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TECHNICAL ARTICLE

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

Qiang Wu · Shukai Fan · Wanfang Zhou · Shouqiang Liu

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Abstract Disasters caused by water inrush affect many coal mines in China. In order to predict and prevent water inrushes during mining of the no. 17 coal seam in the Sanhejian coal mine, the factors that affect water inrush from the underlying Ordovician limestone were studied using the analytic hierarchy process (AHP). The AHP method is based on the geographic information system, through which the sub-thematic layer and the overlying layers of each dominating factor were constructed. An expert system was used to calculate weighting for each factor. Integration of the controlling factors through the AHP allowed us to develop a vulnerability index map in which the mining area was divided into different zones according to the risk level for water inrush during mining. Furthermore, water control measures were recommended in response to each risk level.

Keywords Analytic hierarchy process · Flood · Safety · Risk management · Water inrush · Vulnerability index

Introduction

Mine water inrush events often occur during coal mine construction and production in China and account for a large proportion of the nation's coal mine disasters and accidents (Bai 2009). Mining depths and mining intensity have increased, causing the encountered hydrogeological conditions to become more complicated; water inrush threatens mine safety and coal mine productivity (Wu and Wang 2006; Wu et al. 2004; Yu et al. 2007). One challenge is to prevent or predict water inrushes from the confined karst aquifer that underlies many of the coal seams. Because water inrush from the underlying aquifer is a nonlinear dynamic process, its occurrence is controlled by multiple factors and involves complex mechanisms. Dynamic nonlinear processes are not readily amenable to mathematical equations (Wu and Zhou 2008; Wu et al. 2009a, b). The water inrush coefficient, introduced in Jiaozuo City in the 1960 s as documented by Liu (2009) has been widely used by most Chinese coal mine hydrogeologists because it had the advantages of being a simple physical concept, convenient to calculate, and easy to use. It has been modified several times to better reflect actual water inrush conditions and has played a positive role in resolving the dangerous problem of water inrush from underlying aquifers in China.

However, the water inrush coefficient method only considers two factors: the potentiometric pressure of the underlying confined aquifer and the thickness of the aquitard that functions as a water barrier between the coal seam and the underlying aquifer. Other factors also govern water inrush from underlying aquifers (Duan 2003; Guan 2011). In addition, the water inrush coefficient threshold is empirical and typically determined using reported water inrush incident statistics. Because geological and hydrogeological conditions can vary significantly in different areas, considerable deviations can exist between results of water inrush assessments and reality (Liu 2007). Therefore, a new method is needed to evaluate water inrush vulnerability from underlying aquifers.

Q. Wu (✉) · S. Fan · S. Liu
College of Geoscience and Surveying Engineering, China Univ of Mining and Technology, Beijing 100083, China
e-mail: wuq@cumtb.edu.cn

W. Zhou
ERT Inc, 12710 Buttonwood Ln, Knoxville, TN 37934, USA
e-mail: wanfang.zhou@ertcorp.com

Study Area

The Sanhejian Coal Mine is located in the town of Longgu, in Pei County, about 92 km southeast of Xuzhou City, and 19 km northwest of Yutai County. The studied area is part of the Huanghuai Plain, and the land slopes gently towards the northeast. The ground level is generally between 34.3 and 37.04 m above sea level (Fig. 1).

The study area is in the transition zone of the Yangtze River and Yellow River Basins. There are several surface streams in the study area including natural rivers such as the Dasha River, Hongwei River, and Fuxing River and one man-made channel, the Beijing-Hangzhou Canal. The slope of the streams is less than 1/2000.

Pei County is located in the subtropical and warm temperate transition zone of the mid-latitude. The mean annual temperature is 13.8 °C. The climate is mild and the average annual rainfall is 673.3 mm, with a maximum of 1,198.8 mm (2003) and a minimum of 409 mm (2001) from 1976 to 2011. The average annual evaporation is 1,440 mm.

Geologic Conditions of the Coal Mine

The Sanhejian coal mine is located northwest of the Fengpei coal mine. According to the borehole data, the lithology in the study area consists of Ordovician (O), Carboniferous (C), Permian (P), the Jurassic–Cretaceous (J–K), Neogene (E), and Quaternary (Q) (Fig. 2).

From the Late Ordovician to Early Carboniferous, the land was uplifted by the Caledonian movement. As a result, the Upper Ordovician, Silurian, Devonian and Lower Carboniferous strata are missing. After crustal subsidence, deposition layers of the Carboniferous—Permian system became the primary coal-bearing strata. When the Carboniferous—Permian coal-bearing formation was completed, the land started to be denuded under the influence of different tectonic movements. After the Jurassic–Cretaceous clastic sediments were deposited unconformably on the coal-bearing formation, the Cenozoic sand was deposited in fault basins and the unconsolidated Quaternary sediments then universally covered the various strata.

The Sanhejian Mine was affected by the tectonic movements, forming an incomplete set of NE-trending secondary anticlines, associated with an anticlinal structure in the eastern and western sides of the Longgu anticline. The reverse fault (F_2) did not cut the Jurassic–Cretaceous strata. A series of larger tension fractures cut the Jurassic–Cretaceous strata, and undermined the integrity of the Longgu anticline after severe tectonic movement during the Jurassic (Yanshan). The larger tension fractures align NE, NW, EW, and NNE (Figs. 2, 3).

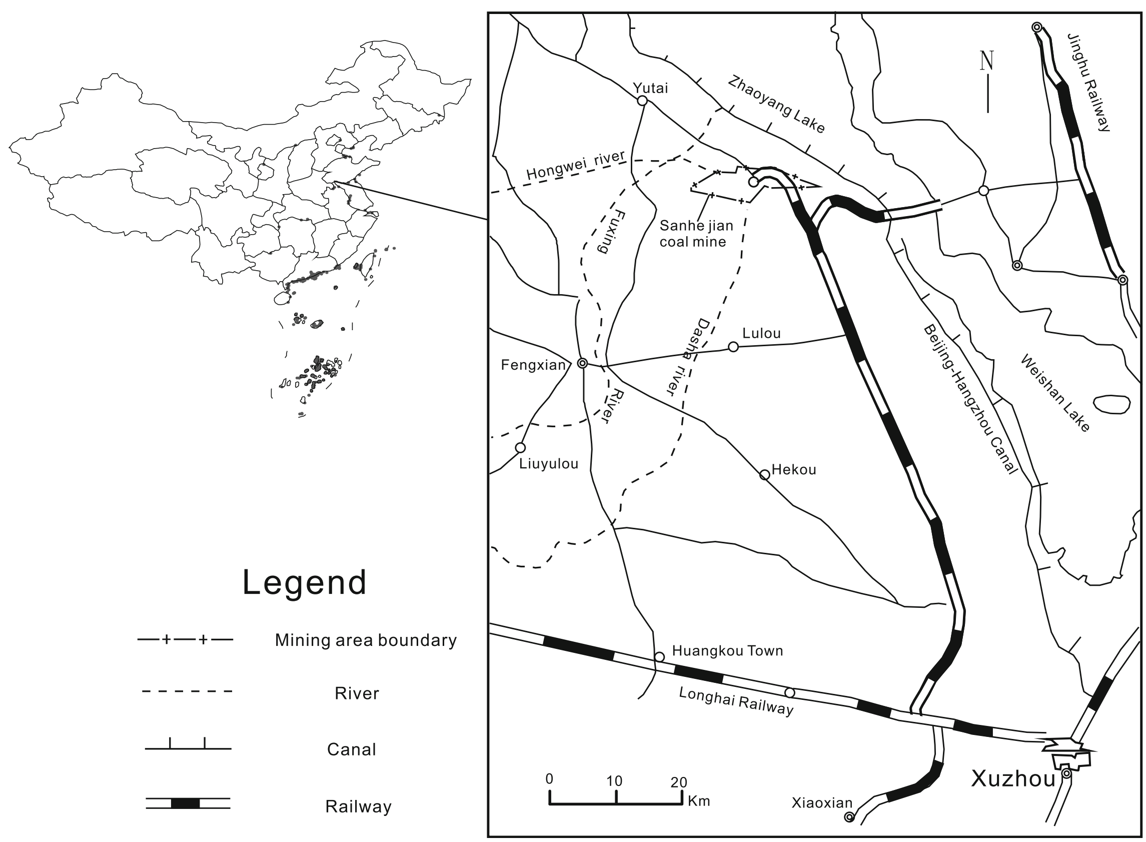

Fig. 1 Location of the Sanhejian coal mine

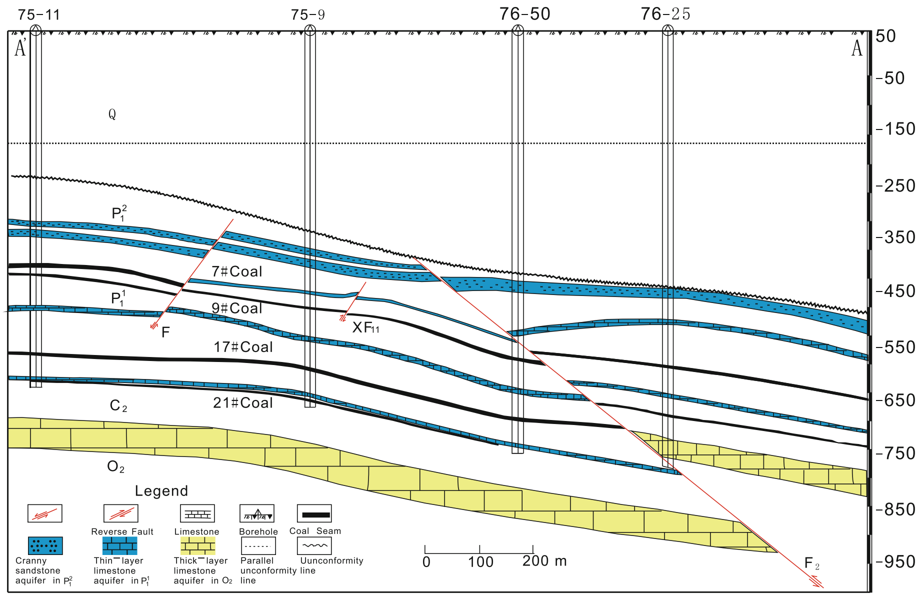

Fig. 2 Geological profile of A–A′

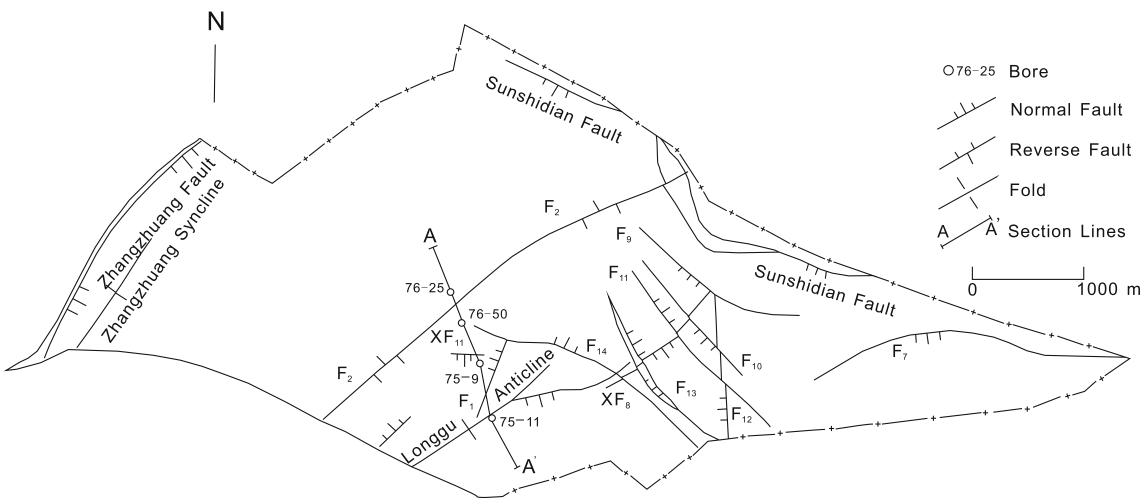

Fig. 3 Geological structures of the Sanhejian coal mine

The no. 17 coal seam is the main mineable coal seam in the Sanhejian mine. It is in the Taiyuan Formation of the Upper Carboniferous. A direct water source is the confined karstified limestone aquifer of the Carboniferous Taiyuan formation, which underlies the coal seam. However, this limestone aquifer tends to have a poor water yield, and dewatering it is relatively easy, so in general, the Taiyuan formation does not pose a serious threat to mining.

In contrast, the karstified Ordovician aquifer, which is an indirect water source to the no. 17 coal seam, is pressurized, is the primary threat to mining; water in the Ordovician aquifer can suddenly flow into the mining areas through faults and fractures when they are exposed by mining. Such an inrush occurred at the no. 21102 working face on Oct. 26, 2002. The maximum instantaneous water inflow reached 2,170 m^3/h with a stable water inflow of 1,020 m^3/h. This incident occurred when an undetected geologic structure connected the Ordovician limestone with the coal seam.

Hydrogeological Characteristics of the Coal Mine

Figure 4 shows the stratigraphy below the no. 17 coal seam. Between the coal seam and the Ordovician limestone is the Carboniferous Taiyuan—Benxi formation, which functions as an aquiclude.

The Ordovician limestone, which has a maximum thickness 58.2 m, lies over 100 m beneath the Sanhejian Coal mine. Its boundaries are faults that block groundwater recharge. Thirteen exploratory wells were drilled into the

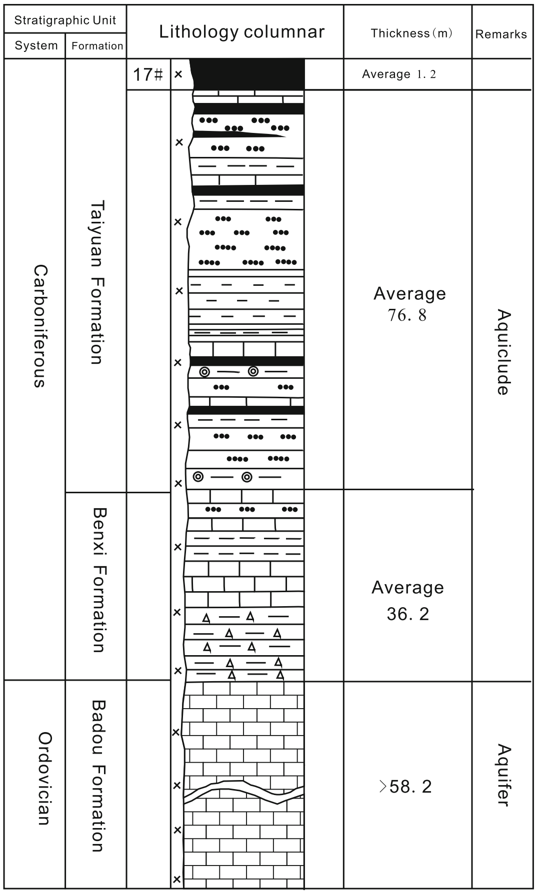

Fig. 4 Stratigraphic column underlying the No. 17 coal seam

confined Ordovician limestone aquifer; loss of water circulation occurred in three boreholes. Three boreholes intercepted two normal faults—F_1 and F_7, while being drilled into the Ordovician limestone. The limestone formation in the tense-shearing fault zone has high water yield and permeability. According to water level measurements, the potentiometric pressure of the Ordovician limestone aquifer is −152.9 to −93.65 m, and the water pressure exerted onto the No. 17 coal seam floor is between 4.32 and 7.26 MPa.

The study area is divided into blocks by the reverse fault (F_2) in the central study area, the Sunshidian normal fault in the north, and a normal fault in the east (Fig. 3). Under natural conditions, the direction of groundwater flow is from the northeast to southwest. Because the coal-bearing stratum is overlain by the thick, relatively impermeable Jurassic–Cretaceous strata, the hydraulic connection between the Quaternary aquifers and coal-bearing stratum is limited. In addition, deep groundwater circulates slowly, drains poorly, and takes a long time to be recharged.

Vulnerability Index Method

Introduction to the Analytic Hierarchy Process

The water inrush process is complex and many factors influence water inrush from a confined underlying aquifer. The analytic hierarchy process (AHP), which was first proposed in the early 1970's by Saaty (1977), is a simple, flexible, and practical method that combines qualitative evaluation with quantitative terms. It has the characteristic of systematic and hierarchical multiple criteria decision-making and is especially suitable for problems that are not amenable to quantification.

AHP functions by initially analyzing the factors of a complicated problem and the relationships among them. The problem is divided into different elements and then merged into a hierarchical structure. A system evaluation model and a mathematical model are established based on this structure. These models are inherently 'fuzzy'; a quantitative indicator or a scale indicator has to be established indicating the influence that the various factors have on the target objects, based on expert judgment. The significance of each factor is obtained from the judgment matrix for each item or level, according to the requirements of the evaluation model; then, the highest level evaluation target is calculated, providing evidence that can be used to confirm the optimal scheme.

Evaluation Steps

1. AHP is used to conduct a comprehensive analysis of the major controlling factors and to calculate the significance or 'weight' of each of these controlling factors to the overall goal. This allows one to establish an evaluation model.
2. Spatial information processing and geographic information system (GIS) analysis can be used to develop a quantified thematic map that can be understood intuitively for each of the major controlling factors. The spatial function of GIS is used to overlay each thematic map in accordance with the weight of the main controlling factor and thus build a vulnerable index distribution map for the water inrush evaluation.
3. A frequency histogram of water inrush is used to calculate a vulnerable index in each unit of the study area, and a threshold value of vulnerability division is determined. Then, evaluation zoning maps are developed; these allow the risk of water inrush to be evaluated rationally.

Application of Vulnerable Index Method to the Sanhejian Coal Mine

Determination of the Main Controlling Factors

In the detailed analysis of the geological and hydrogeological conditions of the Sanhejian Mine, five major factors were selected by synthetic analysis: the Ordovician limestone aquifer, the no. 17 coal seam aquiclude, geological structures, zones destroyed by underground pressure, and confined up-flowing conductive zones. Consequently, the main factors influencing No.17 coal seam Ordovician limestone floor water inrush include:

- The effective thickness of the aquiclude beneath the no. 17 coal seam,
- The thickness of the brittle rock within the aquiclude beneath the no. 17 coal seam floor. The brittle rock breaks, rather than bend in response to stresses.
- Distribution of faults and folds,
- Intersections and endpoints of structures,
- Fault scale index, which is defined as the sum of all faults throw and length per unit area
- The potentiometric pressure of the Ordovician limestone aquifer, and
- The water yield of the Ordovician limestone aquifer

Construction of Thematic Maps

First, borehole data, pumping test data, groundwater level observation data, and knowledge about geological structures (such as faults, folds, and joints) were analyzed statistically. Then, coordinates for geospatial data and quantification values are entered into the GIS data base. The discrete data files are generated using GIS functions such as data storage, spatial data processing, and analysis. GIS is also used to generate continuous raster files for mesh generation and interpolation. Finally, the GIS displays quantification results in a graphical form and creates seven thematic maps (Fig. 5):

1. Thematic map of the effective equivalent thickness of the aquiclude: Aquiclude thickness has an inhibitory effect on coal seam floor water inrush, but the water-resistance of an aquiclude is related to aquiclude thickness, strength, and lithological composition. In order to determine the effective aquiclude equivalent thickness from the no. 17 coal seam to the Ordovician limestone aquifer, the lithological thickness of the aquiclude had to be converted into a corresponding equivalent thickness, based on a summation of all compositions. The natural upward penetration into the aquiclude and the destructive effects of the mine stress were then subtracted from the aquiclude equivalent thickness. Finally, the thematic map of effective aquiclude equivalent thickness from no.17 coal seam floor to Ordovician limestone aquifer was established (Fig. 5a).
2. Thematic map of brittle rock thickness: The lithological composition, spatial distribution, and thickness of the brittle rock play an important role in coal seam floor water bursts. In the study area, the brittle rock in the no. 17 coal seam floor aquiclude has characteristics of typical bedrocks: strong pressure resistance and excellent water-blocking properties. The effectiveness of these properties varies with location; when the brittle rock is distributed within the effective aquiclude, it is more effective in preventing water inrush. The thickness of the aquiclude's brittle rock within the mine stress destructive zone is determined based on drilling logs. Figure 5b is a thematic map of brittle rock thickness below the mine stress destructive zone.
3. Thematic map of faults and folds distribution: The faults and fracture plane are weak interfaces where confined water can 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 the possibility of water bursting from the underlying aquifer. Moreover, where the axial surface of the anticlinal fold is squeezed, the rock body can rupture more easily. Figure 5c is the thematic map of faults and folds distribution.
4. Thematic map of structural intersections and endpoint distribution: The faults and folds spread and cross in space, pinching out and intersecting. Water conductivity increases at intersections of fault and fault, fault and fold, fold and fold, and endpoints. A thematic map of these intersections and endpoints was established (Fig. 5d, e) according to the structure outline map (Fig. 3).
5. Thematic map of the fault scale index: The fault scale index refers to the sum of all faults throw and length per unit area and reflects the 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 density is, the greater the possibility of water bursts. Grid units should be established according to the area of the study region and the distribution characteristics of the faults; we used a grid unit of 500 m × 500 m. The fault throw and the corresponding strike length was counted in each grid unit to calculate the fault scale index. Figure 5f is a thematic map of the fault scale index with the coordinates at the center of the grid unit.
6. Thematic map of potentiometruc pressure of the Ordovician limestone aquifer: Coal floor water bursts

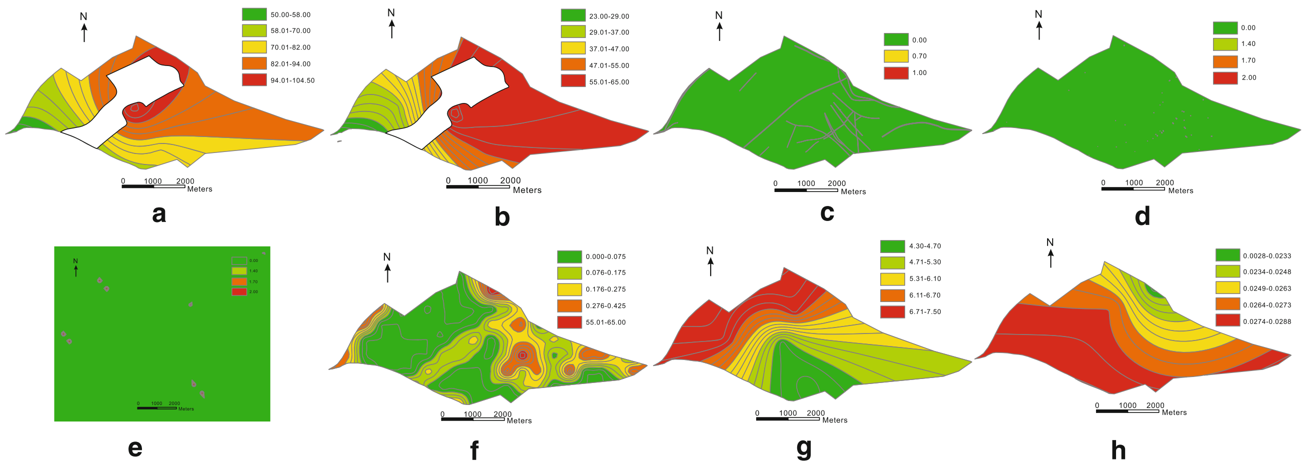

Fig. 5 Thematic maps of main controlling factors (locations of boreholes and mine tunnels shown in Figs. 7 and 8)

occur due to pressures on the impermeable rock; increases in the potentiometric pressure increase the possibility of water bursts. Figure 5g shows the thematic map of the water pressure in the Ordovician limestone and is based on hydrological observations from January to July, 2011.

7. Thematic map of the Ordovician limestone aquifer water yield property: The water yield property refers to the productivity (quantity and duration) of the aquifer. 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: the pore size is 91 mm, and the drawdown of pumped water is 10 m. The thematic map of Ordovician limestone aquifer water yield property is shown in Fig. 5h.

Model Design

The detailed description of AHP and the theoretical background of its application to water inrush are well documented in several papers (Wu and Zhou 2008; Wu et al. 2004, 2009a, b) and is summarized below.

The research was viewed as having three hierarchical levels of difficulty. Vulnerability assessment of the coal seam floor to water bursts is the ultimate objective of the model. Components such as geological structure, confined aquifers, and aquicludes, which determine the likelihood of water inrush events, are criteria layers. The main controlling factors that affect such events are components of the decision layer (Wu et al. 2009a, b).

After the hierarchical model was built, affiliations between the upper and lower level elements were identified. Specifically, the proposed water bursting factors were listed in tables that included each factor that has contributed to numerous water burst disasters. Expert analysis was used to score each major controlling factor, using scoring criteria based on relative importance, in accordance with the 1–9 scale proposed by Saaty (1980). A quantitative value was assigned for each factor by comparing the total score for each factor and the final cumulative score. This allowed us to form evaluation sets about influential factors and to construct a judgment matrix for the assessment. Then, through matrix operations (explained in Wu and Zhou 2008), each major controlling factor was assigned a weighting factor (Table 1).

Vulnerability Assessment Partition of Coal Floor Water Inrush

In order to make the different dimensional data of each main controlling factor comparable and statistically significant, the relevant data need to be normalized by Eq. (1):

$$A_i = \frac{x_i - \min(\mathrm{x_i})}{\max(x_i) - \min(x_i)} \quad (1)$$

where A_i is the normalized data; x_i is the original data before normalization; $\min(\mathrm{x_i})$ is the minimum data of the major controlling indexes to quantify value; and $\max(\mathrm{x_i})$ is the maximum data of the major controlling indexes to quantify value.

During the normalization process, the potential positive and negative correlation of the controlling index on the target events needs to be considered. Of the seven major controlling factors, five factors are positively correlated with coal seam floor water bursts: water pressure, water yield property, distribution of faults and folds, intersection and structural endpoint locations, and the fault scale index. The larger the quantized values, the more likely it is that a water inrush will happen. Thickness of coal floor aquiclude and brittle rock are negatively correlated with the coal

Table 1 Weight of main controlling factors for water inrush

Influential factors	Equivalent thickness of effective aquiclude	Brittle rock thickness below mine stress destruction zone	Distribution of fault and fold (W_3)	Distribution of fault intersection points and endpoints	Fault-scale index	Hydraulic pressure in aquifers	Water abundance of aquifers
Weights (Wi)	0.2620	0.0655	0.1638	0.0394	0.0568	0.3094	0.1031

seam floor water bursts but during the normalization process, these data are normalized so that the results are calculated through positive correlation.

After normalizing the major controlling factors, an attribute database of the factors was created. The thematic maps of the seven factors were set up using a GIS application to process the normalized data.

The information storage layers for the major controlling factors were compounded into one that contained information about all of the relevant factors. Then, the vulnerability index model was used and defined as:

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

where *VI* is the vulnerability index; W_k is the weighting of the major controlling index; $f_k(x,y)$ is valued function describing the effect of each individual factor on water inrush; *x,y* are geographic coordinates, and; *n* is the number of influencing factors.

In the vulnerability evaluation for the no. 17 coal seam, the weighting for the main controlling index is provided in Table 1. As a result, the model for the Sanhejian coal mine is as follows: $VI = \sum_{k=1}^{n} W_k \cdot f_k(x,y) = 0.2620\mathrm{f}_1(\mathrm{x,y}) + 0.0655\mathrm{f}_2(\mathrm{x,y}) + 0.1638\mathrm{f}_3(\mathrm{x,y}) + 0.0394\mathrm{f}_4(\mathrm{x,y}) + 0.0568\,\mathrm{f}_5(\mathrm{x,y}) + 0.3094\mathrm{f}_6(\mathrm{x,y}) + 0.1031\mathrm{f}_7(\mathrm{x,y})$

Next, the water inrush vulnerability index in each grid cell was statistically analyzed. Then, the hierarchical vulnerability index frequency was analyzed using the Jenks optimization method (a function of GIS) on the classification map. The Jenks optimization method, also called the Jenks natural breaks classification method, determines the best arrangement of values into different classes by reducing the variance within classes and maximizing the variance between classes. The statistical frequency distribution map of the vulnerability index was made based on the data groups determined by the Jenks optimization method, giving partition thresholds of 0.23, 0.33, 0.43, and 0.59 (Fig. 6). The coal seam floor water burst vulnerabilities were divided into five zones (Fig. 7):

- Zone 1, $\mathrm{VI} \geq 0.59$, the most vulnerable areas
- Zone 2, $0.59 < \mathrm{VI} \leq 0.43$, potentially vulnerable areas
- Zone 3, $0.43 < \mathrm{VI} \leq 0.33$, transitional areas
- Zone 4, $0.33 < \mathrm{VI} \leq 0.23$, generally safe areas
- Zone 5, $\mathrm{VI} < 0.23$, quite safe areas

As shown in Fig. 7, the orange colored area is potentially vulnerable, with water pressures ranging from 6.3 to 6.9 MPa. The water yield of the Ordovician limestone aquifer ranges from 0.0274 to 0.0288 L/(s m), which is relatively large. The equivalent thickness of the effective aquiclude is at medium levels, ranging from 70.01 to 82.0 m and the thickness of the brittle rock ranges from 37.01 to 51.0 m. Therefore, in these areas, it is essential to closely observe signs of water bursts and take preventive measures during mining and structural development. The red colored area, located in the western part of the study area, is however the most vulnerable. The Ordovician limestone water pressure is high, from 6.9 to 7.5 MPa. The equivalent thickness of the effective aquiclude (50.0–70.0 m) and the thickness of brittle rock from the coal seam floor aquiclude (23.0–39.0 m) are relatively thin. The likelihood of the Ordovician limestone water bursting in this area is the greatest, so appropriate measures should be taken to prevent water inrush events during mining.

Comparison of the Vulnerability Index and Water Inrush Coefficient

In the 1960s, the former Ministry for the Coal Industry organized a series of discussions on how to deal with water inrush problems in coal mines. The water inrush coefficient, defined as water pressure that the unit aquiclude thickness of coal seam floor can sustain, was proposed at that time (Liu 2009). Although it has been modified a few times, the general form remains the same and can be expressed as:

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

where T is the water inrush coefficient (MPa/m); p is the water pressure sustained by the coal seam floor (MPa), and; M is the thickness of the coal floor aquiclude (m). The formula applies to both coal mining and tunneling.

According to Eq. (3), the water inrush coefficient of each point is obtained by dividing the water pressure measured at boreholes by the aquiclude thickness in the area. The value of the water inrush coefficient is calculated in each unit by interpolation. These values are entered into the attribute table of the water inrush coefficient information map. Based on a statistical analysis of data

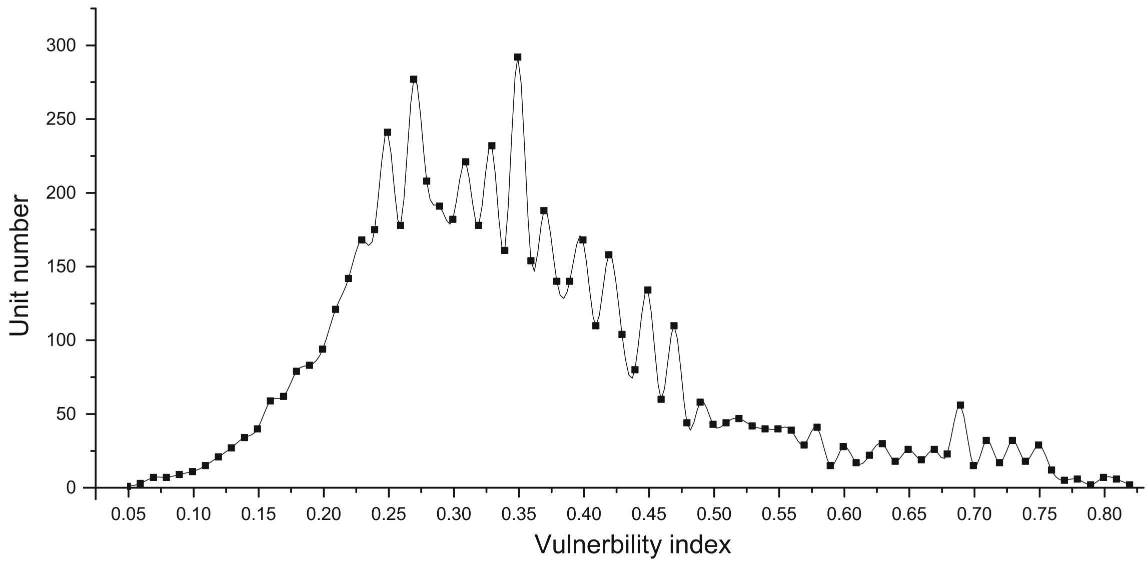

Fig. 6 Frequency histogram of vulnerability index

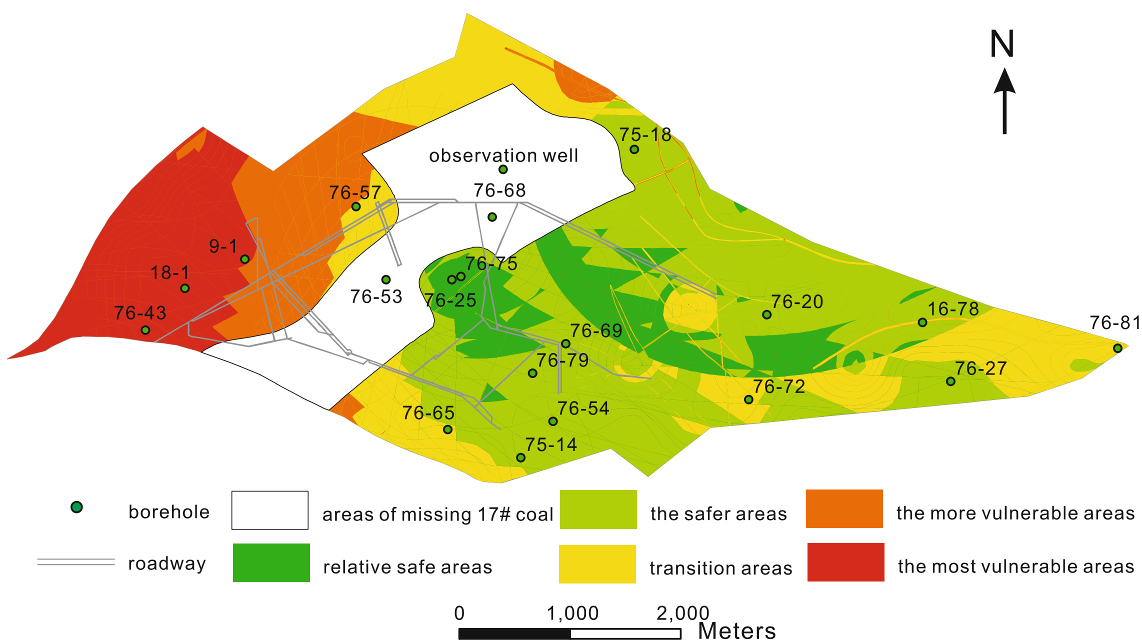

Fig. 7 Water inrush vulnerability zoning of the No. 17 coal seam

collected nationwide, the Regulations for Mine Water Prevention and Control (Ministry of Coal Industry 2009) suggests that water inrush tends not to occur if the water inrush coefficient is greater than 0.06 MPa/m in areas with structures and greater than 0.1 MPa/m in areas without structures. Otherwise, the areas are considered to be prone to water inrushes. Figure 8 shows the two zones for the no. 17 coal seam.

As shown in Fig. 8, the western red area is the water inrush prone area, and the green area is the safe area. Compared with the water inrush vulnerability assessment (Fig. 7), the water inrush coefficient method neglects several key factors, such as the water yield property of the aquifer and geological structure in each grid cell. The prediction shown in Fig. 8 is less precise than that shown in Fig. 7 because only safe and dangerous areas are demarcated, without the transitional areas. Gradual changes in hydrogeological conditions are not reflected. In comparison with the traditional water inrush coefficient method, the vulnerability index method is more comprehensive and provides a more representative guidance to the coal mine safe production.

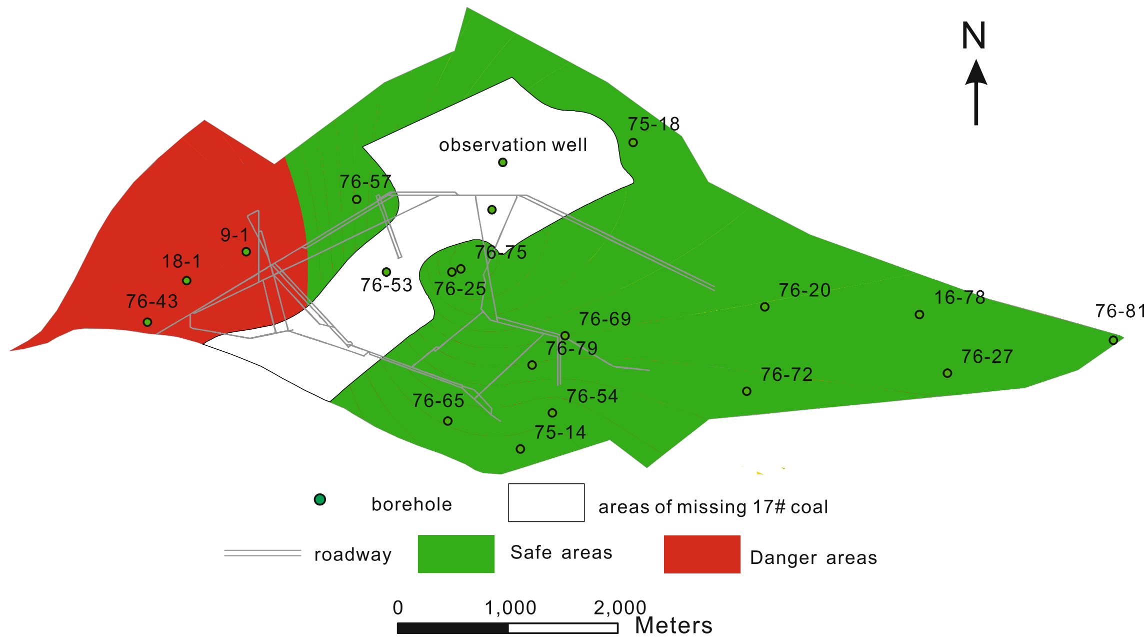

Fig. 8 Division map based on the water inrush coefficient for the No. 17 coal seam

Mine Flood Avoidance

The water inrush vulnerability for the no. 17 coal seam was evaluated and presented in Fig. 7. Different measures shall be taken in each zone to prevent and control water inrush incidents.

1. The green area is quite safe while the light green area is moderately safe. The equivalent thickness of the effective aquiclude and the thickness of brittle rock below the mine stress destructive zone are relatively large, while the water pressure is relatively low. Water inrushes are unlikely to occur in mining. However, this does not mean there is no risk. If the no. 17 coal seam is under pressure during structural development and water yielding structures (unknown faults or fractures) can conduct water, water inrushes can still take place. Where geologic structures, such as faults, are present, preventive measures should be enhanced.
2. The effective aquiclude is relatively thick in the yellow transitional zone, while the water yield of the Ordovician limestone aquifer is relatively small. However, the water pressure of the Ordovician limestone aquifer is still large. Given these multiple factors, the following preventive measures are recommended:
3. Always pay attention to the working faces, water inflow changes, and Ordovician limestone water level changes during mining, and explore the weak zone of the aquiclude at the mine face, potential water-conducting structures (faults, fracture zones) and the water yield and transmissivity of them. Grouting reinforcement of the aquiclude and grouting reconstruction of the corresponding aquifer should be implemented in identified weak zones. It is useful to analyze the hydraulic properties of the aquiclude so that permeable fractures can be sealed by grouting. If feasible, impermeable coal barriers should be left as an additional safety measure.
4. The Ordovician limestone aquifer water pressure is high and the water yield property is relatively large in the orange and red zones, while the effective equivalent aquiclude thickness is small and the brittleness of no. 17 coal seam floor is large. So, there is certainly the possibility of water inrush. If the aquiclude is seriously weakened in the area of structural development, the possibility of water inrush increases significantly. Because the fault scale index is relatively high in the western section of the mine, especially near the western boundary, the following measures are recommended:

- Explore the weak zone of the aquiclude, the Ordovician limestone aquifer, and potential water-conducting faults and fracture zones using geophysical surveys, drilling, and other exploration methods. Consider grouting reinforcement in the aquiclude, grouting reconstruction in the Ordovician limestone aquifer, and sealing and reconstruction of the confining bed. In addition, impermeable coal barriers should be left as an additional safety measure. During mining, waterproof sluice gates may be set up for zone mining.

- If conditions permit, depressurize the Ordovician limestone aquifer by dewatering. The goal is to decrease the confined aquifer's water head values so that the water inrush coefficient is below the threshold of 0.06 MPa/m. Following dewatering, grouting can be used to seal fractured zones of the coal seam floor and water-bearing structures, and to reconstruct the Ordovician limestone aquifer.

The Ordovician limestone aquifer is characterized with heterogeneity. The characteristics of the rock ahead of the mining and the water yield property of limestone should be investigated with geophysical exploration, drilling and other means. Insist on the following principle during mining:

- If in doubt, always conduct exploration before coal extraction and
- Institute control measures before mining coal.

Conclusions

Water inrush from the Ordovician limestone aquifer into the overlying No.17 coal seam is affected by seven factors: the potentiometric pressure of the Ordovician limestone aquifer, the water yield of the Ordovician limestone aquifer, the thickness of the brittle rock below the mine stress destruction zone, the equivalent thickness of the coal floor aquiclude, the distribution of faults and folds, the intersections and endpoints of structures, and the Fault Scale Index.

The water inrush vulnerability model was established using a GIS-based AHP vulnerability index method. The coal mine was divided into five zones with different levels of risks of water inrush, providing a scientific basis for safe production and control of water inrush.

The vulnerability index method is compared with the traditional water inrush coefficient method. The vulnerability index method can consider multiple factors that affect water inrush and better represents the hydrogeological conceptual model for water inrush from the underlying confined aquifers.

Different exploration and prevention measures are recommended according to the zone distribution. This ensures proper allocation of investigative and exploration efforts.

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