



# Principal causes of water damage in mining roofs under giant thick topsoil–lilou coal mine

Chao Niu<sup>1</sup> · Qingfeng Tian<sup>1</sup> · Lele Xiao<sup>1</sup> · Xicheng Xue<sup>1</sup> · Ruiqing Zhang<sup>2</sup> · Dongjin Xu<sup>2</sup> · Shoutao Luo<sup>3</sup>

Received: 1 March 2024 / Accepted: 19 April 2024 / Published online: 30 May 2024  
© The Author(s) 2024

## Abstract

The roof water inrush disaster induced by coal mining is becoming a vital bottleneck restricting mine safety. To accurately predict the water inrush position of the coal seam roof sandstone aquifer and accurately prevent and control it, this paper takes Lilou Coal Mine in Juye Coalfield as an example. Based on the comprehensive analysis of hydrogeological data, drilling data, and geophysiological data, this paper examines the water richness of the roof aquifer, the water insulation and geological structure, and the fracture development characteristics of the roof aquifer. Starting from the general side, nine factors, including fault strength index, tectonic intersection point, tip extinguishing point, development height of water conduction crack zone, roof sandstone aquifer thickness, aquifer drilling unit inrush, geophysical prospecting water-rich anomaly area, roof key layer thickness, roof aquifer thickness, brittle plastic rock thickness ratio, etc., form the roof plate roof. The main control factors for water inrush are deeply discussed. Through the spatial analysis function of GIS, unique drawings of different evaluation indicators are drawn, and the data are normalized. Combined with the AHP hierarchical analysis method, the corresponding weight is determined. Finally, a comprehensive water inrush risk assessment map of the roof of coal seam 3 in Lilou Coal Mine is obtained. Through the verification of the coal mine water inrush survey ledger over the years, it has been found that the evaluation results of the coal seam roof water inrush model are consistent with the actual situation. The evaluation results are reasonable and accurate, which can provide a reference basis for coal seam mining and water damage prevention and control in the future.

**Keywords** Roof water inrush · Fracture zone · Water-rich zoning · Risk assessment · Huge thickness topsoil layer

## Introduction

As one of the significant hydrogeological disasters affecting the safe production of coal mines in China, roof water damage seriously restricts the safe and efficient exploitation of coal resources (Wang et al. 2021; Xiao et al. 2022). In recent decades, water inrush from the roof of coal mines in our country has happened frequently, resulting in more than 1000 deaths and serious consequences in the form of

direct economic losses in the billions of yuan. In typical cases, such as May 7–20, 2000, during the face mining process at Baodian coal mine 5308, the roof water increased significantly, followed by a threefold increase in pressure accompanied by the face water burst increase, and the mine water inflow reached 141 m<sup>3</sup>/h (Liu 2004). On July 4, 2011, a water inrush (540 m<sup>3</sup>/h) occurred at the Dongtan coal mine 14301 working face due to the roof of the water-resisting layer rock failure deforming into new cracks, which activated the non-conductive fault and let the upper aquifer water into the working face (Liu and Fu 2003). An abnormal water burst occurred at the 31401 working faces in the four-pan area of the Shandong Mining District's Supplementary Lianta Coal Mine, where the water surges abnormally within the advancing range of 1650–2552 m and the top of the working face is constantly dripping and seeping. During the two large water bursts, the working face was flooded, the depth of water accumulation was up to about 2 m, and the maximum water surges were up to 400 m<sup>3</sup>/h. The water

✉ Qingfeng Tian  
m18834173248@163.com

<sup>1</sup> College of Geology and Environment, Xi'an University of Science and Technology, Xi'an 710054, China

<sup>2</sup> College of Earth Sciences & Engineering, Shandong University of Science and Technology, Qingdao 266000, China

<sup>3</sup> Hancheng Mining Co., Ltd, Shanxi Coal and Chemical Industry Group Co., Ltd, Xi'an 710065, China

surges at the working face change on a regular basis (Wang 2008; Xu 2017). Therefore, the prevention and control of mine roof water damage is a significant bottleneck that needs to be solved to ensure mine safety in China.

Water inrush from coal seam roofs is a dynamic phenomenon formed by many geological and hydrogeological factors. Whether water inrush from coal seam roofs occurs under specific geological and hydrogeological conditions is a problem that concerns many scholars, but it is also of great practical significance for coal mine safety and efficient production (Xu 2017; Wang 2022). Currently, the prediction model and evaluation method of water inrush from the roof of a coal seam tend to be perfect, among which the prediction of the water-rich property of the roof aquifer and the risk of water inrush from the roof are the index basis of mine water disaster prevention and control. The evaluation methods of aquifer water abundance mainly include the geophysical prospecting method, hydrologic tests (such as pumping tests, discharging tests, etc.), and the multi-factor comprehensive analysis method (Ding et al. 2022; Cheng et al. 2020; Dong et al. 2022). The first two methods mainly use the physical properties of rock layers and hydrogeological parameters to determine the water-rich aquifer; the latter is an index system based on the lithologic and structural characteristics of coal seam roof aquifer (such as the brittle-plastic ratio of bedrock, sand content, sand-mud ratio, sand-mudstone interaction layers, etc.), equivalent thickness of the aquifer, rock quality index, geological structure (such as fault strength, structure annihilation point, intersection point, etc.), unit water inflow, groundwater level, permeability coefficient, consumption of drilling flushing fluid and sedimentary characteristics, etc. (Han et al. 2022; Hou et al. 2016; Xu et al. 2019; Wu et al. 2017; Bu et al. 2005), and then through numerical analysis and mathematical statistics and other methods to determine the impact of the degree of indicators, it mainly includes GIS, Fisher, entropy weight, analytic hierarchy process, coefficient of variation, principal component analysis, grey theory, neural network, unascertained measure theory and variable fuzzy set coupling (Luo 2014; Wang 2007; Shi et al. 2020; Hou et al. 2019; Feng and Wu 2016; Yao et al. 2021; Li et al. 2018; Wei et al. 2020; Huang et al. 2022). The risk prediction of roof water inrush is based on the evaluation of the water-rich aquifer, the spatial distribution of the factors such as mining conditions (coal seam depth and mining thickness, etc.), variation coefficient of coal seam dip angle, structure of the water-resisting layer (water-resisting property of the roof key layer, clay thickness), development of the water-conducting fracture zone, etc. The main factors affecting water inrush from the roof of a coal mine are quantified and superimposed, the water-resisting property of the roof key layer, clay thickness, the development of the water-conducting fracture zone, etc. The main factors affecting water inrush from the

roof of a coal mine are quantified and superimposed, and the water-resist

As the largest coalfield in East China, the Juye Coalfield now has proven total geological reserves of 5.5 billion tons. Yuncheng County's Well-field system is located in the northern section of Juye County's Coalfield. It is a completely concealed minefield covered by a huge, thick, loose bed. In the next 3–5 years, the plan is mainly to mine coal seam 3. The minefield structure is of medium complexity and is controlled by regional structures. Coal mining in Yuncheng County is currently facing a typical roof water hazard problem. At present, Mine Water Hazard Prevention and control mainly includes water hazard assessment, water inflow prediction, water hazard monitoring and early warning, and water hazard detection and control. The research work on mine water disaster is too scattered and lacking.

Timeliness, space, dynamic, and comprehensive research, and the comprehensive technical system of mine water prevention and control are not perfect, lacking three-dimensional and systematic research. In order to meet the needs of research and decision-making in different areas and at different stages of on-site roof water disaster prevention and control in Yuncheng County coal mine, this paper will combine the prediction research and engineering practice of roof water inrush in coal mine in recent years, this paper summarizes the progress of domestic and foreign scholars on the mechanism of water inrush from roof water disaster, starting from the development of structures and fissures, the water-rich property of aquifer, the water-resisting property of water-resisting layer and so on, and according to the actual hydrogeological conditions, nine evaluation indexes are selected, including fault strength index, structural crossing point and pinch-out point, development height of water-conducting fracture zone, thickness of roof sandstone aquifer, unit water inflow of aquifer borehole, geophysical water-rich anomaly area, thickness of roof key layer, thickness of roof water-resisting layer and thickness ratio of brittle-plastic rock, the prediction and evaluation model of water inrush from roof of coal mine was established, and the risk of water inrush from roof aquifer of 1301 and 1303 working faces in Yuncheng County Coalfield was predicted and partitioned, it provides reliable technical support for the scientific, rapid, and accurate formulation of mine water disaster prevention and control program.

## Overview of Lilou coal mine research area

### Location and physical geography of the mine

The Juye County Coalfield, the largest in eastern China and located in the southwest of the province, has proven total geological reserves of 5.5 billion tons. Seven pairs of mines

are planned for the Juye County Coalfield: the Zhaolou and Wanfu mines of the Yankuang Group, the Longgu mine of the Xinwen Mining Group, the Pengzhuang and Guotun mines of the Luneng Group, the Lilou mine of the Shandong Prison Administration Bureau, and the Liangbaosi mine of the fertilizer mining group. The Lilou coal mine is located at the northern end of the Juye County Coalfield; the Guotun coal mine is in the south; and the Pengzhuang coal mine is in the southeast. The Lilou coal mine is one of the seven largest coal mines in the Juye County Coalfield planned by the state and is located northeast of the county seat of Yuncheng County, Heze. The minefield area is 198.284 km<sup>2</sup>. The mine was put into operation in April 2017 with a designed production capacity of 2.40 Mt/a and a service life of 111.7 years. The central parallel extraction ventilation method is adopted, as is the long wall backward mining method, fully mechanized mining, and the top coal mining process. All collapse methods are adopted to manage the roof. The landform is the Yellow River alluvial plain, flat terrain, slightly high in the west and low in the east; the ground elevation is +42.0 m +45.38 m; and the natural terrain slope is 0.2‰. 1.0. Under the influence of the Yellow River flooding and the swing of the water route, the local topography fluctuates slightly, and the micro-geomorphology forms such as gentle slope land, channel depression land, dune, Sand Ridge, and so on are distributed. Most of the river channels in the area are artificially excavated, forming a water conservation system for water diversion and irrigation in the dry season and flood control and drainage in the rainy season. Major river systems include the northern Juanyunxin River, the central Zhuzhaoxin River, and the southern Wanfu River, which originate from the Yellow River and flow eastward into the Grand Canal and Nanyang Lake. The Juanyunxin River and the Zhuzhaoxin River branch, and the Xiangyang River and the Harvest River pass through the Well-field system in Yuncheng County (please see Fig. 1).

## Mine geology and hydrogeology

### Stratigraphic profile

The Lilou coal mine is a completely concealed north China-type carboniferous Permian coal field with a relatively small Cenozoic strata thickness (472.80–591.30 m). It shows a trend that the middle is deep to the northeast and southwest, from shallow to deep undulating to the southeast, gradually becoming shallower. The coal system formation is based on Ordovician limestone (52.52 m thick), the sedimentary carboniferous Benxi Formation (26.20–37.95 m thick), Carboniferous Taiyuan Formation (42.00–170.95 m thick), Permian Shanxi Formation (0–81 m thick), and Stone Box Formation (0–653.5 m thick), and the overlying strata are Neogene (338.2–460.4 m thick) and Quaternary Formation

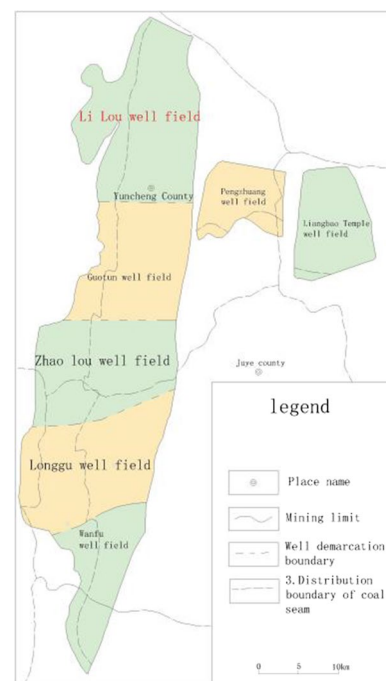


Fig. 1 Distribution map of adjacent mines of Lilou coal mine

(105–139.6 m thick). The main coal-bearing strata are the Taiyuan Formation and Shanxi Formation, which mainly mine coal seam 3 of the Permian Shanxi Formation. The coal seam thickness is 3.96–7.88 m, the average is 6.87 m, and the mining depth is about 1000 m. The coal seam is located in the middle and lower parts of the Shanxi Formation of Permian, which occurred in the middle and east parts of the minefield, was denuded in the west, and was sunk and deficient in the Chengtun and Xiaoting areas at the North End. The coal seam roof is mostly mudstone, sandy mudstone, and siltstone; the floor is mostly mudstone, sandy, carbonaceous mudstone, siltstone, and fine sandstone (please see Fig. 2).

### Structural overview

The Lilou coal mine is a completely concealed minefield covered by a huge, thick, loose layer. The overall well field is a mono-oblique structure near the north and south to the east. The axial direction is closer to the north and south, and the wing inclination The angle is mostly 515, the east along the Tianqiao fault is 20, the local section can reach 26, the central and southern parts are gentle, and the north and eastern are steeper. The faults in the minefield are controlled by regional structures; the strike is consistent with the regional faults, the Tianqiao fault and the Wensi fault; and the strike is nearly north–south, with a few northeast and near-east–west faults. It has an obvious east–west Zonation: Rendian Fault and Pandu Fault are the main faults along

Stratum	Histogram	Thickness/m	Water abundance	The way to enter	Remarks
Quaternary sand layer		105.00-139.60 122.09	medium	No	No participation
Neogene sand layer		338.20-460.40 394.72	low	Balizhuang fault	Less participation
Permian Shihezi Formation sand layer		0-653.50 359.35	low-medium	Water-conducting fracture zone / Balizhuang fault / leading overburden movement fracture	Main participation/ The passage is located on the roof of the coal seam
Permian Shanxi Formation sand layer		0-81.00 50.15	low		
Coal seam 3		6.70-7.31 7.03			
Carboniferous Taiyuan Formation 3 th limestone layer		1.79-6.30 5.20	low-medium	fault	Less likely to participate
Carboniferous Taiyuan Formation 10 th limestone layer		2.06-7.45 4.41	medium	Karst fissure/ Balizhuang fault / leading overburden movement fracture	Studies have shown that only three ash aquifers in Taiyuan formation are recharged and not involved
Ordovician limestone layer		>800	medium-high		

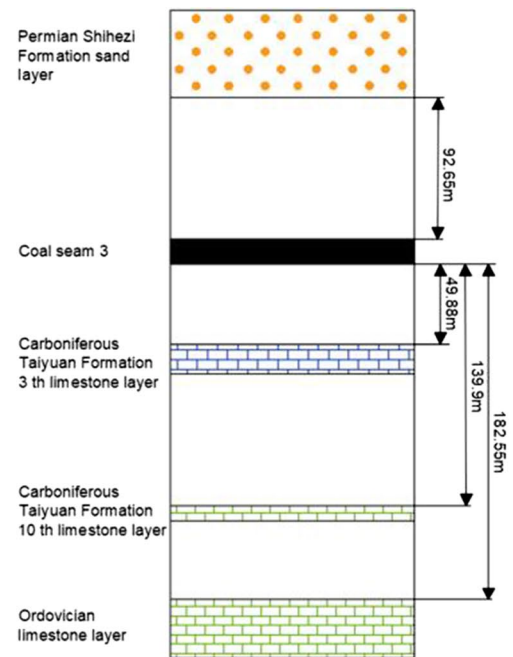


Fig. 2 Schematic diagram of distance between coal seam and main aquifer

the Ordovician limestone and coal seam 16 outcrops in the west; Balizhuang and Balizhuang faults are the main faults in the middle; and Tianqiao Fault is the representative in the east. Through various exploration projects, 361 faults have been developed in the Well-field system, including 21 faults 100 m, 34 faults 99–50 m, 72 faults 49–20 m, and 234 faults < 20 m.

**Hydrogeology**

The Quaternary and Neogene clay of the Lilou coal mine is a good water barrier, and there is no Austrian ash outcrop in the coalfield, which is a closed water-bearing structure. The main aquifers, from top to bottom, are as follows: Quaternary Sandy Gravel Pore Aquifer and Neogene Bottom Sandy Gravel Pore Aquifer, Permian Shihezi Sandstone Fissure Aquifer, coal seam 3 roof and floor sandstone fissure aquifer (3 sand for short), 3 Ash, 10 lower limestone karst fissure aquifer, and Ordovician limestone fissure aquifer. The sandstone aquifer in the roof and floor of coal seam 3 and the three-ash aquifer of Taiyuan Formation are the main water-filled aquifers for mining the upper coal seam, and the other aquifers are the indirect water-filled aquifers for mining coal seam 3. Quaternary sandstone aquifers are mainly sand aquifers in the upper section, which belong to loose aquifers with medium water abundance because of poor continuity between sand layers. The upper part of the pore water-bearing layer in the bottom of Neogene is thick and continuous, the middle and lower parts are discontinuous

and loose, and the upper part has a strong water-enriching ability. The middle and upper sand layers of the lower section have strong continuity, the bottom sand layer is thick, and the lower section has weak water-rich capacity. The sandstone fractured aquifer of the Permian Shihezi Formation has poor continuity, and the water-rich ability is weak to moderate. The sandstone aquifer of the Shihezi Formation will also become the main aquifer affecting mining. The coal seam roof and floor sandstone fracture aquifer sand body continuity are good, the water-rich overall consistency is good, and the local section has good supply conditions and strong water richness.

**Comprehensive evaluation model of water risk of aquifer roof**

**Key elements of water inrush from roof aquifers**

The water inrush from the roof of the coal seam is a phenomenon in which the stress field and the seepage field act together to cause the overlying rock mass to destroy the aquifer and flood into the mine.<sup>[27]</sup> However, many factors affect the risk of water inrush from roof water-filled aquifers, and they are directly or indirectly related to each other.

**Geological structure and fracture development factors**

1. Fault strength index

Faults will destroy the integrity of rock mass and affect the water-resisting layer above the coal seam and the fissure water of sandstone, thus increasing the probability of roof water inrush. The Fault Strength Index can objectively and comprehensively reflect the fault complexity of a section in a mine and can reflect the comprehensive complexity of fault drop, fault horizontal extension length, and fault number. In other words, the bigger the index of fault strength is, the weaker the water resistance of the rock stratum is, and the greater the risk of water inrush.

## 2. Construction of intersection points and sharp extinction points

The rock mass at the crossing point of the structure (including fault and fold) and the distribution area of the pinch-out point are relatively more broken, the ground stress is more concentrated, the fracture zone is relatively well developed, and its water conductivity is relatively good. This is due to the high incidence of roof water inrush.

## 3. Height of hydraulic fracture zone development

Coal seam mining breaks the original equilibrium state of the rock stress, which leads to the redistribution of stress. The overlying coal seam generates fissures and joints in the process of movement, deformation, and destruction, forming water-conducting fissure zones. When the water-conducting fracture zone leads to the overlying water-filled aquifer and the aquifer is rich in water, the water in the aquifer may rush into the mine and induce the water inrush accident. Therefore, the analysis of the development height of the hydraulic fracture zone of the mining overburden is also a crucial part of predicting the risk of water inrush in the roof aquifer.

### Water-rich factors in roof aquifers

#### 1. Thickness of the sandstone aquifer on the roof

The sandstone aquifer is the main source of water supply for coal mine roof bursts. It is generally believed that the greater the thickness of the sandstone aquifer, the better its water storage capacity, i.e., the stronger its water richness. Therefore, the thickness of the sandstone aquifer on the roof is an important factor in the evaluation of the risk of water breakout on the roof, and the cumulative thickness of the sandstone (mainly the thickness of fine, medium, and coarse sandstone) within the development height of the hydraulic fracture zone is usually used to characterize the strength of the water-richness of the aquifer.

#### 2. Aquifer borehole unit surge volume

Water inflow per unit of aquifer boreholes is an important index for evaluating the capacity of the aquifer to produce water (Liu et al. 2022). That is to say, the larger the unit water inflow, the stronger the water-rich aquifer, and the greater the risk of water inrush. The pumping test, water injection test, and water discharge test are the common methods to obtain the unit water inflow of the borehole, so it is important to analyze the unit water inflow of the aquifer for the risk prediction of water inrush in the roof aquifer.

#### 3. Physical prospecting of water-rich anomalous zones

Surface and underground geophysical prospecting technology have become the most effective means to detect abnormal water-rich areas in the roadway and the roof and floor of the coal face. The transient electromagnetic method uses ungrounded return lines or grounded line sources to transmit a pulse magnetic field into the ground. By observing the secondary induction field during the interval of the primary pulse magnetic field, we can know the distribution of the electric property, the scale, and the attitude of the underground geological body. The high-density direct current method is used to determine the water-rich distribution of rock and ore bodies through the observation of the distribution of the earth's current field. Therefore, the analysis of geophysical water-rich anomaly areas is of great significance for evaluating the risk of water inrush from roof aquifers.

### The impermeable factor of the roof barrier

#### 1. Key layer thickness of the top slab

The key layer theory considers that during the movement of the overlying rock mass, some stronger rock layers are developed in the height range of the water-conducting fracture zone, which can not only control the movement of the rock stratum but also play a key role in the prevention and control of water inrush from the roof. Consequently, the thickness of the coal seam roof key layer is also one of the key indicators of roof aquifer water inrush risk assessment.

#### 2. Thickness of the top slab water barrier

The roof water-resisting layer mainly refers to mudstone and sandy mudstone with strong plasticity, undeveloped fissures, and certain water-resisting properties, which can effectively prevent the water from flowing into the mine from the sandstone fissures above the coal seam. The overburden rock produces a lot of fissures under the influence of coal seam mining, which leads to the decline of the water-resisting performance of the water-resisting layer. That is, the greater the thickness of the roof water barrier, the stronger the water resistance, and the less the risk of water



inrush. Accordingly, it is pretty important to calculate the thickness of the water-resisting layer within the development height of the hydraulic fracture zone for the risk assessment of water inrush from the roof aquifer.

### 3. Thickness ratio of brittle plastic rock

The brittle rock in the roof water-resisting layer includes the carbonate rock or the sandstone layer, whose rock mechanics strength is big, and the plastic rock includes the mudstone and shale, whose rock mechanics strength is weak, etc. The thickness ratio of brittle rock and plastic rock determines its water resistance and compressive strength to a great extent. The greater the thickness ratio of brittle-plastic rock in the roof water-resisting layer, the weaker the water-resisting property of the water-resisting layer is, the greater the risk of water inrush. Therefore, it is very important to calculate the thickness ratio of brittle-plastic rock in a water-resisting layer for the risk assessment of water inrush from a roof aquifer.

### "Three sides, nine points" roof water inrush risk prediction method based on GIS and AHP coupling

Based on years of research and engineering practice, the author puts forward the "Three sides, nine points" roof water inrush risk prediction based on GIS and AHP. Based on borehole data statistics and geophysical data analysis, this method is based on three aspects: the water-rich property of the roof aquifer, the water-resisting property of the roof water-resisting layer, and the characteristics of geological structure and fracture development, the evaluation system is established by selecting 9 main controlling factors, such as fault strength index, structural crossing point, and pinch-out point, development height of water-conducting fracture zone, the thickness of roof sandstone aquifer, unit water inflow of aquifer borehole, geophysical water-rich anomaly area, the thickness of roof key layer, the thickness of roof water-resisting layer, thickness ratio of brittle-plastic rock, etc., then, using numerical analysis and mathematical statistics, the Comprehensive Evaluation Index of each borehole is obtained (Ma and Zhao 2019; Jiang 2022). The risk assessment of water inrush from roof aquifers is carried out by using GIS and AHP to draw thematic maps of different evaluation indexes and determine the corresponding weight superposition analysis.

### Model principles of AHP and GIS analysis

Hierarchical analysis (AHP) is a combined qualitative and quantitative hierarchical weighted decision analysis method for solving complex problems with multiple objectives proposed by American operations researcher Professor T. L. Saaty

at the University of Pittsburgh in the early 1970s by applying network system theory and multi-objective comprehensive evaluation methods. This method has the advantages of being systematic, convenient for decision-making, and having small quantitative information requirements. It is also widely used in the evaluation of water protrusion in coal-seam roof aquifers (Wu et al. 2011). The problem can be decomposed into different constituent factors and the combination of different levels according to the interconnection and affiliation between the factors, forming a multilevel analysis structure model for the evaluation of the top slab and finally obtaining the ranking of the relative importance weights of the lowest level relative to the highest level. AHP can be divided into the following steps: building a hierarchical model; constructing a discriminant matrix; calculating the weight phasor; and doing consistency testing.

The Geographic Information System (GIS) supports the acquisition, management, processing, analysis, modeling, and display of spatial data and can solve complex planning and management problems. And its unique spatial analysis function is one of the core functions of GIS, which is an analysis technique to obtain information about the spatial location, distribution, morphology, formation, and evolution of geographic objects from spatial data. By using the spatial assignment superposition tool of GIS, the main control factors are superimposed according to their influence weights to obtain a realistic model for evaluating the risk of water breakout in coal bed roof aquifers.

### The AHP model determines the weights of the influencing factors.

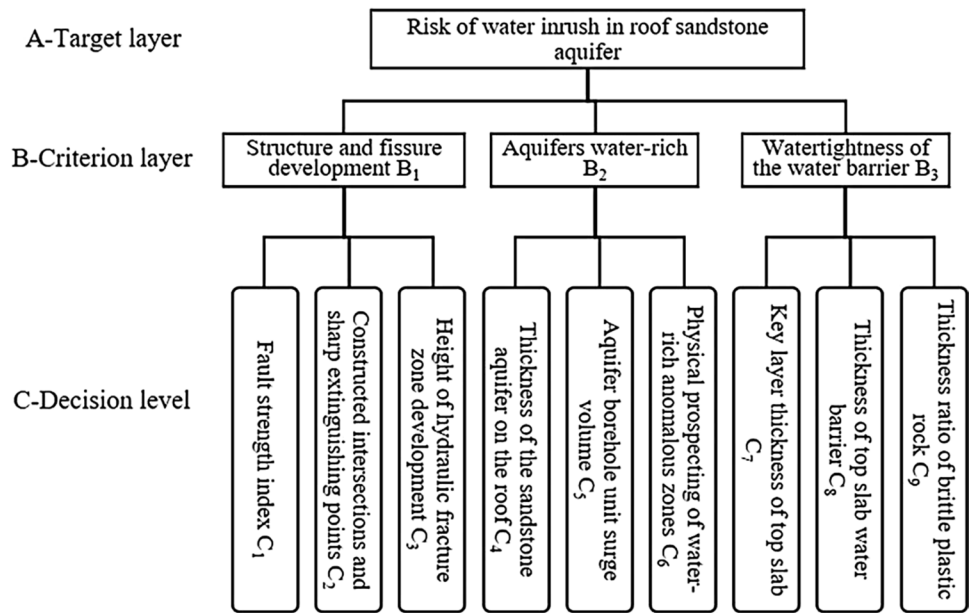
By analyzing the key factors affecting the risk of water burst in the roof aquifer, determine the index system for evaluating the risk of water burst, build a recursive hierarchy (i.e., judgment matrix), and then establish the A, B, and C hierarchy analysis models (please see Fig. 3).

According to the importance of the evaluation index of roof aquifer water inrush risk, a judgment matrix  $C$ :

$$C = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1j} \\ a_{21} & a_{22} & \dots & a_{2j} \\ \dots & \dots & \dots & \dots \\ a_{i1} & a_{i2} & \dots & a_{ij} \end{bmatrix} \quad (1)$$

Through expert scoring, hierarchical single ranking, hierarchical total ranking, and consistency tests, the weights of nine evaluation indexes affecting the risk of water burst in the roof aquifer were finally determined.

**Fig. 3** Hierarchical analysis model



**Table 1** Judgment matrix A-B

A	$B_1$	$B_2$	$B_3$	Eigenvector $W_B$	$l_{max}$	CR
$B_1$	1	0.8	0.75	0.279	3	0
$B_2$	1.25	1	1.2	0.379		
$B_3$	1.33	0.83	1	0.342		

**Table 2** Judgment matrix B1-C

$B_1$	$C_1$	$C_2$	$C_3$	Eigenvector $W_B$	$l_{max}$	CR
$C_1$	1	1.4	1.1	0.382	3	0
$C_2$	0.71	1	0.9	0.286		
$C_3$	0.91	1.11	1	0.332		

**Table 3** Judgment matrix B2-C

$B_2$	$C_4$	$C_5$	$C_6$	Eigenvector $W_B$	$l_{max}$	CR
$C_4$	1	1.2	0.71	0.311	3	0
$C_5$	0.83	1	0.67	0.270		
$C_6$	1.4	1.5	1	0.419		

### Example application of aquifer in Yuncheng well field

#### Analysis of the results of the zoning of sudden water hazard evaluation

For the evaluation of the risk of water inrush in the roof aquifer of 3 coal seams in Yuncheng coalfield, the key factors of roof water damage written by the author are verified by AHP and GIS methods.

#### Determination of the weight of key factors

AHP is applied to determine the weights of evaluation factors, and after determining the objectives and evaluation indicators, constructing and calculating the judgment matrix and consistency test, the judgment matrix is constructed according to the method of hierarchical single ranking as shown in Tables 1, 2, 3, and 4.

From Tables 1, 2, 3, and 4, it can be seen that the average random consistency index CR of the judgment matrix is less

**Table 4** Judgment matrix B3-C

$B_3$	$C_7$	$C_8$	$C_9$	Eigenvector $W_B$	$l_{max}$	CR
$C_7$	1	1.3	1.4	0.402	3	0
$C_8$	0.78	1	1.2	0.322		
$C_9$	0.71	0.83	1	0.276		

than 0.1. According to the hierarchical analysis method, if  $CR < 0.10$ , the judgment matrix is considered to have satisfactory consistency; otherwise, the judgment matrix needs to be adjusted, and the above calculation results show that the consistency of this constructed judgment matrix is better.

By taking the weight vectors of each level and calculating them level by level along the hierarchical model, the weights of each indicator  $C_i$  on the total target ( $W_i$ ) can be established (Table 5).

### Establishment of thematic maps of key factors

According to the drilling data and physical exploration data in the mine area, the influence of the water-richness of the slab aquifer, the water-insulation of the roof water barrier, and the characteristics of geological structure and fissure development were fully considered, and nine factors were selected as the main control factors, such as fault strength index, tectonic intersection point, and sharp extinction point, the height of water-conducting fissure zone development, the thickness of the sandstone aquifer in the roof, the unit water gush in the borehole of the aquifer, the abnormal area of water-richness in the physical exploration, the thickness of the key layer of the roof, the thickness of the roof water barrier, the thickness ratio of brittle to plastic rock, etc. (please see Fig. 4). Plastic rock thickness ratio and the other 9 factors as the main control factors of the coal bed roof water (please see Fig. 4).

#### 1. Structural factors

1. Fault strength index Fault strength can more objectively and comprehensively reflect the complexity of a section of the fault and can objectively and truly reflect the complexity of the fault drop, the horizontal extension length of the fault, and the number of faults. Other factors being

the same, the scale of fault strength is positively correlated with the risk of a water breakout. Using GIS to simplify the statistics of coal seam 3 fault features, assign values to each fault drop according to the actual situation in the software, and finally generate a thematic map of fault strength scale using the line density function after completion (Fig. 4a),

From Fig. 4a, it can be seen that the high-value area is mainly located in the middle section of the fracture development in the 1300 working face of the Lilou coal mine, which is related to its dense fault and long-term violent activity. The middle-value area is located along the fractures in the south of the 1301 and 1303 working faces of the Lilou coal mine, which is related to the low number of faults. 1301 and 1303 working faces, on the east and west sides, have few faults and a small scale, and the fault index is relatively low.

2. To construct the crossing point and the pinch-out point. The structural fissure zones are usually developed at the point of fault pinch-out and the joint of fault and fault. At the same time, the fissure zones at the pinch-out and joint are also relatively good at conducting water. When the crossing point of these faults is touched in the artificial mining process, it can lead to fissure activation and a water inrush accident, so it is very important to make reasonable and comprehensive statistics on the distribution of the crossing point and pinch-out point between fault and fault in the study area for the water inrush accident caused by the structure. Therefore, the paper deals with the structural intersection and the structural pinch-out point of the roof of coal seam 3, respectively, and uses GIS to generate the thematic map of the structural intersection and the structural pinch-out point in turn.

**Table 5** Weight value of the main control factor ( $W_i$ )

Influencing factor	Weight	Influencing factor	Weight
Fault strength index	0.107	Physical prospecting of water-rich anomalous zones	0.159
Constructed intersections and sharp extinguishing points	0.080	Key layer thickness of top slab	0.137
Height of hydraulic fracture zone development	0.093	Thickness of top slab water barrier	0.110
Thickness of the sandstone aquifer on the roof	0.118	Thickness ratio of brittle plastic rock	0.094
Aquifer borehole unit surge volume	0.102		



**Fig. 4** Thematic maps of main controlling factors

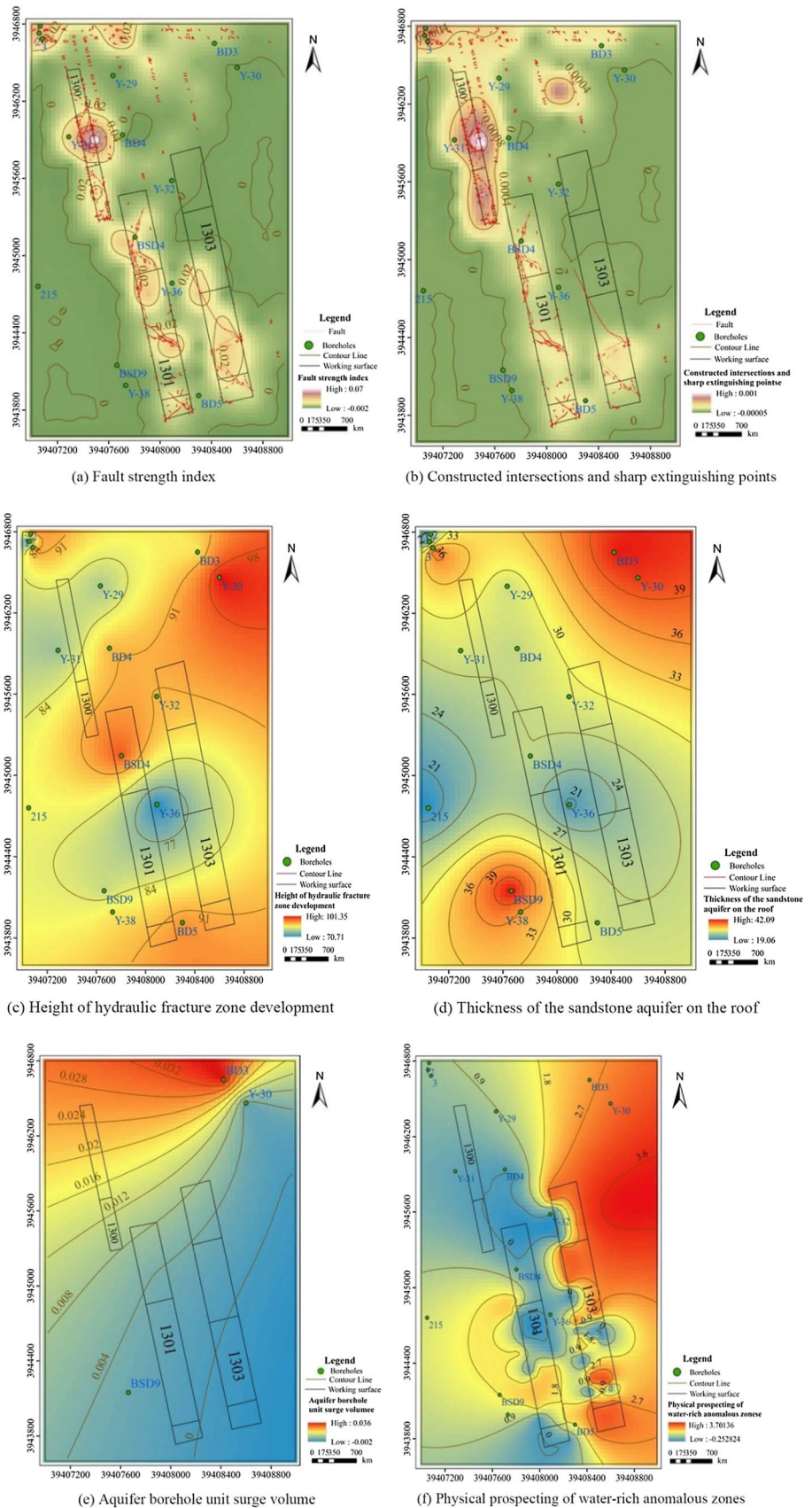
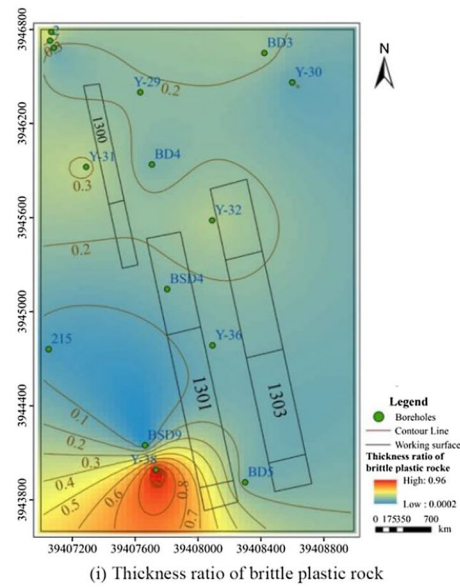
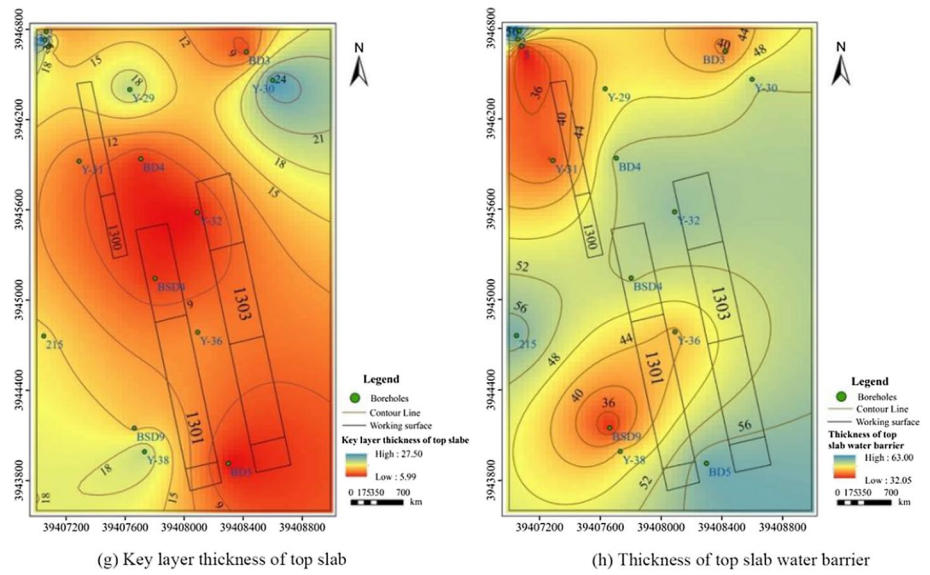


Fig. 4 (continued)



From Fig. 4b, the tectonic intersection and pinch-out point are concentrated in the area of the 1301 working face of the Lilou coal mine, which is also a large area of fault development. In the south of the 1301 and 1303 working faces, the crossing points of structures and the pinch-out points are relatively concentrated. Due to the development of faults in the east and north of the 1300 working face, there is a small range of high values in the east and north regions. In addition, there are no intersection points or pinch-out points on the east and west sides of the face, which shows that the structure is relatively simple.

3. The height of the water-conducting fracture zone The roof water disaster forms a hydraulic fracture zone due to the influence of coal mining activity. If the hydraulic

fracture aquifer in the height range of the hydraulic fracture zone is channeled, it may cause a large amount of water from the water-bearing layer above the coal seam to rush into the roadway. According to the principle of "No low, no high," using a 12.77 actual fracture-to-mining ratio of 1301 working faces combined with the concrete conditions of coal seam 3 in the current mining range, through analogy analysis, select the full-coal thickness (6.87 m) fully mechanized caving mining, then get the predicted height of the water-conducting fracture zone, and generate the corresponding thematic map (Fig. 4c).

From Fig. 4c, the highest value of the hydraulic fracture zone appears in the northeast of the mining area, and the

high-value area on the working face is mainly located in the south of the 1300 working face and the north of the 1301 working face (> 80 m), while the low-value area is located in the middle of the 1300, 1301, and 1303 working faces and shows the wavy characteristic of "high-low-high" on the whole.

## 2. The water-rich property of the aquifer

1. Thickness of the aquifer The sandstone aquifer at the top of the coal seam plate is the main source of water for the top slab, and the thickness of the aquifer is positively correlated with its water richness if other conditions and influencing factors remain unchanged. The thicker the thickness of the aquifer, the stronger its water storage capacity. Therefore, the thickness of the aquifer is an important factor affecting the water richness of the aquifer.

From Fig. 4d, the uneven distribution of aquifer thickness in the study area reflects the uneven characteristics of the water richness of the sandstone on the roof of the area. 1300 working face north and 1301 working face southwest aquifer thickness is large and relatively strong water richness. 1301 and 1303 working faces central area aquifer thickness is relatively small and has relatively weak water richness characteristics.

2. Water inflow per unit The amount of water gushing per unit is the amount of water gushing per meter of the water level in the hole during the pumping test. It is an important index to compare the capacity of the aquifer. The bigger the unit water inflow of the aquifer is, the more harmful the roof water inrush is, and the more difficult it is to deal with the water inrush.

From Fig. 4e, it can be seen that the distribution of water inflow per unit in the mining area is gradually decreasing from north to south and from west to east; the unit water gushing of 1300 faces is larger than that of the other two faces. If a water-gushing accident occurs, it will cause greater loss.

3. Water-rich anomaly area Due to the different geological and hydrological conditions, there is a large amount of groundwater in abnormally water-rich areas, which is dangerous to mining. In this study, the abnormal area in the working face is explored by electrical prospecting.

From Fig. 4f, there are six water-rich abnormal areas in 1303 working faces, and the risk of water inrush is high in most of the water-rich abnormal areas. There is also one water-rich abnormal area in 1301 working faces, and the risk of water inrush is general. However, there is also

a large area of the abnormally water-rich area on the left side of the 1301 working face, so the risk of water inrush is general.

## 3. Water separation from the water barrier layer

1. Thickness of the key layer According to the key layer theory, there is a layer of high-strength sub-layer within the height of the hydraulic fracture zone that can not only control the movement of the rock layer but also play an important role in preventing and controlling water breakout. GIS software was used to identify the lithology and thickness of the key layer within the height of the water-conducting fracture zone in the roof of the 3-coal seam, and a corresponding thematic map was produced (Fig. 4g).

From Fig. 4g, the high-value areas of key layer thickness are mainly located in the north of the 1300 working face, the west of the 1301 working face, and the east of the mining area, while the middle and low-value areas are located near the 1300, 1301, and 1303 working faces, especially the south and north of the working face, which belong to the lowest value area, which will be the important hidden danger area of mine water inrush.

2. Thickness of the water-resisting layer In the coal seam roof burst water out, the roof water barrier mainly plays the role of blocking the sandstone fracture water above the coal seam, but due to the disturbance of artificial mining, the roof will continue to collapse and generate a large number of mining fractures, resulting in the water barrier's water resistance decreasing, so the statistics of the thickness of the water barrier in the roof hydraulic fracture zone are essential for the analysis of the roof burst water. Other circumstances are the same: the thickness of the water barrier and the risk of the roof burst water. The thickness of the water barrier is inversely proportional to the risk of sudden water on the roof, i.e., the thicker the water barrier on the roof, the lower the risk of sudden water on the roof, and vice versa, the greater the risk of sudden water on the roof of the coal seam.

From Fig. 4h, the distribution of the cumulative thickness of the water-resisting layer in the study area is quite different. The thickness of the water-resisting layer in the north of the 1303 working face and 1301 working face is thicker than 40 m. The thickness of the water-resisting layer on the 1300 working face is relatively thin. From the factor of the water-resisting layer, most areas in the north of 1300 working faces and the middle of 1301 working faces have a water inrush threat.



3. Brittle plastic ratio of the roof The water resistance of the water-resisting layer is mainly related to the proportion of brittle rock and plastic rock in the water-resisting layer, and the permeability of the plastic rock is unchanged when it is subjected to tectonic stress. However, the water conductivity of brittle rock is greatly enhanced when it is subjected to tectonic stress. Under the same conditions as other factors, the bigger the brittle-plastic ratio of rock, the higher the proportion of brittle rock, and the worse the water-inrush resistance.

From Fig. 4i, the brittle-plastic ratio in the study area is quite different. The high value appears in the southern area of 1301 working faces, reaching 0.5 or more, and in the northern area of 1300 working faces and 1303 working faces, the ratio of brittle to plastic is about 0.5, but the ratio is relatively small in the middle of 1301 working faces and the south of 1303 working faces.

**Comprehensive zoning of the water risk assessment of the coal roof of the working face**

Based on the above analysis, the risk of roof water inrush is analyzed by the coupling technology of the AHP method of GIS. The contribution weights of the fault strength index, structural intersection, and pinch-out point, the development height of the hydraulic fracture zone, the thickness of the roof sandstone aquifer, the unit water inflow of the aquifer borehole, the geophysical water-rich anomaly area, the thickness of the roof key layer, the thickness of the roof water-resisting layer, and the thickness ratio of brittle-plastic rock to water-inrush risk are obtained by AHP. Because each factor belongs to a different type, its dimension can't be compared, so its data are normalized first. In this choice range transformation method for data normalization processing, the nine factors are divided into the benefit factors (such as the index of fault strength, the crossing point of structure, and the point of collapse) and the cost factors (such as the thickness of the water-resisting layer and the thickness of the key layer), which are positively related to the water inrush, and through (1) and (2) two-way processing.

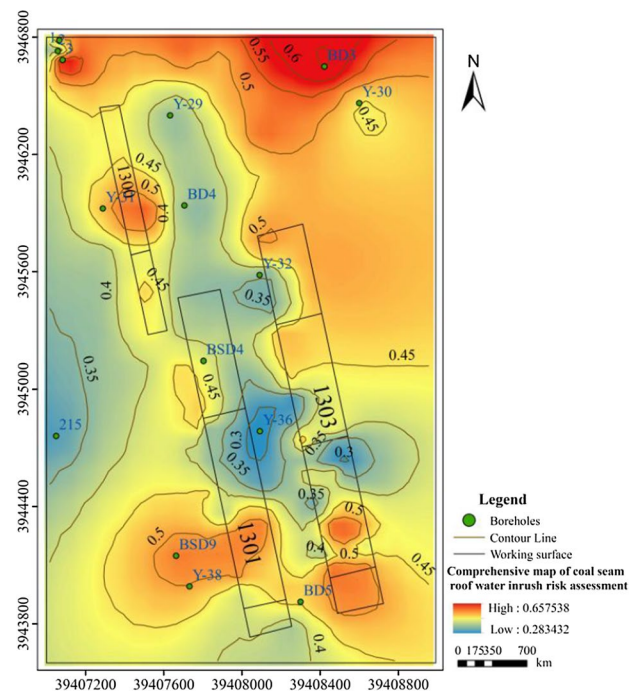
The benefit factor:

$$X_i = \frac{x_i - \min x_i}{\max x_i - \min x_i} \quad i = 1, 2, \dots, n \tag{1}$$

Cost factors:

$$X_i = \frac{\max x_i - x_i}{\max x_i - \min x_i} \quad i = 1, 2, \dots, n \tag{2}$$

In the formula, Xi is the data after normalization, xi is the data before normalization, max (xi) and min (xi) are



**Fig. 5** Comprehensive map of coal seam roof water inrush risk assessment

**Table 6** Coal seam 3. roof water inrush risk index zoning threshold

Partition	Safety zone	Sub-safety zone	Transition area	Sub-hazardous areas	Hazardous areas
Threshold value	0.2834	0.3788	0.4287	0.4756	0.5460

the maximum and minimum values of the original data, and n is the number of the original data.

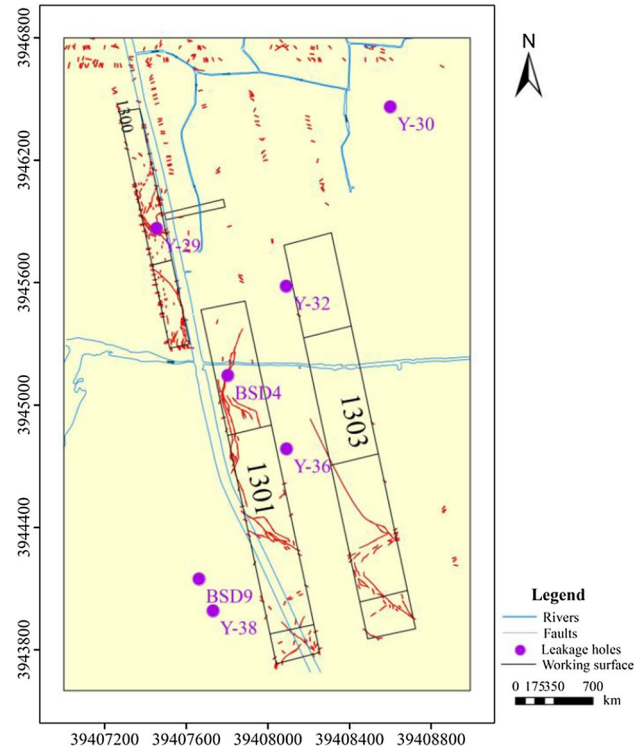
Based on the normalized data, a thematic map of the normalized factors is established according to the weight value of these factors. Using the powerful data management and spatial analysis functions of GIS and the information fusion technology to process the calculation results of AHP, and using the intuitive 9 thematic maps to carry on the compound superposition, a comprehensive zoning map of the water inrush risk of sandstone aquifers in coal seam roofs is generated (please see Fig. 5). The overall water inrush risk of the study area was classified into 5 categories by using the natural discontinuity point classification method, and then according to the partition threshold (Table 6), the study area is divided into 5 areas: hazardous area, sub-hazardous area, transition area, sub-safety zone, and safety zone.

### Test of the evaluation results

According to the investigation account of water inrush in the past years in the Lilou coal mine, the actual water inrush point information in the working area is mapped (please see Fig. 6). By comparing the comprehensive zoning map of the roof water inrush risk assessment of coal seam 3 with the sketch map of water leakage drilling in the sandstone aquifer

of Shihezi Formation, the accuracy of the comprehensive zoning for the risk assessment of water inrush from the coal seam roof is verified.

In Fig. 6, there are 7 water inrush points, among which 3 are in the more dangerous area, 2 are in the transition area, and 2 are in the safe area. The analysis shows that the water inrush on Y-29 and BSD4 is mainly caused by faults, especially Y-29. The water inrush on Y-29 is caused by the activation of the Fy15 fault and the communication of the overlying aquifer. It is inferred that the water inrush on Y-32 may be caused by some small fissures connecting the water-rich abnormal area in the north of the 1303 working face. Through the above verification, it is proven that the model of coal seam roof water inrush constructed in this paper is consistent with the actual situation, and the evaluation result is reasonable and accurate. Photoed by Qingfeng Tian on 28 March 2023 at the water inrush point at the 1303 working face of the lilou coal mine (Fig. 7).

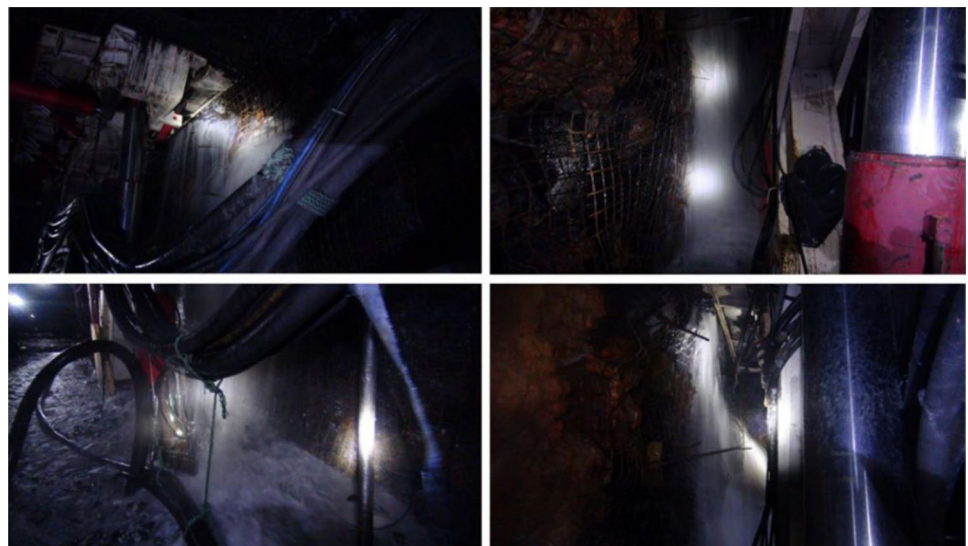


**Fig. 6** Schematic diagram of making borehole in sandstone aquifer of Shihezi Formation

### Conclusion

1. Based on the analysis of key factors of roof water disaster in mining under thick topsoil in the Lilou coal mine of Juye County coalfield, the author combined with many years of on-site experience of mine water disaster prevention and control, the water-rich property of roof aquifer, the water-resisting property of roof aquifer and the characteristics of geological structure and fracture development are comprehensively considered, nine key factors, such as fault strength index, tectonic crossing point, and pinch-out point, development height of water-conducting fracture zone, the thickness of roof sandstone aquifer, unit water inflow of aquifer borehole, geophysical water-rich anomaly area, thickness of roof

**Fig. 7** Water inrush scene map of 1300 working face





key layer, thickness of roof water-resisting layer and thickness ratio of brittle-plastic rock, are determined, these factors together affect the occurrence of water inrush disasters in coal seam roof.

2. Based on the powerful spatial data processing system of GIS, a thematic map of key factors of water protrusion on the roof of the coal seam in the Lilou coal mine in the study area was established, and the hierarchical model of evaluation indexes and the weight values of each control factor were determined in combination with the AHP. According to GIS information fusion, this paper comprehensively evaluates the degree of influence of each key factor on the roof water inrush of coal seam 3 in the Lilou coal mine.
3. In the light of the GIS and AHP coupling "Three sides, nine points" roof water inrush risk prediction method, a roof sandstone aquifer water risk prediction model was established to predict the water risk of the roof of coal seam 3 in the Lilou coal mine. The results of the water risk evaluation show that the water risk of the entire 1300 working face is relatively high, especially in the central area; the water risk of the 1301 working face is higher in the south side, followed by the possibility of water risk in the northwest side; the 1302 working face is the most complicated working face, with the highest water risk in the south, followed by the north side; but due to the presence of a large number of water-rich anomalies in the working face, there are water risks in its central part. There are also sporadic areas with the possibility of water protrusion. Based on the prediction, it is found that the evaluation model of the water inrush risk of the roof sandstone aquifer can deal with the fusion of different influence indexes, the final evaluation results can meet the actual needs of production, and the evaluation model can provide a new idea for the prevention and control of roof water disasters in the mining area.

**Funding** This article has not received any financial support.

## Declarations

**Conflict of Interest** This article has no conflicts of interest with any organization or individual.

**Ethical approval** Submitted works should be original and have not been published elsewhere, in whole or in part, in any form or language. The manuscript has not been simultaneously submitted to multiple journals for review.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes

were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

## References

- Bu Q, Chen C, Yang C, Meng X, Guan Y (2005) Water-richness zoning index of coal seam roof rock and its water surge prediction. *J Shandong Univ Sci Technol (natural Science Edition)* 03:28–31
- Cheng J, Zhao J, Dong Y et al (2020) Quantitative prediction of water-richness in rock formations by the transient electromagnetic method in mines based on LBA-BP. *J Coal* 45(01):330–337
- Ding H, Zhan R, Li H et al (2022) AHP and GIS-based evaluation of the risk of water burst on the roof of 11–2 coal seam in Xinji mining area. *Coal Sci Technol* 43(02):87–93
- Dong F, Yin H, Cheng W, Li Y, Qiu M, Zhang C, Tang R, Xu G, Zhang L (2022) Study on water inrush pattern of Ordovician limestone in North China Coalfield based on hydrochemical characteristics and evolution processes: a case study in Binhu and Wangchao coal mine of Shandong Province. *China J Cleaner Prod* 380:134954. <https://doi.org/10.1016/j.jclepro.2022.134954>
- Feng S, Wu Q (2016) Study on water-richness of aquifers based on AHP-variance coefficient method integrated weighting. *Coal Eng* 48(B11):138–140
- Han C, Wei J, Zhang W et al (2022) Quantitative permeation grouting in sand layer with consideration of grout properties and medium characteristics. *Constr Build Mater* 327:126947
- Hou E, Tong R, Wang S et al (2016) Prediction of water-richness of weathered bedrock in Jurassic coal fields of northern Shaanxi by Fisher model. *J Coal* 41(09):2312–2318
- Hou E, Ji Z, Che X et al (2019) Water-richness prediction method for weathered bedrock based on the coupling of improved AHP and entropy weight method. *J Coal* 44(10):3164–3173
- Huang L, Gou Q, Han X et al (2022) Water-richness evaluation method of aquifers based on unconfirmed measure theory. *J Changjiang Acad Sci* 39(07):23–28
- Jiang W. (2022). Study on the prediction of sudden water hazard in Hanglaiwan coal mine in Yushen mining area. *China University of Mining and Technology*.
- Li Z, Zeng Y, Liu S et al (2018) Application of BP artificial neural network in water-richness evaluation. *Coal Eng* 50(08):114–118
- Liu R. (2004) Analysis of water inrush in the large span fully mechanized top coal caving face of the 5308 thick coal seam in Baodian Coal Mine[C]// geological society of china. current status of coal resources and technological advances in exploration, development, and environmental protection - Proceedings of the 2004 academic exchange meeting of the geological society of China and the coalfield geology professional committee of the China coal society. Editorial department of "coal geology & exploration," 3.
- Liu X, Fu M (2003) Awareness of sudden water in 14301 working face of Dongtan coal mine. *Shandong Coal Sci Technol* 06:9–11
- Liu T, Xu D, Shi L, Qu L, Ji K (2022) Trapezoidal collapse model to calculate the height of the overburden collapse zone in coal seam mining: an example from Guo'Jiahe Coal Mine. *Western China Energy* 256:124609
- Luo B. (2014). GIS-based analysis of water damage conditions in roof slabs and comprehensive evaluation of multi-source information-Take Pingshuo Gongsan Mine 39110 working face as an example. *China University of Mining and Technology*.

- Ma L, Zhao B (2019) Calculation method of the unit water influx of borehole for water release test in roof aquifer. *China Safety Prod Sci Technol* 15(03):49–54
- Shi L, Zhang R, Xu D et al (2020) Water prediction of floor plate protrusion based on GWO-Elman neural network. *J Coal Sci*. 45(7):2455–2463. <https://doi.org/10.13225/j.cnki.jccs.DZ20.0716>
- Wang M. (2007). Establishment and application of prediction model of mine roof surge based on grey theory. Shandong University of Science and Technology.
- Wang Z (2008) Study on the influence of the main key layer of overburden on the evolution of hydraulic fractures. *China Univ Mining Technol*. <https://doi.org/10.3321/j.issn:1000-6915.2009.02.023>
- Wang H, Dong S, Qiao W et al (2021) Construction and application of a remote service cloud platform for water damage prevention and control in mines. *Coalfield Geol Explor* 49(01):208–216
- Wang P, Jiang Y, Ren Q (2022) Roof hydraulic fracturing for preventing floor water inrush under multi aquifers and mining disturbance: a case study. *Energies* 15:1187
- Wei J, Zhao Z, Xie D et al (2020) Evaluation of water-richness of sandstone aquifers based on lithology and structural characteristics. *J Shandong Univ Sci Technol (natural Science Edition)* 39(03):13–23
- Wu Q, Fan Z, Liu S et al (2011) Water-richness index method based on GIS information fusion for aquifer evaluation. *J Coal* 36(07):1124–1128
- Wu Q, Wang Y, Zhao D et al (2017) Water-richness evaluation of loose aquifers based on sedimentary characteristics. *J China Univ Mining Technol* 46(3):460–466
- Xiao L, Li F, Niu C et al (2022) Evaluation of water inrush hazard in coal seam roof based on the AHP-CRITIC composite weighted method. *Energies* 16(1):114–114
- Xu D, Shi L, Qu X, Tian J, Wang K, Liu J (2019) Leaching behavior of heavy metals from the coal gangue under the impact of site Ordovician limestone karst water from closed Shandong coal mines. *North China Energy & Fuels* 33(10):10016–10028
- Xu D. (2017). Study on the failure mechanism and model of arch-fractured rock mass under mining conditions. China University of Mining and Technology (Beijing).
- Yao X, Hou E, Niu C et al (2021) Evaluation of water-richness of coal bed roof aquifers based on GIS. *China Coal Geol* 033(003):20–24

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.