \) is the comment set; \( v_1, v_2, v_3, ..., v_n \) are the assessment levels of assessment factors and are generally divided into 3−5 levels.

**Step 2:** GIS-based single factor fuzzy assessment and construction of assessment matrix.

First, a single-factor assessment for the single-factor \( U_i \) \((i = 1, 2, 3, ..., n)\) in the assessment factor set was made. The membership degree of the factor \( U_i \) to the assessment level \( V_j \) is \( R_{ij} \), and the single factor assessment set of the \( i \)th factor \( U_i \) can be obtained as \( R_i = (R_{i1}, R_{i2}, ..., R_{in}) \). In this paper, the ArcGIS system is used to determine the membership degree of the assessment factors: Kriging space interpolation, grid calculator, and other tools are used to quantify the assessment factors to generate a dimensionless thematic map, and then the membership degree is determined by classifying the area element. The specific details are as follows:

a. Dimensionless of the thematic map.

To eliminate the conflict between different dimensions of the assessment indicators, eqs 1 and 2 are used to process the indicators with dimensionless. If the indicator has a positive correlation with the object to be evaluated, it is a benefit-type indicator, and eq 1 is used for dimensionless processing; otherwise, if the indicator has a negative correlation with the object to be evaluated, it is a cost-type indicator, and eq 2 is used for processing.

\[
\begin{align*}
    r_{ij} &= \frac{a_{ij} - \min(a_{ij})}{\max(a_{ij}) - \min(a_{ij})} \\
    r_{ij} &= \frac{\max(a_{ij}) - a_{ij}}{\max(a_{ij}) - \min(a_{ij})}
\end{align*}
\]

In the above equations, \( a_{ij} \) is the attribute value of the assessment factor, and \( r_{ij} \) is the data after dimensionless processing.
b. Determine the membership degree of assessment factors.

The assessment factor map is partitioned by the natural discontinuous point method in ArcGIS, and the partitioning principle is shown in eq 3.\

\[ SSD_{i-j} = \sum_{k=1}^{i} (A[K] - \text{mean}_{i-j})^2 \] (3)

In eq 3, SSD_{i-j} is the sum of squares of total deviation; i_{ij} is the classification serial number; A[K] is the value set of a classification; K = h, ..., j; \text{mean}_{i-j} is the average value of classification. The membership degree of the assessment factors is determined by the method of classifying the area element.

\[ r_j(x) = \frac{S_j}{S} \] (4)

In the above, \( r_j(x) \) is the membership degree of \( v_j \) and \( S_j \) is the area of the \( j \)th classification area of the \( j \)th assessment index thematic map. Finally, the membership degrees of each assessment factor are arranged in rows to form an assessment matrix, and the assessment matrix can be stated as

\[ R = \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1n} \\
    r_{21} & r_{22} & \cdots & r_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix} \] (5)

Within the above matrix, \( n \) is the number of comment sets, and \( m \) is the number of assessment indicators.

Step3: Determine the weight vector of factors.

Weight is a value measuring the importance of assessment index factors. In this paper, the improved analytic hierarchy process and the entropy weight assessment index factors. In this paper, the improved AHP calculation; \( n \) is the order of the judgment matrix (the number of assessment indexes); \( \lambda_{\text{max}} \) is the maximum eigenvalue.

b. Calculate the objective weight of assessment factors with the entropy weight method.

In Information Theory, entropy is a measure of the uncertainty of random variables, which can be used to measure the amount of information contained in the data itself and the degree of dispersion of the data. The more discrete the data, the smaller the information entropy, the greater the information deviation, the greater the amount of information contained, and the greater the impact on the output results. Therefore, the corresponding weight is greater, and vice versa. In the above, \( u_i \) is the weight of the improved AHP calculation; \( n \) is the order of the judgment matrix (the number of assessment indexes); \( \lambda_{\text{max}} \) is the maximum eigenvalue.

The calculation equation of information entropy:

\[ E_j = -\frac{1}{\ln(n)} \sum_{i=1}^{n} U_{ij} \ln(U_{ij}) \] (11)

In the above, \( U_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}, x_{ij} \) is the value of the \( j \)th factor in the \( i \)th group of data, where \( i = 1, 2, ..., n; j = 1, 2, ..., p \).

The calculation equation of the weight \( w_j \) based on the information entropy:

\[ w_j = \begin{cases} \frac{S(i) - S(j)}{S_{\text{max}} - S_{\text{min}}}(b_m - 1) + 1, S(i) \geq S(j) \\ 1 - \frac{S(j) - S(i)}{S_{\text{max}} - S_{\text{min}}}(b_m - 1) + 1, S(i) < S(j) \end{cases} \] (6)
The Water abundance of unconfined aquifer $u_1$
The water head of unconfined aquifer $u_2$
Unconfined aquifer thickness $u_3$
The permeability of unconfined aquifer $u_4$
The Water abundance of weathered bedrock aquifer $u_5$
The water head of weathered bedrock aquifer $u_6$
Weathered bedrock aquifer thickness $u_7$
The permeability of weathered bedrock aquifer $u_8$
Relief degree of land surface (Valley area) $u_9$
Fold undulation degree $u_{10}$
Height of fractured water-conducting zone $u_{11}$
Aquifer thickness (The laterite of BaoDe formation) $u_{12}$
Aquifer thickness (bedrock) $u_{13}$
Burial depth of coal seam $u_{14}$
Coal seam thickness $u_{15}$

Figure 3. Assessment index system of water inrush risk of undrained water.

$$w_j = \frac{1 - E_j}{\sum_{i=1}^{p} (1 - E_i)} \quad (12)$$

$1 - E_j$ describes the information deviation degree of the $j$th factor. The larger the value, the higher the information content of the factor.

c. Determine the comprehensive weight of assessment indexes.

The subjective and objective weights of the assessment factors were brought into eq 15 to obtain the comprehensive weight of the assessment factors:

$$Z_i = \sum_{i=1}^{m} w_i \cdot u_i \quad (13)$$

In eq 13, $Z_i$ is the comprehensive weight of the assessment factor, $u_i$ is the subjective weights of the assessment factor, and $w_i$ is the objective weight of the assessment factor.

Step 4: Establishment of the IAHP-EWM roof water inrush risk assessment model.

Based on the assessment factor matrix and weight vector, a water inrush risk assessment model of working face is established:

$$B = A \times R \quad (14)$$

$$(b_1, b_2, ..., b_n) = (Z_1, Z_2, ..., Z_m) \times \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (15)$$

4. ESTABLISHMENT OF THE ROOF WATER INRUSH RISK ASSESSMENT INDEX SYSTEM

This paper uses the multifactor and multi-index comprehensive assessment method. The main influencing factors of roof water inrush before and after drainage are determined through systematic analysis of the geological conditions and field measured data in Liangshuijing mining area, and the assessment index system of roof water inrush risk before and after drainage is established.

4.1. Assessment Index System of Water Inrush Risk Before Drainage.

When the coal seam roof is not drained, roof water inrush is affected by the combined effect of the water inrush source, water inrush channel, and mining. Therefore, considering these three factors, an assessment index system for the risk of water inrush before roof drainage is established, which includes 15 assessment indicators. Figure 3 shows the assessment index system of water inrush risk of undrained water.

The factors in the system are as follows:

- Water abundance of the aquifer ($u_1, u_4$): The stronger the water abundance of the aquifer, the higher the risk of water inrush from the roof during coal mining is.
- Aquifer thickness: A high aquifer thickness can reduce the risk of water inrush.
- Relief degree of land surface: A high relief degree can reduce the risk of water inrush.
- Fold undulation degree: A high fold undulation degree can increase the risk of water inrush.
- Height of fractured water-conducting zone: A high height can increase the risk of water inrush.
- Aquifer thickness (The laterite of BaoDe formation): A high aquifer thickness can reduce the risk of water inrush.
- Aquifer thickness (bedrock): A low aquifer thickness can increase the risk of water inrush.
- Burial depth of coal seam: A deep burial depth can reduce the risk of water inrush.
- Coal seam thickness: A thick coal seam can reduce the risk of water inrush.

The risk level of the evaluated object is determined according to the principle of maximum membership degree, which can be stated as follows: if $A_i \in F(U)$ ($i = 1, 2, ..., n$) is defined, and $u_0 \in U$, and $i_0$ exists, then

$$A_i(u_0) = \max\{A_i(u_0), A_2(u_0), ..., A_n(u_0)\} \quad (16)$$

$A_i(u_0)$ is the membership degree value.
aquifers are considered. In this paper, the unit water inflow data ($q$) of boreholes are used to quantify the water abundance of aquifers.

The water head of the aquifer ($u_{22}$, $u_{23}$): The water head of the aquifer reflects the water-rich degree of the aquifer. The higher the water head in the aquifer, the higher the risk of water inflow from the roof is.

The permeability of the aquifer ($u_{23}$, $u_{24}$): The permeability coefficient represents the ability of the aquifer to transfer water. The larger the coefficient, the larger the water permeability of the aquifer, and the higher the risk of water inflow from the roof is.

Aquifer thickness ($u_{20}$, $u_{21}$): The aquifer is the source of roof water inflush. The thicker the aquifer, the greater the water content per unit thickness of the aquifer, and the higher the risk of roof water inflush.

Relief degree of land surface (gully area) ($u_{25}$): The surface relief in the Liangshuijing mining area is relatively large, and there are valley areas in some sections. The valley area is a surface catchment area with strong water richness. When the mining fissure zone spreads to the surface, the water inflush threat to the working face is greater.

Fold undulation degree ($u_{26}$): When predecessors established the roof water inflush index system, the influence of fold undulation degree on water inflush was not considered. In the actual mining process, the water inflow of the working faces is greatly affected by the fluctuation degree of folds. Figure 4 shows the water inflow corresponding to fold relief. It can be seen from Figure 4 that the variation degree of water inflow in the working face is basically the same as the fluctuation state of the fold. When the working face is recovered to the anticline position, the water inflow of the working face decreases. In the inclined position, the water inflow of the working face increases. The variation of water inflow of the working face is controlled by the degree of fold fluctuation. Therefore, when evaluating the risk of roof water inflush in the working face, the fluctuation degree of folds should be taken into account. Based on the concept of "surface relief" in surveying, "Fold undulation degree ($F_{ud}$)" to quantify the relief shape of folds is proposed in this paper. The calculation equation is: \[ F_{ud} = H - H_{\text{min}} \] (17)

In eq 17, $F_{ud}$ represents the fold fluctuation degree, $H$ represents the elevation value of the bottom surface of the aquifer, and $H_{\text{min}}$ represents the minimum elevation value of the bottom surface of the aquifer.

Height of the fractured water-conducting zone ($u_{13}$): The higher the height of the fractured water-conducting zone is developed during coal mining, the more aquifers penetrate, and the greater the risk of water inflush.\n
Aquifuge thickness ($u_{15}$): The aquifuge has the function of blocking the hydraulic connection between the aquifer and the coal seam and preventing the development of cracks. The thicker the aquifuge thickness, the lower the risk of roof water inflush during coal mining.

Burial depth of coal seam ($u_{14}$): The deeper the coal seam is buried, the more obvious the roof rock pressure is during coal seam mining, and the easier it is to cause water inflush accidents.

Coal seam thickness ($u_{11}$): The greater the mining thickness of the coal seam, the stronger the disturbance to the overlying rock, the more serious the deformation and damage of the roof overlying rock, and the greater the risk of water inflush from the roof of the coal seam.

4.2. Assessment Index System of Water Inrush Risk after Drainage. Taking into account the influences of water inflush water source, water inflush channel, and drainage effect, an assessment index system of water inflush risk after drainage is established, which includes 13 assessment factors, as shown in Figure 5.

The factors in the system are as follows:

Aquifer head ($u_{1}′$, $u_{2}′$): The water head value of the aquifer indirectly reflects the water abundance of the aquifer. The higher the water head value after the aquifer is drained, the greater the risk of water inflush during coal mining.

Aquifer head attenuation degree ($u_{2}′$, $u_{4}′$): The water level attenuation rate of the aquifer reflects the degree of influence of the drilling drainage water on the aquifer. The higher the water level attenuation rate of the aquifer, the better the drainage effect is. The less the remaining water in the aquifer, the lower the risk of water inflush from the roof.

The initial water inflow of the borehole ($u_{1}′$): The initial water inflow of the borehole reflects the water abundance of the aquifer. The larger the initial water inflow of the borehole, the better the water abundance of the aquifer and the greater the risk of water inflush from the roof.

The water inflow of the borehole ($u_{1}′$): Borehole water inflow reflects the water abundance of the aquifer after the water is drained. The larger the borehole water inflow, the better the water abundance of the aquifer and the greater the risk of water inflush.

Attenuation rate of borehole water inflow ($u_{1}′$): The attenuation rate of borehole water inflow reflects the drainage effect of water-draining boreholes. The greater the attenuation rate of the water inflow from the borehole, the better the drainage effect of the borehole, and the lower the risk of water inflush from the roof.

Figure 4. Schematic diagram of water inflow corresponding to fold relief; when the working face is recovered to the fold anticline, the water inflow of the working face decreases, and when the working face is recovered to the fold syncline, the water inflow of the working face increases.
The volume of water drainage ($u_{13}'$): Draining water volume reflects the effect of drilling drainage. The larger the drainage water volume, the better the drilling drainage effect. The lower the water storage capacity in the aquifer, the lower the risk of water inrush.

The assessment factors of relief degree of land surface (gully area) ($u_{5}'$), fold undulation degree ($u_{6}'$), height of the fractured water-conducting zone ($u_{7}'$), and aquifuge thickness ($u_{9}'$) are the same as those in Section 3.1, and repeated analysis will not be performed.

Through the analysis of the geological and hydrogeological data of the Liangshuijing coal mine, the assessment index suitable for the assessment of the water inrush risk of the roof of the 42205 working face is selected from the above index system. When the 42205 working face is not drained, the index set of the assessment index system is $U_1 = \{\text{the water abundance of weathered bedrock aquifer} (u_5'), \text{the water head of weathered bedrock aquifer} (u_6'), \text{the permeability of weathered bedrock aquifer} (u_8'), \text{fold undulation degree} (u_{10}'), \text{height of the fractured water-conducting zone} (u_{11}'), \text{aquifuge thickness} (u_{12}'), \text{buried depth of coal seam} (u_{14}), \text{coal seam thickness} (u_{15}), \text{water head of the aquifer} (u_{13}')\}$.

### 5. RESULTS AND DISCUSSION

#### 5.1. Establishing a Single-Factor Assessment Matrix Based on GIS

According to previous studies, the
roof water inrush risk level is divided into 5 levels. The water inrush risk comment set is \( V = \{ \text{higher, high, medium, lower, low} \} \). According to the drainage data of 17 exploration boreholes in the mining area and 66 boreholes in the 42205 working face, the assessment factors are collected and normalized through GIS, and a thematic map of assessment indicators is established. The membership of evaluation indicators can be determined from the thematic maps. Exploration drilling data is shown in Table 1. The drainage drilling data is shown in Table 5.

The water abundance of weathered bedrock aquifer \( (u_6) \), the water head of weathered bedrock aquifer \( (u_6) \), weathered bedrock aquifer thickness \( (\Delta u_4) \), the permeability of weathered bedrock aquifer \( (u_6) \), fold undulation degree \( (u_{10}) \), height of the fractured water-conducting zone \( (u_{11}) \), buried depth of coal seam \( (u_{13}) \), coal seam thickness \( (u_{13}) \), the water head of weathered bedrock aquifer \( (u_1) \), fold undulation degree \( (u_1) \), height of the fractured water-conducting zone \( (u_1) \), the initial water inflow of the borehole \( (u_{10}) \), and the water inflow of the borehole \( (u_{14}) \) are the benefit-type indicators, and eq 1 is used to normalize the assessment factors. The attenuation rate of the borehole water inflow \( (u_{14}) \), and the volume of water drainage \( (u_{15}) \), aquifer thickness \( (u_{13}, u_6) \), the attenuation rate of water head \( (u_1) \), the attenuation rate of the borehole water inflow \( (u_{14}) \), and the volume of water drainage \( (u_{15}) \) belong to the cost-type indicators, and eq 2 is used to normalize the assessment factors. Figures 6 and 7 show the dimensionless thematic maps of assessment factors before and after drainage through ArcGIS. The thematic map of assessment factors is divided into five areas by the natural discontinuity method: \( \{S_1, S_2, S_3, S_4, S_5\} \), the membership degree of the assessment factors is determined by eq 4, and the assessment matrix is formed by determining the membership degree of each factor. \( R_2 \) is the judging matrix of the 42205 working face before drainage, and \( R_3 \) is the judging matrix of the 42205 working face after drainage.

\[
R_2 = \begin{bmatrix}
0.2227 & 0.2891 & 0.2328 & 0.2055 & 0.0499 \\
0.1392 & 0.1675 & 0.1941 & 0.1899 & 0.3093 \\
0.168 & 0.138 & 0.1231 & 0.1004 & 0.4705 \\
0.0766 & 0.2821 & 0.2151 & 0.1843 & 0.2419 \\
0.1168 & 0.1379 & 0.1543 & 0.1568 & 0.4342 \\
0.2202 & 0.2227 & 0.2051 & 0.1892 & 0.1628 \\
0.1958 & 0.1937 & 0.1816 & 0.1886 & 0.2403 \\
0.1195 & 0.1391 & 0.1531 & 0.1541 & 0.4342 \\
0.3171 & 0.2813 & 0.1096 & 0.1181 & 0.1739 \\
0.1436 & 0.1609 & 0.2213 & 0.3562 & 0.1191 \\
0.0642 & 0.2582 & 0.1878 & 0.2723 & 0.2175 \\
0.0766 & 0.2821 & 0.2151 & 0.1843 & 0.2419 \\
0.1168 & 0.1379 & 0.1543 & 0.1568 & 0.4342 \\
0.2202 & 0.2227 & 0.2051 & 0.1892 & 0.1628 \\
0.1924 & 0.2139 & 0.2105 & 0.1353 & 0.2479 \\
0.0809 & 0.1237 & 0.2183 & 0.3721 & 0.205 \\
0.3739 & 0.2052 & 0.1176 & 0.1905 & 0.1128 \\
0.005 & 0.055 & 0.2433 & 0.2954 & 0.4013 \\
\end{bmatrix}
\]

\[
R_3 = \begin{bmatrix}
0.2227 & 0.2891 & 0.2328 & 0.2055 & 0.0499 \\
0.1392 & 0.1675 & 0.1941 & 0.1899 & 0.3093 \\
0.168 & 0.138 & 0.1231 & 0.1004 & 0.4705 \\
0.0766 & 0.2821 & 0.2151 & 0.1843 & 0.2419 \\
0.1168 & 0.1379 & 0.1543 & 0.1568 & 0.4342 \\
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0.0642 & 0.2582 & 0.1878 & 0.2723 & 0.2175 \\
0.0766 & 0.2821 & 0.2151 & 0.1843 & 0.2419 \\
0.1168 & 0.1379 & 0.1543 & 0.1568 & 0.4342 \\
0.2202 & 0.2227 & 0.2051 & 0.1892 & 0.1628 \\
0.1924 & 0.2139 & 0.2105 & 0.1353 & 0.2479 \\
0.0809 & 0.1237 & 0.2183 & 0.3721 & 0.205 \\
0.3739 & 0.2052 & 0.1176 & 0.1905 & 0.1128 \\
0.005 & 0.055 & 0.2433 & 0.2954 & 0.4013 \\
\end{bmatrix}
\]

5.2. Assessment Factor Weight Vector Set. 5.2.1. Weight Vector before Drainage. Table 2 shows the standard deviation of assessment factors before drainage. The subjective weights of assessment factors before drainage are obtained by substituting standard deviation data of assessment factors into eqs 1, 2, 9, and 10. Table 1 shows the attribute value of assessment factors before drainage. The objective weights of assessment factors before drainage are calculated by substituting the attribute values of evaluation factors into eqs 11 and 14. The comprehensive weights of assessment factors before drainage are obtained by substituting subjective weights and objective weights into eq 11, and Table 3 shows the weight calculation results of each assessment factors. From Table 3, the assessment weight vector \( A_1 \) can be obtained before drainage.

\[
A_1 = (0.3684, 0.4174, 0.0226, 0.0213, 0.0116, 0.0373, 0.0045, 0.0160, 0.1005) \]

5.2.2. Weight Vector after Drainage. Table 4 shows standard deviation of assessment factors after drainage. The subjective weights of assessment factors after drainage are obtained by substituting standard deviation data of assessment factors into eqs 1, 2, 9, and 10. Tables 5 and 6 show the attribute value of assessment factors after drainage. The objective weights of assessment factors after drainage are calculated by substituting the attribute values of evaluation factors into eq 11 and 14. The comprehensive weights of assessment factors after drainage are obtained by substituting subjective weights and objective weights into eq 11, and Table 7 shows the weight calculation results of each assessment factors. From Table 7, the weight vector \( A_2 \) of each factor after the drainage can be determined.

\[
A_2 = (0.1335, 0.0101, 0.0067, 0.0013, 0.0209, 0.0282, 0.3958, 0.0149, 0.1335)
\]

5.3. Water Inrush Risk Assessment before and after the Drainage in the 42205 Working Face. 5.3.1. Risk Assessment of Water Inrush before Drainage. Based on the pre-drainage assessment factor assessment membership matrix and assessment factor weight vector obtained in Sections 4.1 and 4.2, the water inrush risk assessment model for the 42205 working face before drainage is established as follows:

\[
B_1 = A_1 \times R_2
\]
After calculation, $B_1 = A_1 \times R_1 = (0.1898, 0.2269, 0.1979, 0.1852, 0.2000)$. According to the maximum membership criterion to determine the water inrush risk level of the working face, 0.2269 is “high” in the corresponding comment set; thus, the roof water inrush risk assessment level before water discharge is high.

5.3.2. Risk Assessment of Water Inrush after Drainage.

Based on the pre-evacuation assessment factor assessment matrix and assessment factor weight vector obtained in Sections 4.1 and 4.2.2, the water inrush risk assessment model for the 42205 working face after water evacuation is established as follows:

$$B_2 = A_2 \times R_3$$

(20)

In eq 20, $B_2$ is the assessment vector of the risk of water inrush before the drainage of the working face, $A_2$ is the weight vector of the assessment factors before the drainage, and $R_3$ is the assessment membership matrix of the assessment factors after the drainage:

$$B_2 = (0.1178, 0.1507, 0.2176, 0.2836, 0.2303) \quad (21)$$

After calculation, $B_2 = A_2 \times R_3 = (0.1178, 0.1507, 0.2176, 0.2836, 0.2303)$. The water inrush risk level of the working face is determined according to the maximum...
0.2836 is “low” in the corresponding comment set; therefore, the roof water inrush risk assessment level is low after the drainage.

5.4. Verification of Assessment Results. Geophysical detection results are often used to determine the dangerous area for the occurrence of roof water inrush in the Liangshuijing mining area, and the water inrush risk of the working face is determined by the proportion of the dangerous area. Figure 8 shows the regional distribution of geophysical dangerous areas in the aquifer. The geophysical prospecting staff delineated the

Figure 7. Dimensionless thematic map after drainage of 42205 working face (calculation of the area ratio of classified areas to determine membership degree of each factor): (a) water head of the weathered bedrock aquifer, (b) attenuation rate of the water table (weathered bedrock aquifer), (c) fold undulation degree, (d) height of the fractured water-conducting zone, (e) aquifuge thickness, (f) initial water inflow of the borehole, (g) water inflow volume of the borehole, (h) attenuation rate of the borehole water inflow volume, and (i) volume of water drainage.

Table 2. Standard Deviation of Influencing Factors

| factors | u_5 | u_6 | u_7 | u_8 | u_9 | u_{10} | u_{11} | u_{12} | u_{13} | u_{14} | u_{15} | u_6  |
|---------|-----|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-----|
| standard deviation | 0.0020 | 0.0120 | 1.9130 | 3.7740 | 0.4320 | 6.4060 | 15.8810 | 0.0300 | 3.2110 | |

Table 3. Composite Weights of Influencing Factors

| factors | u_5 | u_6 | u_7 | u_8 | u_9 | u_{10} | u_{11} | u_{12} | u_{13} | u_{14} | u_{15} | u_6  |
|---------|-----|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-----|
| subjective weight | 0.1787 | 0.1782 | 0.1067 | 0.0680 | 0.1573 | 0.0415 | 0.0143 | 0.1772 | 0.0776 | |
| objective weight | 0.2710 | 0.3080 | 0.0279 | 0.0412 | 0.0900 | 0.1183 | 0.0415 | 0.0119 | 0.1702 | |
| composite weights | 0.3694 | 0.4174 | 0.0226 | 0.0213 | 0.0116 | 0.0373 | 0.0045 | 0.0160 | 0.1005 | |

Table 4. Standard Deviation of Influencing Factors after Drilling Drainage

| factors | u_5 | u_6 | u_7 | u_8 | u_9 | u_{10} | u_{11} | u_{12} | u_{13} | u_{14} | u_{15} | u_6  |
|---------|-----|-----|-----|-----|-----|-------|-------|-------|-------|-------|-------|-----|
| standard deviation | 2.1320 | 0.0643 | 3.7744 | 0.4322 | 6.4060 | 16.0385 | 2.8041 | 0.0485 | 22636.87 | |

membership criterion. 0.2836 is “low” in the corresponding comment set; therefore, the roof water inrush risk assessment level is low after the drainage.
danger area for roof water inrush. It can be seen from Figure 8a that when the working face is not drained, the dangerous area is large and accounts for 50% of the total area of the working face. The risk level is high when the working face is mined. It can be seen from Figure 8b that when the working face is drained, the dangerous area is significantly reduced, and accounts for 10% of the total area of the working face. The risk level is low.

Comparison of the aquifer resistivity changes before and after drainage shows that the drainage effectively reduced the risk of water inrush in the working face. The evaluation results are as follows: the risk level is 'high' when the working face is not drained, which is consistent with the geophysical detection results. The risk level is 'low' when the working face is drained, which is consistent with geophysical detection results as well.

From May 2021 to November 2021, during the actual mining process of the working face, there was no water inrush accident on the roof of the working face, the water inflow of the working face was small, and the average water inflow was maintained at 20 m$^3$/h. Therefore, the results of geophysical exploration and the field measurement data of the working face show that the IAHP-EWM assessment model based on GIS can reliably assess

Table 5. Draining Water Drilling Data

| hole number | $q_1-1$ | $q_1-2$ | $q_1-3$ | $q_1-4$ | $q_1-5$ | $q_1-6$ | $q_2-1$ | $q_2-2$ | $q_2-3$ | $q_2-4$ | $q_2-5$ | $q_2-6$ | $q_2-7$ | $q_2-8$ | $q_2-9$ | $q_2-10$ | $q_2-11$ | $q_2-12$ |
|-------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| $u_1'$      | 77.0    | 72.0    | 24.0    | 27.5    | 104.0   | 36.0    | 36.0    | 30      | 32.5    | 180.0   | 36.0    | 36.0    | 240.0   | 89.0    | 170.0   | 110.0   | 110.0   | 60.0    |
| $u_2'$      | 7       | 7       | 7       | 7       | 7       | 10      | 10      | 10      | 10      | 10      | 10      | 10      | 10      | 9       | 6       | 6       | 6       | 6       |
| $u_3'$      | 0.91    | 0.90    | 0.71    | 0.75    | 0.93    | 0.81    | 0.72    | 0.67    | 0.70    | 0.95    | 0.72    | 0.95    | 0.95    | 0.93    | 0.96    | 0.95    | 0.95    | 0.95    |

Table 6. Water Head of the Aquifer in the Working Face

| no. | $u_1'$ | $u_2'$ |
|-----|--------|--------|
| 1   | 7.9    | 0.72   |
| 2   | 6.5    | 0.77   |
| 3   | 5.1    | 0.83   |
| 4   | 6.2    | 0.80   |
| 5   | 11.1   | 0.66   |
| 6   | 8.1    | 0.76   |
| 7   | 3.7    | 0.89   |
| 8   | 7.5    | 0.79   |
| 9   | 12.2   | 0.67   |
| 10  | 9.3    | 0.75   |
| 11  | 6.1    | 0.83   |
| 12  | 5.8    | 0.84   |

The risk level is high when the working face is mined. It can be seen from Figure 8b that when the working face is drained, the dangerous area is significantly reduced, and accounts for 10% of the total area of the working face. The risk level is low. Comparison of the aquifer resistivity changes before and after drainage shows that the drainage effectively reduced the risk of water inrush in the working face. The evaluation results are as follows: the risk level is 'high' when the working face is not drained, which is consistent with the geophysical detection results. The risk level is 'low' when the working face is drained, which is consistent with geophysical detection results as well. From May 2021 to November 2021, during the actual mining process of the working face, there was no water inrush accident on the roof of the working face, the water inflow of the working face was small, and the average water inflow was maintained at 20 m$^3$/h. Therefore, the results of geophysical exploration and the field measurement data of the working face show that the IAHP-EWM assessment model based on GIS can reliably assess

Table 7. Assessment Factor Weights

| factors         | $u_1'$ | $u_2'$ | $u_3'$ | $u_4'$ | $u_5'$ | $u_6'$ | $u_7'$ | $u_8'$ |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|
| subjective weight | 0.9803 | 0.9985 | 0.9999 | 0.9998 | 0.9969 | 0.9581 | 0.9416 | 0.9978 |
| objective weight | 0.1233 | 0.1234 | 0.1232 | 0.1234 | 0.1231 | 0.1228 | 0.1233 | 0.1234 |
| composite weights | 0.1335 | 0.0101 | 0.0067 | 0.0013 | 0.0209 | 0.2828 | 0.3958 | 0.0149 |
Figure 8. Regional distribution of geophysical water inrush dangerous areas in the roof aquifer of the 42205 working face; (a) undrained water of the 42205 working face; (b) drained water of the 42205 working face (the roof water inrush risk area of the working face is large before drainage, and the roof water inrush risk area is small after drainage).

the risk of water inrush before and after drainage of the working face.

5.5. More Applications. To further verify the applicability of the IAHP-EWM model, the risk levels of water inrush for the 42202, 42203, and 42204 working faces after water are assessed. A period of 1 month of dredging water is applied in the 42204 working face, and the amount of drainage water is 160,000 m$^3$. A period of 6 months of dredging water is applied in the 42203 and 42204 working faces, and the amount of drainage water are 640,000 and 800,000 m$^3$, respectively. The assessment results show that the water inrush risk level of the 42204 working face is ‘extremely high’ after the water is dredged and the mining conditions are not met while the results for the 42202 and 42203 working faces are both ‘low’ and meet the safe mining conditions. Figures 9–11 show the assessment factors’ dimensionless thematic maps after drainage for the 42202, 42203, and 42204 working faces. Figure 12 shows the regional distribution of geophysical water inrush dangerous areas in the roof aquifer. It can be seen from Figure 12 that the area of water inrush risk (water-rich area) of the roof aquifer is relatively large. If mining is carried out at this time, the risk of water inrush at the working face is high, and roof drainage needs to be strengthened. The data of water inflow during the actual mining process of the 42203 and 42204 working faces show that no water inrush accident occurred in the mining face after the water was dredged, and the water inflow of the working face was low and the average water inflow was maintained at 30 and 20 m$^3$/h. There is no risk of water inrush in the mining of the working face. Therefore, the assessment results of the 42202, 42203, and 42204 working faces show that the IAHP-EWM model based on GIS can effectively evaluate the risk of roof water inrush after the working face is drained. The model can be used to provide a reference for the assessment of the risk of water inrush at the working face before and after drainage in the Liangshuijing mining area and the effect of drainage.

6. CONCLUSIONS

(1) A multifactor index system is established for evaluating the risk of water inrush from the roof of the working face before and after drainage. The introduction of the “fold undulation degree (Fw)” index quantifies the influence of the fold spatial positional undulation shape on water inrush.

(2) A mathematical model of roof water inrush risk assessment (IAHP-EWM) is established and applied to evaluate the water inrush risk of the 42205 working face. The results show that the water inrush risk level is “high”; the working face is mined after the water is dredged, and the water inrush risk level is “low”. The applicability and effectiveness of the model are verified by the results of geophysical exploration and the actual water inflow in the mining face.

(3) The model is extended and applied to the 42202, 42203, and 42204 working faces. The results show that the model can provide a reference for the assessment of the risk of water inrush at the working face before and after drainage in the Liangshuijing mining area and the effect of drainage.

7. FURTHER STUDY

The hydrochemical influence of the aquifer cannot be ignored in the evaluation of water inrush risk. In the future, the hydrochemical characteristics of groundwater should also be taken into account in the selection of evaluation indexes.63–65

A. APPENDIX

A.1. Weight vector before drainage

a. Improved Analytic Hierarchy Process to Calculate Subjective Weights of Assessment Factors

The standard deviation of each assessment factor of 42205 working faces is calculated from the thematic map, as shown in Table 9. Substitute the standard deviation of each assessment factor into eqs 1 and 2 to obtain the relative importance assessment matrix $R_i$:

$$R_i = \begin{bmatrix} 1.0000 & 1.0050 & 1.9627 & 2.9003 & 1.2166 & 4.2264 & 9.0000 & 1.0141 & 2.6170 \\
0.9949 & 1.0000 & 1.9577 & 2.8953 & 1.2116 & 4.2213 & 8.9949 & 1.0090 & 2.6120 \\
0.5094 & 0.5107 & 1.0000 & 1.9375 & 0.5726 & 3.2636 & 8.0372 & 0.5131 & 1.6542 \\
0.3447 & 0.3453 & 0.5161 & 1.0000 & 0.3726 & 2.3260 & 7.0996 & 0.3464 & 0.7792 \\
0.8219 & 0.8253 & 1.7461 & 2.6837 & 1.0000 & 4.0097 & 8.7833 & 0.8315 & 2.4004 \\
0.2366 & 0.2368 & 0.3064 & 0.4299 & 0.2493 & 1.0000 & 5.7736 & 0.2374 & 0.3832 \\
0.1111 & 0.1111 & 0.1244 & 0.1408 & 0.1138 & 0.1732 & 1.0000 & 0.1112 & 0.1354 \\
0.9860 & 0.9910 & 1.9486 & 2.8862 & 1.2025 & 4.2122 & 8.9858 & 1.0000 & 2.6029 \\
0.3821 & 0.3828 & 0.6044 & 1.2832 & 0.4165 & 2.6093 & 7.3829 & 0.3841 & 1.0000 \end{bmatrix}$$
By calculating the maximum eigenvalue of the matrix of 9.1967, CI = 0.02459, RI = 0.016959, and RI < 0.1, the matrix R passed the consistency test. From this, the subjective weight values of each assessment factor are obtained as follows:

\[
\begin{align*}
    w_1 &= 0.1787, \\
    w_2 &= 0.1782, \\
    w_3 &= 0.1067, \\
    w_4 &= 0.0680, \\
    w_5 &= 0.1573, \\
    w_6 &= 0.04155, \\
    w_7 &= 0.01438, \\
    w_8 & = 0.1772, \\
    w_9 & = 0.0776.
\end{align*}
\]

b. Entropy Weight Method to Calculate the Objective Weight of Assessment Factors

The data in Table 8 were substituted into eq 11 to calculate and obtain the entropy value of each assessment factor, as shown in Table 8.

The information entropy value of each assessment factor was substituted into eq 14 to obtain the objective weight of each assessment factor:

\[
\begin{align*}
    w'_1 &= 0.2710, \\
    w'_2 &= 0.3080, \\
    w'_3 &= 0.0279, \\
    w'_4 &= 0.0412, \\
    w'_5 &= 0.009, \\
    w'_6 &= 0.1183, \\
    w'_7 &= 0.0415, \\
    w'_8 &= 0.0119, \\
    w'_9 &= 0.1702.
\end{align*}
\]

c. Assessment Factor Weight

The subjective weight value and objective weight value of the assessment factor were brought into eq 11 to obtain the comprehensive weight of the assessment factor before drainage, as shown in Table 9:

A.2. Weight Vector after Drainage

a. Improved Analytic Hierarchy Process to Calculate Weight Vector

The judgment matrix R is established by substituting the data in Table 10 into eqs 7 and 8:

Using MatLab calculation, the maximum eigenvalue is 7, RI = 2.41 \times 10^{-7}, RI < 0.1, and the judgment matrix...
passes the consistency test and meets the requirements. From this, the subjective weight vector of each influencing factor is obtained:

\[ w_1 = 0.1233, w_2 = 0.1234, w_3 = 0.1232, w_4 = 0.1234, w_5 = 0.1231, w_6 = 0.1228, w_7 = 0.1233, w_8 = 0.1234, w_9 = 0.0137. \]

b. Entropy Weight Method to Calculate Weight Vector

The attribute value of the assessment factor was substituted into the formula 11, and the entropy value of each influencing factor can be calculated.

From this, the weight vector of each influencing factor can be calculated.
Figure 11. Regional distribution of geophysical water inrush dangerous areas in the roof aquifer of the 42204 working face.

Figure 12. Dimensionless thematic map after drainage of the 42204 working face (calculation of the area ratio of classified areas to determine membership degree of each factor): (a) water head of the weathered bedrock aquifer, (b) attenuation rate of the water table (weathered bedrock aquifer), (c) fold undulation degree, (d) height of the fractured water-conducting zone, (e) aquifuge thickness, (f) initial water inflow of the borehole, (g) water inflow volume of the borehole, (h) attenuation rate of the borehole water inflow volume, and (i) volume of water drainage.

Table 8. Assessment Factor Entropy Value

| factors | $u_1$ | $u_2$ | $u_3$ | $u_5$ | $u_7$ | $u_9$ | $u_{10}$ | $u_{11}$ | $u_{12}$ | $u_{13}$ |
|---------|------|------|------|------|------|------|-------|-------|-------|-------|
| information entropy | 0.8904 | 0.8755 | 0.9887 | 0.9833 | 0.9960 | 0.9521 | 0.9831 | 0.9951 | 0.9312 | |

Table 9. Composite Weights of Influencing Factors

| factors | $u_4$ | $u_6$ | $u_7$ | $u_8$ | $u_9$ | $u_{10}$ | $u_{11}$ | $u_{12}$ | $u_{13}$ | $u_{14}$ |
|---------|------|------|------|------|------|-------|-------|-------|-------|-------|
| subjective weight | 0.1787 | 0.1782 | 0.1067 | 0.0680 | 0.1573 | 0.0415 | 0.0143 | 0.1772 | 0.0776 | |
| objective weight | 0.2710 | 0.3080 | 0.0279 | 0.0412 | 0.0090 | 0.1183 | 0.0415 | 0.0119 | 0.1702 | |
| composite weights | 0.3684 | 0.4174 | 0.0226 | 0.0213 | 0.0116 | 0.0373 | 0.0045 | 0.0160 | 0.1005 | |
Table 10: Assessment Factor Entropy Value

| Factors | $u_1'$ | $u_2'$ | $u_3'$ | $u_4'$ | $u_5'$ | $u_6'$ | $u_7'$ | $u_8'$ | $u_9'$ | $u_{10}'$ | $u_{11}'$ | $u_{12}'$ | $u_{13}'$ |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------|----------|----------|----------|
| Information Entropy | 0.9803 | 0.9985 | 0.9999 | 0.9998 | 0.9969 | 0.9581 | 0.9416 | 0.9978 | 0.8226 | 0.0645 | 0.0101 | 0.0067 | 0.0013 |

Table 11: Composite Weights of Influencing Factors

| Factors | $u_1'$ | $u_2'$ | $u_3'$ | $u_4'$ | $u_5'$ | $u_6'$ | $u_7'$ | $u_8'$ | $u_9'$ | $u_{10}'$ | $u_{11}'$ | $u_{12}'$ | $u_{13}'$ |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|----------|----------|----------|----------|
| Subjective Weight | 0.9803 | 0.9985 | 0.9999 | 0.9998 | 0.9969 | 0.9581 | 0.9416 | 0.9978 | 0.8226 | 0.0645 | 0.0101 | 0.0067 | 0.0013 |
| Objective Weight | 0.1233 | 0.1234 | 0.1232 | 0.1234 | 0.1231 | 0.1228 | 0.1233 | 0.1234 | 0.0137 | 0.0209 | 0.2828 | 0.3958 | 0.0149 |
| Composite Weight | 0.1335 | 0.0101 | 0.0067 | 0.0013 | 0.0209 | 0.2828 | 0.3958 | 0.0149 | 0.1335 |

$w_1' = 0.0645, w_2' = 0.0049, w_3' = 0.0032, w_4' = 0.0006, w_5' = 0.0101, w_6' = 0.1372, w_7' = 0.1912, w_8' = 0.0072, w_9' = 0.5808.$

c. Composite Weights of Influencing Factors
Combining the weight calculated by the improved AHP method with the weight calculated by the entropy weight method can obtain the composite weight of each influencing factor after the dredging. The composite weight of each factor is shown in Table 11:

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Notes
The authors declare no competing financial interest. No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that this paper is new, neither the entire paper nor any part of its content has been published or has been accepted elsewhere. It is not being submitted to any other journal.

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