CrossMark

ORIGINAL ARTICLE

Vulnerability assessment of water bursting from Ordovician limestone into coal mines of China

Yifan Zeng[1,2] · Qiang Wu[1,2] · Shouqiang Liu[1,2] · Yanliang Zhai[3] · Wei Zhang[4] ·
Yuanzhang Liu[5]

Abstract No. 10 coal seam in Wangjialing Coal Mine is threatened with floor water bursting from aquifers underlying the coal seam. A geographic information system (GIS)-based analytic hierarchy process (AHP) vulnerability index method was used to assess the floor water bursting. Based on detailed analysis of the geological and hydrogeological conditions of the mine, eight main factors were determined that control the No. 10 coal seam floor water bursting from the karstified Ordovician limestone. Subsequent to acquisition and normalization of the main controlling factor data, the sub-thematic layers of each dominating factor and the overlay layer were established using GIS for the eight factors. AHP was used to determine the weight of each main controlling factor. The GIS-based AHP vulnerable evaluation model resulted in coal floor water bursting vulnerability zoning scheme for the coal mine, which is used for taking necessary control measures to avoid water bursting.

Keywords Coal floor water bursting · Ordovician karst water · AHP · Wangjialing Coal Mine · China

✉ Yifan Zeng
  zengyifan_1011@sina.com

1 China University of Mining and Technology (Beijing),
   Beijing 100083, China

2 National Engineering Research Center of Coal Mine Water
   Hazard Controlling, Beijing 100083, China

3 The 4th Geological Team of Hebei Geology and Mining
   Bureau, Chengde 067000, China

4 Northwest Nonferrous Survey Engineering Co. Ltd,
   Xi'an 710054, China

5 Beijing Institute of Hydrogeology and Engineering Geology,
   Beijing 100195, China

Introduction

Mine water inrush is one of the main disasters during coal mine construction and production in China and accounts for a large proportion of the nation's coal mine disasters and accidents (Bai 2009). More complicated hydrogeological conditions have been experienced with the increase in mining depths and mining intensity. Threatens from the confined aquifers underlying the coal seams have become more and more serious, which directly affects coal mine safety and high-efficiency production (Wu et al. 2004, 2013; Wu and Wang 2006; Yu et al. 2007). Water inrush from coal seam floor is considered as an engineering problem, most of coal mines facing in China, in the process of mining, and it is not readily described by mathematical equations (Coalfield Geological Central Bureau of China 2000; Wu and Zhou 2008; Wu et al. 2009a, 2011a). The water inrush coefficient assessment method introduced in Jiaozuo City in the 1960s has been widely used by Chinese coal mines because of its simplicity in calculation and implementation. This method has played an important role in reducing water inrushes from occurring in coal mines of China. Although the equation for calculating the water inrush coefficient has been revised multiple times to account for various factors in site-specific applications, this method has flaws. The method considers only two indices: the thickness of aquiclude and groundwater pressure to aquiclude floor (Duan 2003; Guan 2011; Wu et al. 2013). Furthermore, the water inrush critical value is an empirical value that was typically estimated from the reported water inrush incidents. Because geological and hydrogeological conditions of coal mines are often heterogeneous in different areas, the water inrush coefficient threshold value calculated from one area may not be applicable to other areas (Coulthard 1999; Liu 2007). So it is imperative to

adopt a new technology to accurately describe so complex water inrush mechanism and evolution process of coal seam floor. The vulnerability index method is applied to Wangjialing Coal Mine of Shanxi province, China, to demonstrate that this new method is a viable tool in predicting water inrush risks of the mine.

Study area

The Wangjialing Coal Mine is located in the southwest of Xiangning County of Shanxi province, which is in the southernmost of Loess Plateau of Western Shanxi Province. The study area, approximately 120 km^2, is part of the Yumenkou Spring domain system. The ground surface elevation is between 419.8 and 1420.6 m above sea level (Fig. 1).

Karst features such as sinkholes and small surface depressions are present in the southeastern periphery area of the mining field. Hubei and Shunyi Rivers are seasonal, and they belong to the Yellow River system. The climate type belongs to the semiarid continental monsoon climate with an uneven distribution of annual rainfall. Concentrated rainfalls occur in July, August, and September. The annual average rainfall is 567.2 mm.

The No. 10 coal seam is in the Carboniferous Taiyuan formation and is one of the main coal seams in Wangjialing Coal Mine. The coal seam is indirectly underlain by the Ordovician limestone, which is a karstic fissure aquifer (Zeng 2016). The Ordovician karst aquifer is characterized with high potentiometric pressure and great water yield. This carbonate aquifer formation severely threats the mining of the No. 10 coal seam. So it is of great significance to develop an advanced evaluation method to evaluate the vulnerability of Ordovician karst water bursting into the mining areas. The vulnerability assessment helps with reasonable and effective prevention of water inrushes to ensure mine safety in production and improve mine economic benefit.

Geological conditions and hydrogeological characteristics of the coal mine

Wangjialing Coal Mine is mostly covered by the Quaternary strata, which are in the upper and lower valleys in the scattered stone formation. The geological formations consist of the following from old to new: Ordovician, Carboniferous, Permian, and Quaternary, as shown along the A–A′ cross section (Fig. 2). The geological structures are in general simple, and faults and folds are primary forms. Monoclinal structures strike northeast and dip to northwest. Secondary rolling folds are present and are accompanied by faults with dip angles ranging from 5° to 37°. Few
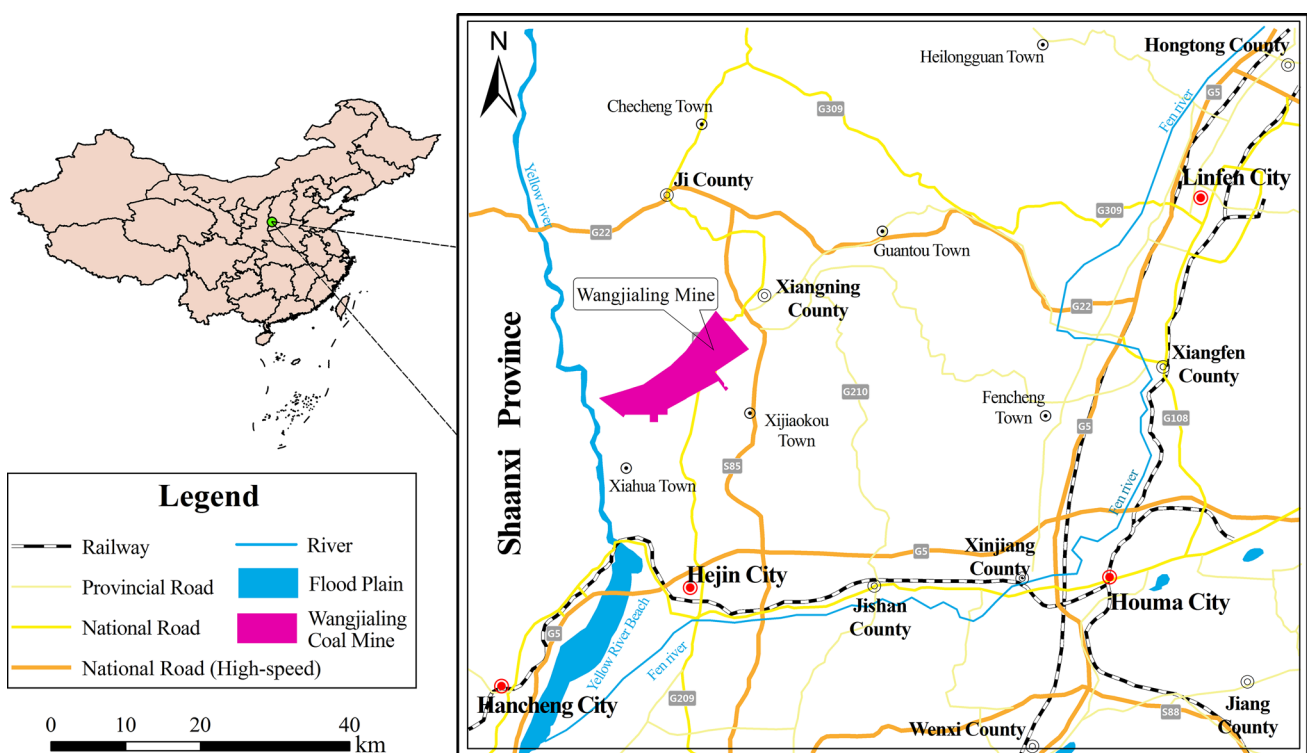
Fig. 1 Location of Wangjialing Coal Mine, China
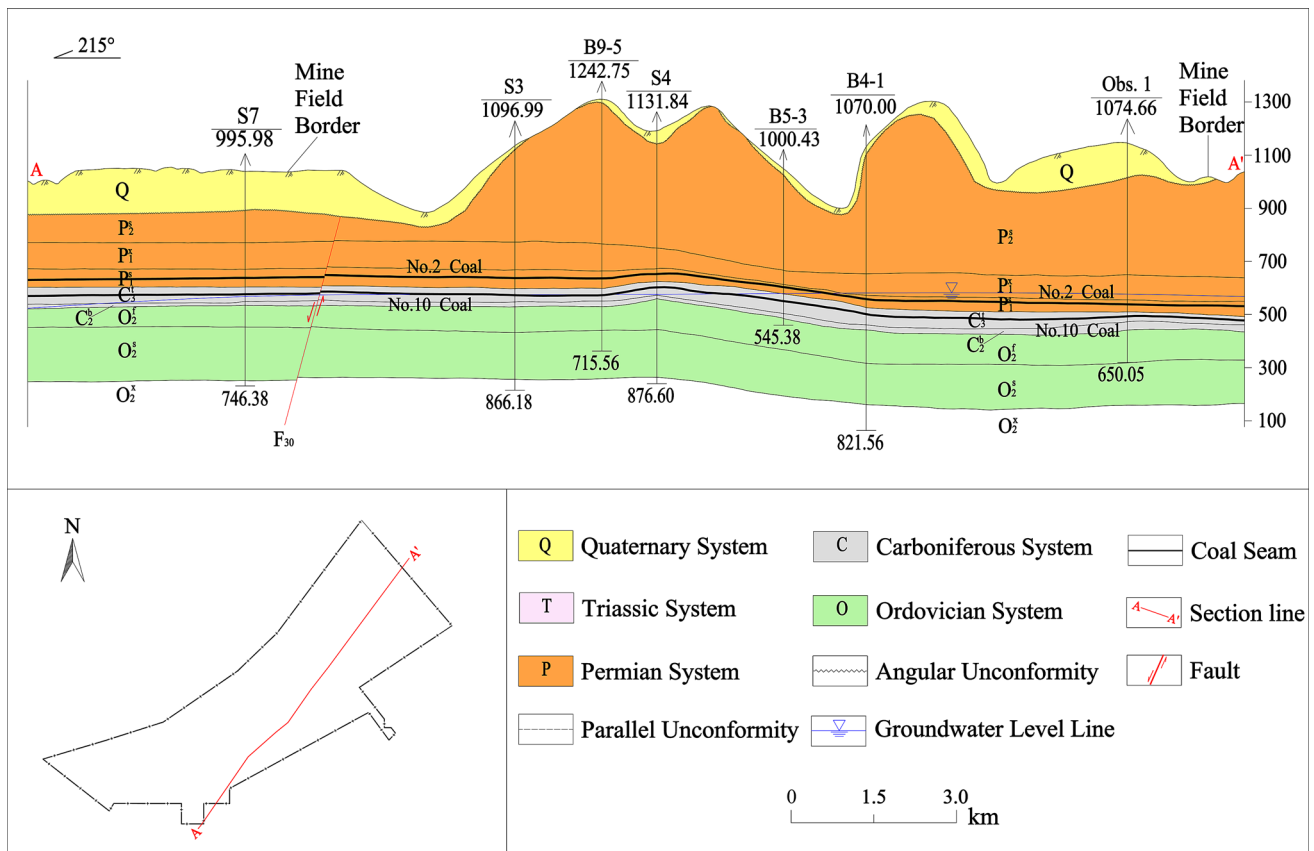
Fig. 2 Hydrogeological cross section in Wangjialing Coal Mine area (Zeng et al. 2016)

collapse columns are reported, and there is no magmatic rock intrusion.

Between the No. 10 coal seam and the Ordovician limestone confined aquifer is an impermeable layer group of the Taiyuan formation and Benxi formation. The depth to the Ordovician limestone ranges from 238.35 to 806.65 m below ground surface. The depth tends to become gradually deeper from the southeast to the northwest and from the south to the north. The Ordovician limestone aquifer is heterogeneous with strong water yield in some parts. The water level elevation in the Ordovician limestone is between 380 and 580 m above sea level. The range of pressure exerted by the Ordovician limestone aquifer to No. 10 coal seam ranges from 0 to 3.111 MPa. The overall groundwater flow direction is from northeast to southwest. The groundwater discharges to the Yellow River at Yumenkou as spring.

Regional Ordovician karst water analysis

According to topography, structure characteristics and the runoff and drainage conditions of groundwater, Wangjialing Coal Mine is located in western region of the Yumenkou karst water system, and the mine karst water transport is mainly governed by the occurrence of the system. From recharge through runoff to discharge, the Yumenkou karst water system is a complete hydrogeological unit (Fig. 3). The system is located at southwest of the southern tip of Luliangshan Longzici spring area, and the Izumiguchi elevation is approximately 398 m above sea level with the outcrops of the Cambrian and Ordovician limestone.

The boundary properties of the Yumenkou karst water system differ in structure and topography. The northern section of the eastern boundary is surface watershed between the Gaotian Mountain and Matou Mountain, extending in a north–south direction of Taitou Mine and Zhaojiawan Mine. Located in the southern section of the eastern border of the Xijiaokou line, this boundary is at elevations up to 1400 m above sea level. In the west near the Xijiaokou line, the groundwater divide is the border. The northeastern boundary is the surface watershed. In the western part, the Ordovician limestone is at depth of more than 800 m below ground surface and the water in the Ordovician limestone aquifer is stagnant. Yellow River is the western border where the groundwater discharges as springs. The southern boundary line of the Changcheng
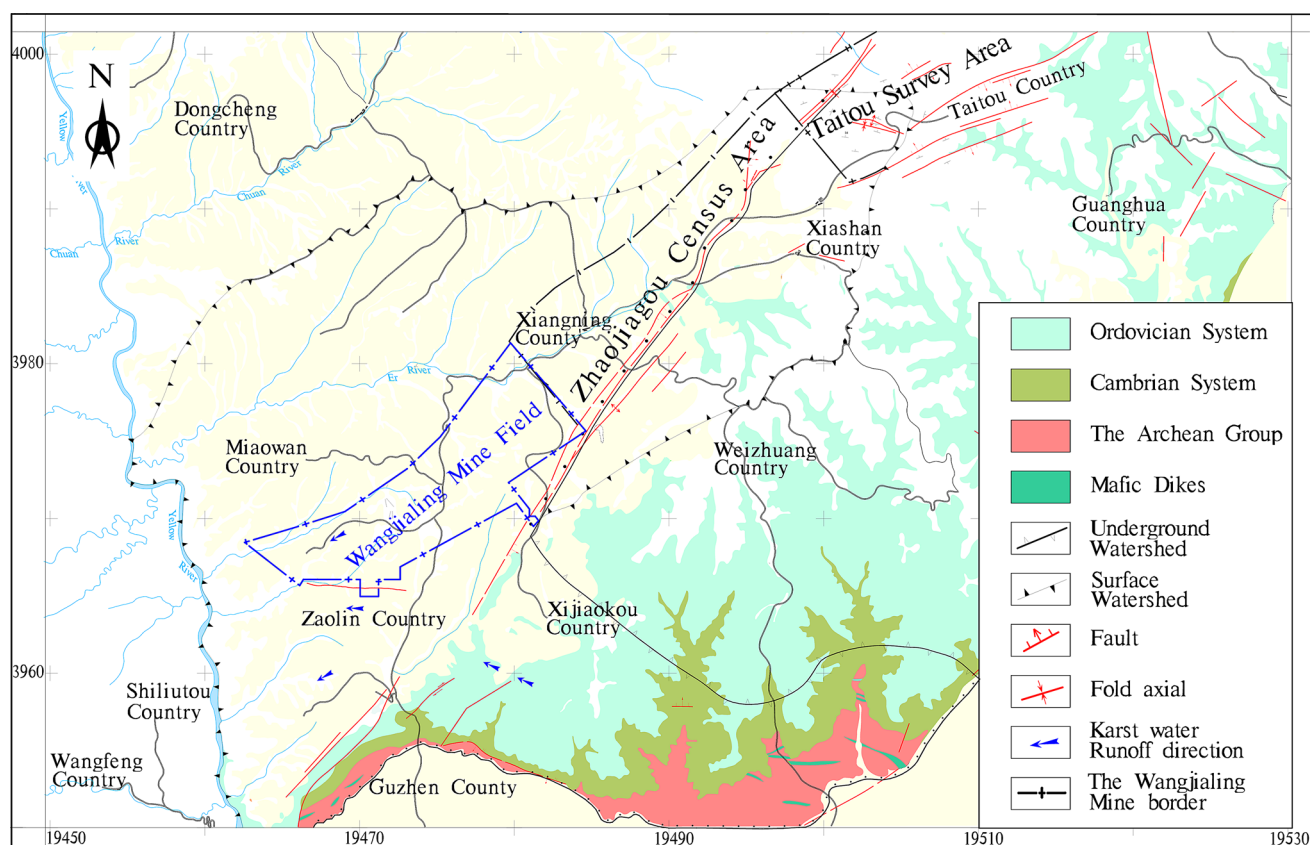
Fig. 3 Regional hydrogeology (Zeng et al. 2016)

formation consists of Proterozoic strata, which is an impermeable boundary of the system.

Precipitation is the main recharge source of the karst groundwater. The recharge areas are mainly located in the eastern part of the karst water system where the carbonate rock outcrops with an exposed area of approximately 319.5 km². The exposed carbonate rocks are affected by tectonic movements and undergo long-term weathering and erosion, and they are characterized with caves, sinkholes, and other karst features. These karst features provide favorable conditions for rainfall infiltration and groundwater collection and storage migration. In addition, the distribution of the Holocene cover in the mountains and the valley by the Upper Pleistocene fluvial red, hillsides, ridge loess, partly in bushes and trees, creates even more favorable conditions for infiltration.

After receiving recharge from precipitation, the karst water flows from southeast to northwest in the eastern part of the system and discharges into Yellow River in the Yumenkou area. The water level elevation ranges from 380 to 580 m above sea level. In the eastern area where the Ordovician limestone is shallow, the groundwater hydraulic gradient is 5 ‰, reflecting the strong runoff and high water yield. The karst groundwater hydraulic gradient in the mid-west is relatively large, usually 15–30 ‰, reflecting poor flow and poor runoff characteristics.

The Yumenkou area is characterized with springs that have a total flow of 1.7 m³/s. The excretion of local sites is artisanal mining excretion, as in Xiangning County sixty-four water supply wells tap the Ordovician karst aquifer at depths from 500 to 800 m below ground surface to solve the local water supply and drinking water problems. Due to the current decrease in rainfall, excessive artificial exploitation of groundwater, coal excavation, and other factors, the positions of the springs have dropped below the water level of the Yellow River. As a result, the spring flow rates are substantially reduced.

Analytic hierarchy process vulnerable index method

Introduction to analytic hierarchy process

The analytic hierarchy process (AHP) is proposed by Saaty (1977). The basic theory of AHP is well documented and discussed in Wu et al. (2013). Based on the relationship between every two elements, the AHP arranges every element in accordance with a certain subjection relation to

build the hierarchical structure model. The quantitative analysis according to a certain standard leads to a judgment matrix to calculate the maximum eigenvalue and correspondent orthogonalization eigenvector. Then, the weighting of each element in the same layer representing its relative importance is achieved. On this basis, the weighting of each factor of every layer is determine and passed on the information of upper layer to next layer, and then, the total hierarchy permutation of relative importance for all elements is determined. Finally, based on the results of the total hierarchy permutation, the problem to be solved and studied can be analyzed and decided.

Evaluation steps of vulnerable index method

1. Utilize spatial data processing function of geographic information system (GIS) to quantize and normalize major controlling factors and develop quantified thematic maps that can be expressed intuitively for each of the major controlling factors (Chen 1999; Wu et al. 2013).
2. Comprehensively analyze the major controlling factors and determine their weights to overall goal by using AHP method, and then, set up evaluation model to forecast water inrush model.
3. Utilize the spatial images processing function of GIS to overlay each thematic map in accordance with the weight of every main controlling factor and thus build a vulnerable index distribution map for water inrush of coal seam floor.
4. Determine a threshold value of vulnerability division according to frequency histograms of vulnerable index of water inrush in each unit of the study area and develop evaluation zoning maps; rationally evaluate the risk of water inrush of coal seam floor.

## Application of vulnerable index method to Wangjialing Coal Mine

Determination of main controlling factors

It is essential to select reasonable and appropriate major controlling factors that are important to develop AHP model and achieve accurate result. Based on detailed analysis of the geological and hydrogeological conditions of Wangjialing Coal Mine, eight major factors are selected and they are: (1) potentiometric pressure of the Ordovician limestone aquifer; (2) water yield property of the Ordovician limestone aquifer; (3) equivalent thickness of effective aquiclude underlying No. 10 coal seam floor; (4) brittle rock thickness beneath zones destroyed by underground

stress of No. 10 coal seam floor; (5) paleocrust on top of the Ordovician limestone; (6) distribution of faults and folds; (7) intersections and endpoints of structures; and (8) fault scale index.

Data collection and quantization and construction of thematic maps for main controlling factors

1. Thematic map of potentiometric pressure of the Ordovician limestone aquifer: The essence of coal seam floor water inrush is due to loss of the stabilization of the effect that is formed by potentiometric pressure of aquifer acting on the confining bed. Water pressure is one of the most important factors affecting water inrush disasters of coal seam floor. The greater the pressure is, the greater the possibility of water inrush is. Figure 4a is a thematic map of potentiometric pressure of the Ordovician limestone aquifer calculated according to hydrographic data of Wangjialing Coal Mine in December 2014.
2. Thematic map of water yield property of the Ordovician limestone aquifer: Water yield property refers to the productivity (quantity and duration) of the aquifer, and its value directly influences quantity and time of water inrush from coal seam floor. The unit water inflow of drilling can be used to measure aquifer water yield property. Unit water inflow from drilling data collected in the study area was converted into a standardized format based on Chinese regulations for mine water prevention and control: Pore size is 91 mm, and drawdown of pumped water is 10 m. The thematic map of the Ordovician limestone aquifer water yield property is shown in Fig. 4b.
3. Thematic map of the equivalent thickness of effective aquiclude: Aquiclude thickness has an inhibitory effect on coal seam floor water inrush. The water resistance of an aquiclude is related to aquiclude thickness, strength, and lithological composition. In order to calculate equivalent thickness of the effective aquiclude from No. 10 coal seam to Ordovician limestone aquifer, we firstly consider the influence of zone destroyed by underground stress and zone of pressure water inducing height (the height value is 0 because of existence of paleocrust of weathering). Then, we calculate the equivalent effective aquiclude that is converted from different lithological thickness within effective aquiclude. We finally get the thematic map of (Fig. 4c).
4. Thematic map of brittle rock thickness beneath zones destroyed by underground stress: Lithology composition, spatial distribution, and thickness of aquiclude play an important role in coal seam floor water bursts. In the study area, brittle rock in the aquiclude of No. 10
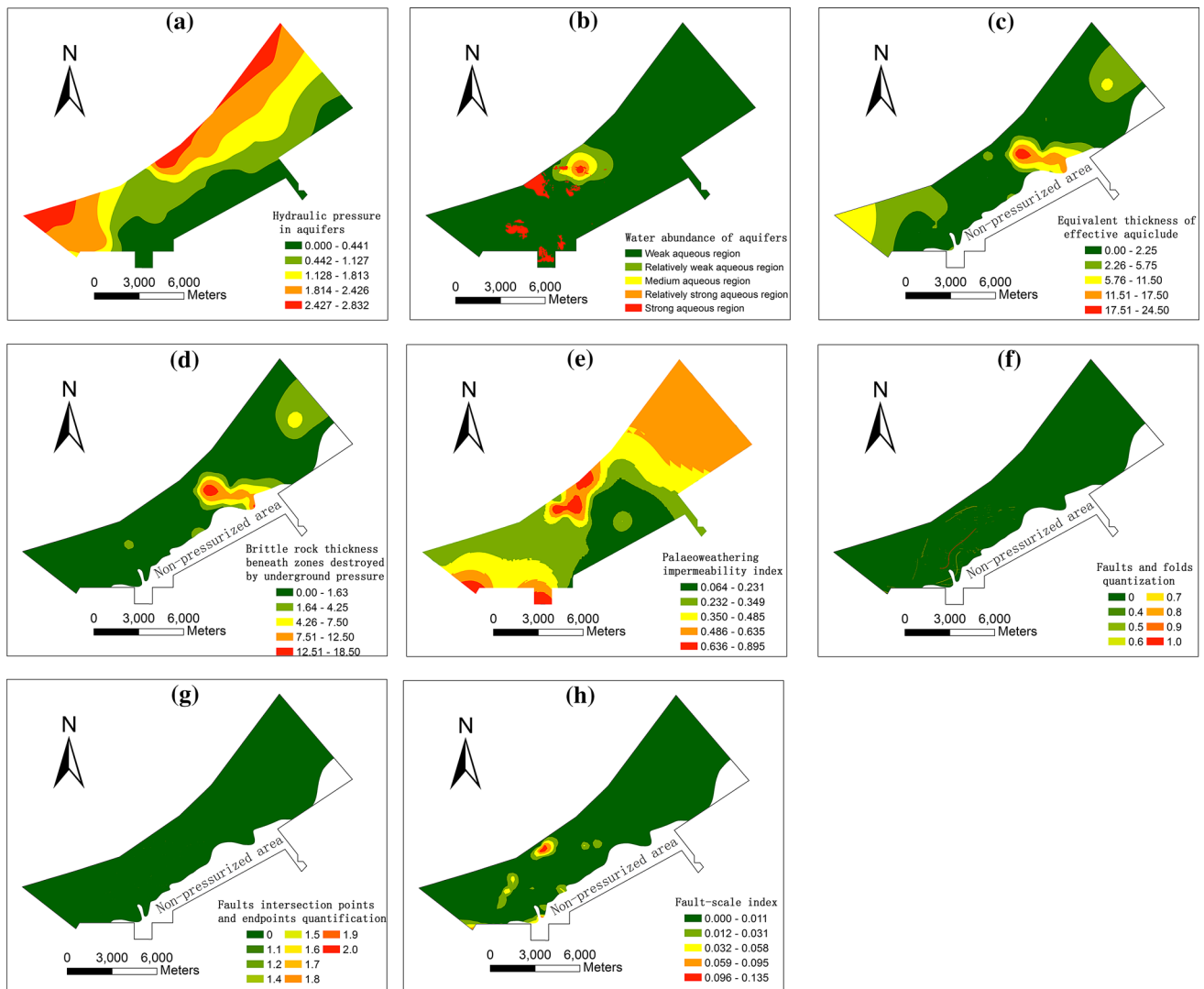
Fig. 4 Thematic map of main controlling factors

coal seam floor has characteristics: hard, strong pressure resistance, and excellent water-blocking properties. The effectiveness of these properties varies with location; it has a pivotal role in preventing water inrush only if the brittle rock is located within effective aquiclude. Brittle rock thickness of the aquiclude beneath zones destroyed by underground is counted based on drilling logs. Figure 4d is a thematic map of brittle rock thickness beneath zones destroyed by underground pressure.

5. Thematic map of paleocrust: The North China-type coalfields in China have gone through long-term denudation after the Ordovician limestone deposition, which led to weathering of the karstic-fractured Ordovician limestone. The fractures are typically filled with clay, calcite, and red clay and form the aluminum mudstone of Benxi group. The fillers cause the permeability of paleocrust to decline sharply. The paleocrust prevents water flowing and increases the total thickness and resistance property of the aquiclude. Based on the thickness of paleocrust of weathering, core recovery, and development and filling degree of karstic fracture, the thematic map of paleocrust is developed and shown in Fig. 4e.

6. Thematic map of faults and folds distribution: Faults and fracture planes are the weak interfaces where confined water breaks through the coal seam floor. Such structural defects, especially fault zones, damage the integrity of rock mass, conduct water easily, shorten the distances between the coal seam and the aquifer, and increase possibility of water bursting from the underlying aquifer. Moreover, water-blocking effect is dramatically reduced because of rock body ruptured, where axial surface of the anticlinal fold is

squeezed. Figure 4f is a thematic map of faults and folds distribution referring to well field structure outline map of Wangjialing Coal Mine.

7. Thematic map of structural intersections and endpoint distribution: Faults and folds spreading and crossing in space form a certain pattern pinching out and intersecting points. Water conductivity increases at intersections of fault and fault, fault and fold, fold and fold, and endpoints. We establish a thematic map of these intersections and endpoints (Fig. 4g) according to the structure outline map.

8. Thematic map of the fault scale index: The fault scale index refers to the sum of all faults throw and length in per unit area, and reflects size and density of the faults. The fault scale index is directly proportional to both the size and density of the faults. The greater the fault scale index is, the greater the possibility of water bursts. According to the area of the study region and distribution characteristics of the faults, we establish a grid unit of 500 m × 500 m and then count fault throw and corresponding strike length in each grid unit to calculate the fault scale index. Figure 4h is a thematic map of the fault scale index with the coordinates at the center of the grid unit.

AHP model design

Model construction and judgment matrices

As discussed in Wu et al. (2013), the research objectives are divided into three hierarchical levels (A, B, C) after the main controlling factors affecting No. 10 coal seam water inrush are analyzed. The Ordovician limestone water bursting vulnerability assessment of No. 10 coal seam is the ultimate objective that is treated as the target layer (A level). The possibility of water inrush events determined by three groups of information consisting of confined aquifer, aquifuge, and geological structure, and they constitute the criteria layers (B level). The main controlling factors, as the decision layer (C level), affect the water inrush event (C level) (Wu et al. 2009b, 2011b). The hierarchical structure is shown in Fig. 5.

Once the hierarchical model is established, the affiliations of elements between the upper and lower levels are identified (Wu et al. 2013). Expert analysis is used to give the weight for all the main controlling factors, according to the 1–9 scales, as proposed by Saaty (1980). The judgment matrices are established by the following process (Wu et al. 2013):

1. List all the main controlling factors.
2. Evaluate relative importance of each factor and assign a quantitative value for each factor based on experts' experience from water inrush accidents.

3. Compare total score for each factor according to the final cumulative score and generate expert evaluation sets with regard to the main controlling factors.
4. Establish a judgment matrix for assessing coal seam water inrush.

Calculate weight of main controlling factors

The calculated weights of main controlling factors are presented in Table 1.

Water inrush vulnerability assessment zoning of coal floor

Removing the data dimension and establish thematic maps of the main controlling factors

In order to compare and calculate data of main controlling factor with different dimensions, these relevant data are normalized in accordance with Eq. (1):

$$A_i = a + \frac{(b - a) \times (x_i - \min(x_i))}{\max(x_i) - \min(x_i)} \tag{1}$$

where A_i is the normalized data; a and b represent the lower limit and upper limit of normalization range, respectively, with values from 0 to 1; x_i is the original data; and $\min(x_i)$ and $\max(x_i)$, respectively, for the main controlling factors of the minimum and maximum values of the quantization.

When performing normalization, the potential positive or negative correlation of the main controlling factors on the objective events must be considered. Wu et al. (2013) details the normalization process for each controlling factors. After finishing the data normalization, the attribute database of the controlling factors is established. The thematic maps of these eight factors are developed after processing normalized data with GIS application.

Overlay thematic maps and establish vulnerability index model

The layers of every main controlling factor that store information are compounded into one upper layer including all information of relevant factors. Then, the vulnerability index model is:

$$VI = \sum_{k=1}^{n} W_k \cdot f_k(x, y) \tag{2}$$

where VI is vulnerability index; W_k is the weight of major controlling factor k; $f_k(x, y)$ is a function about single-factor value; x and y is geographic coordinate; and n is the number of controlling factors.

Fig. 5 AHP hierarchical structure model (Wu et al. 2004)
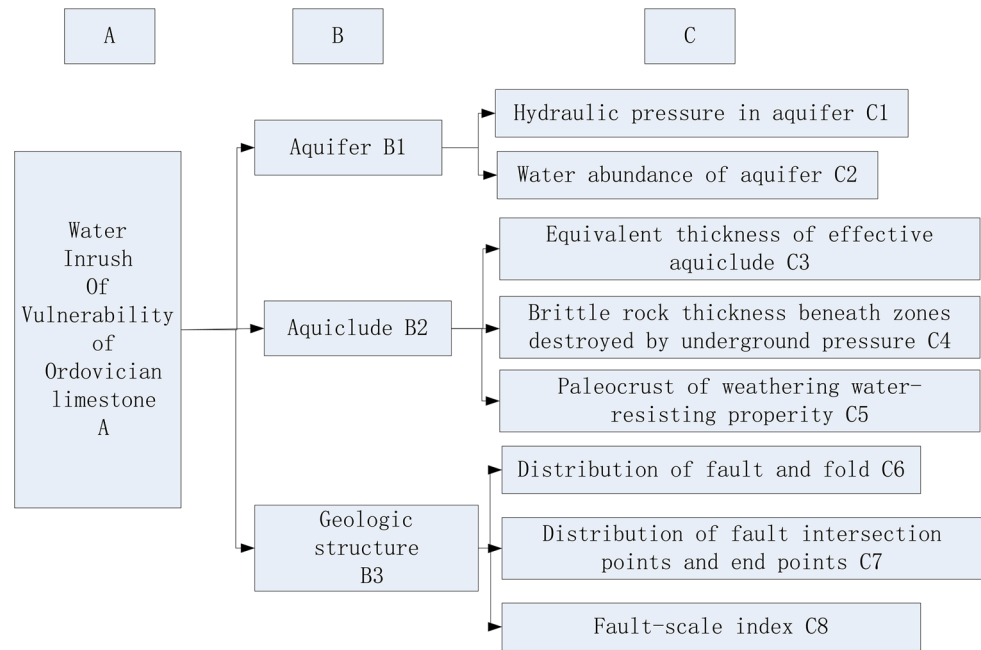
Table 1 Weights of main controlling factors for water inrush

Influential factors	Hydraulic pressure in aquifers (W1)	Water abundance of aquifers (W2)	Equivalent thickness of effective aquiclude (W3)	Brittle rock thickness beneath zones destroyed by underground pressure (W4)	Paleocrust of weathering water-resisting property (W5)	Distribution of fault and fold (W6)	Distribution of fault intersection points and endpoints (W7)	Fault scale index (W8)
Weights (Wi)	0.2467	0.1644	0.2043	0.0785	0.045	0.1652	0.0502	0.0457

In the vulnerability assessment of Ordovician limestone water bursting for No. 10 coal seam, the weights for main controlling factors are presented in Table 1 and $W_1 = 0.2467$, $W_2 = 0.1644$, $W_3 = 0.2043$, $W_4 = 0.0785$, $W_5 = 0.045$, $W_6 = 0.1652$, $W_7 = 0.0502$, $W_8 = 0.0457$. So the model of vulnerability assessment for Wangjialing Coal Mine No. 10 is as follows:

$$VI = \sum_{k=1}^{n} W_k \cdot f_k(x, y) = 0.2467 f_1(x, y) + 0.1644 f_2(x, y)$$
$$+ 0.2043 f_3(x, y) + 0.0785 f_4(x, y) + 0.045 f_5(x, y)$$
$$+ 0.1652 f_6(x, y) + 0.0502 f_7(x, y) + 0.0457 f_8(x, y)$$

Water inrush vulnerability assessment zoning of coal floor

The vulnerability index of water inrush in each grid cell is statistically analyzed based on above vulnerability index model. Then, take the vulnerability index frequency that requires classification as study object on the classification map, and using the Jenks optimization method (a function of GIS) (Wu et al. 2013), giving partition thresholds of 0.39, 0.42, 0.52, and 0.60 (Fig. 6). The coal seam floor water burst vulnerabilities are divided into five zones (Fig. 7): $VI \geq 0.60$, the most vulnerable areas; $0.60 < VI \leq 0.52$, potentially vulnerable areas; $0.46 < VI \leq 0.52$, transitional areas; $0.39 < VI \leq 0.46$, relatively safe areas; $VI < 0.39$, safe areas.

As shown in Fig. 7, the relatively vulnerable areas marked orange color are located in the northwest, northeast, and central part of this diggings, as well as regions affected by faults in transitional areas. In this case, the western part is a potentially vulnerable area under bigger possibility of water inrush because of bigger water pressure suffered by aquiclude seam from Ordovician limestone aquifer, smaller equivalent thickness of the effective aquiclude and brittle rock thickness beneath zones destroyed by underground pressure. The most vulnerable areas marked red color are in western and central part of this diggings, as well as places where develop faults and

Fig. 6 Frequency histogram of vulnerability index
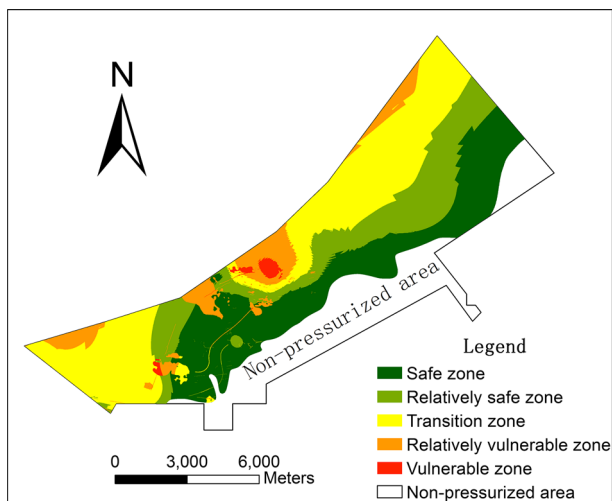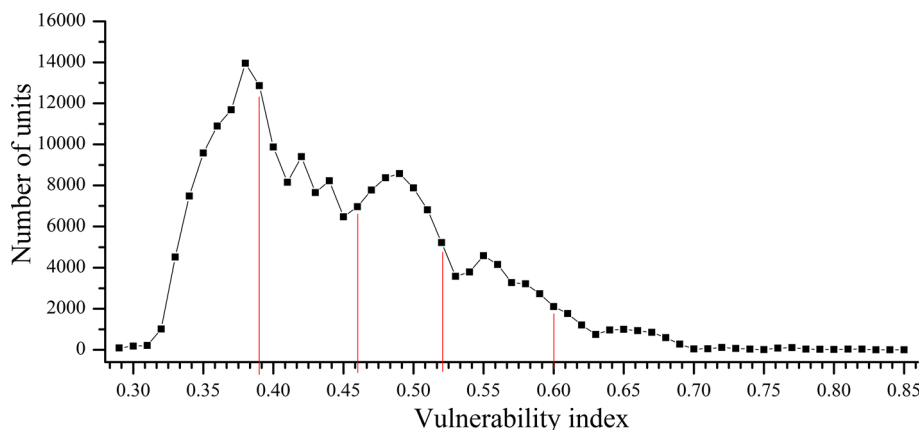
Fig. 7 Water inrush vulnerability zoning of No. 10 coal seam

folds within potentially vulnerable areas. Because these faults and folds destroy the continuity of aquiclude, they could be as water passages that directly or indirectly introduce Ordovician limestone aquifer into working face causing serious consequences. Aquiclude thickness in western part of No. 10 coal seam is relatively thin; moreover, there is no aquiclude in local area. Water yield property and structure are abundant in central part. The probability of the Ordovician limestone water inrush in these areas is the greatest, so countermeasures are recommended to take to avoid water inrush events during mining.

Comparison of assessment between vulnerability index method and water inrush coefficient method

In the 1960s, technicians from the former Ministry for Coal Industry of China proposed water inrush coefficient according to water inrush data and the experience with analysis of the national coal mine water inrush (Liu 2009). Water inrush coefficient is defined as a unit of coal seam floor impermeable layer thickness to withstand water

pressure and is a quantitative index to measure the danger level of water inrush under the condition of mining with water pressure. Chinese regulations for mine water prevention and control define this formula as following in 2009 after it is modified several times.

$$T = \frac{p}{M} \qquad\qquad (3)$$

where T is water inrush coefficient, MPa/m; p is water pressure sustained by the bottom of impermeable layer, MPa; and M is thickness of the coal floor aquiclude, m. This formula applies to coal mining and tunneling face. Water inrush coefficient of coal seam regions destroyed by tectonic is rarely more than 0.06 MPa/m, and normal region is rarely more than 0.1 MPa/m calculated with this formula according to materials for the whole country (Ministry of Coal Industry 2009).

Figure 8 shows water inrush coefficient zones for the no. 10 coal seam based on wellbores data.

As shown in Fig. 8, the traditional water inrush coefficient method divides the study area only into two zones: safe and danger. The western and northern red areas are
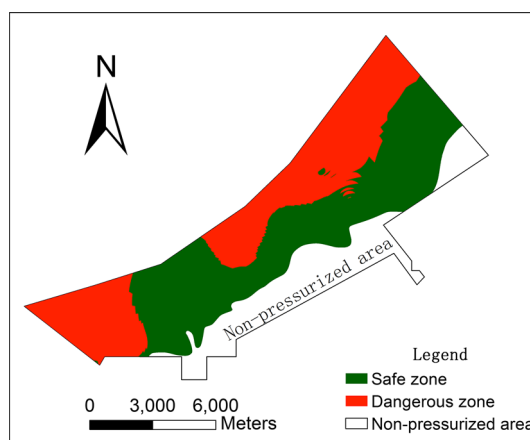
Fig. 8 Water inrush coefficient method zoning of No. 10 coal seam Ordovician limestone

danger zones that are more susceptible to water inrushes, whereas the green area is safe. Compared with the assessment result of vulnerability index method, the water inrush coefficient method ignores some important factors, such as the geological structure and water yield property of the aquifer. The assessment results shown in Fig. 8 only divided the mining area into safe and dangerous zones without the potentially vulnerable zone, transitional zone, and relatively safe zone. As a result, the prediction shown in Fig. 8 seems to be less precise than that in Fig. 7. The assessment result of traditional water inrush coefficient method cannot reflect the gradual changes in hydrogeological conditions. Such comparisons confirmed the findings in Wu et al. (2013) that the vulnerability index method is more comprehensive and provide a more representative guidance to the coal mine safe production than the traditional water inrush coefficient method.

Conclusions

Based on analysis of the coalmine situation, geological background, hydrogeological condition of Wangjialing, we applied the AHP vulnerability index method to assess No. 10 coal seam water inrush in Wangjialing Coal Mine and draw the following conclusions:

- Eight factors control the water inrush of Ordovician limestone for No. 10 coal floor seam. The eight factors are water pressure of the Ordovician limestone aquifer, water yield of Ordovician limestone aquifer, brittle rock thickness below the mine stress destruction zone, equivalent thickness of coal floor effective aquiclude, distribution of faults and folds, paleocrust, intersections and endpoints of structures, and fault scale index.
- Application of the GIS-based AHP vulnerability index method results in a division of five zones with different risking level of water inrush. Such a partition provides a scientific basis for control of water inrush and safe production for the mine.
- Making a comparison between the traditional water inrush coefficient method and the GIS-based AHP vulnerability index method confirmed the findings that the vulnerability index method is more comprehensive and provides a more representative guidance to the coal mine safe production.

References

Bai Y (2009) Causes analysis and control technology of water disaster in coal mine. Coal Technol 28(11):85–87 **(in Chinese)**

Chen S (1999) Introduction of geography information system. Science Press, Beijing, pp 101–163 **(in Chinese)**

Coalfield Geological Central Bureau of China (2000) Coalfield hydrogeology of China. Coal Industry Publishing House of China, Beijing, pp 15–59 **(in Chinese)**

Coulthard MA (1999) Applications of numerical modelling in underground mining and construction. Geotech Geol Eng 17(3):373–385

Duan S (2003) Probe into the calculation formula of coefficient of water bursting from coal seam floor. Hydrogeol Eng Geol 1:96–99 **(in Chinese)**

Guan E (2011) Water bursting coefficient and coal mine water disaster control. Coal Eng 1:46–48 **(in Chinese)**

Liu D (2007) Theoretical basis of water inrush coefficient in north china coalfield and practice in the Huainan mining area. Coal Sci Technol

Liu Q (2009) A discussion on water inrush coefficient. Coal Geol Explor 3:85–88; 37(4):34–42 **(in Chinese)**

Ministry of Coal Industry (2009) The regulations for mine water prevention and control. Coal Industry Publishing House of China, Beijing **(in Chinese)**

Saaty TL (1977) A scaling method for priorities in hierarchical structures. J Math Psychol 1:234–281

Saaty TL (1980) The analytic hierarchy process. McGraw-Hill, New York

Wu Q, Wang M (2006) Characterization of water bursting and discharge into underground mines with multi-layered groundwater flow systems in the north China coal basin. Hydrogeol J 14(6):882–893

Wu Q, Zhou W (2008) Prediction of groundwater inrush into coal mines from aquifers underlying the coal seams in China: vulnerability index method and its construction. Environ Geol 56(2):245–254

Wu Q, Wang M, Wu X (2004) Investigations of groundwater bursting into coal mine seam floors from fault zones. Int J Rock Mech Min Sci 41(4):557–571

Wu Q, Zhou W, Wang J (2009a) Prediction of groundwater inrush into coal mines from aquifers underlying the coal seams in China: application of vulnerability index method to Zhangcun Coal Mine. China Environ Geol 57(5):1187–1195

Wu Q, Zhou W, Pan G, Ye S (2009b) Application of a discrete-continuum model to karst aquifers in North China. Ground Water 47(3):453–461

Wu Q, Liu Y, Yang L (2011a) Using the vulnerable index method to assess the likelihood of a water inrush through the floor of a multi-seam coal mine in China. Mine Water Environ 30(1):54–61

Wu Q, Liu Y, Liu D, Zhou W (2011b) Prediction of floor water inrush: the application of GIS-based AHP vulnerable index method to Donghuantuo coal mine, China. Rock Mech Rock Eng 44:591–600

Wu Q, Fan S, Zhou W, Liu S (2013) Application of the analytic hierarchy process to assessment of water inrush: a case study for the No. 17 coal seam in the Sanhejian Coal Mine, China. Mine Water Environ 32:229–238

Yu B, Zhu W, Xu J (2007) Numerical simulation of surface subsidence induced by deep mining. J Min Saf Eng 24(4):422–426 **(in Chinese)**

Zeng Y (2016) Research on the risk evaluation method of groundwater bursting from aquifers underlying the coal seams and its applications in the Coalfield of North China. Unpublished PhD dissertation. Beijing, China: China University of Mining & Technology, Beijing (in Chinese)

Zeng Y, Liu S, Zhang W, Zhai Y (2016) Application of artificial neural network technology to predicting small faults and folds in coal seams. China. Sustain Water Resour Manag 2(2):175–181