Mine Water Environ (2017) 36:96–103
DOI 10.1007/s10230-016-0410-8

TECHNICAL ARTICLE

Risk Assessment of Water Inrush from Aquifers Underlying the Gushuyuan Coal Mine, China

Qiang Wu[1,2] · Xiaoming Guo[2] · Jianjun Shen[1,2] · Shuang Xu[1,2] · Shouqiang Liu[1,2] · Yifan Zeng[1,2]

Received: 29 October 2015 / Accepted: 8 July 2016 / Published online: 20 July 2016

Abstract Mining of the No. 15 seam in the Gushuyuan coal mine is threatened by water inrush from the underlying Ordovician limestone aquifer. Water pressure and yield of the aquifer, the equivalent thickness of the water-resisting layer(s), and the properties of geologic structures are the major factors that control water inrush. The water inrush risk was evaluated using the vulnerability index (VI) method, which couples GIS with the analytic hierarchy process. Comparing the results with that of the traditional water inrush coefficient method in a specific mining area clearly showed the advantage of the VI method, especially in mines underlain by a thin water-resisting layer.

Keywords Thin water-resisting layer · Vulnerability Index method · Water inrush coefficient method

Introduction

Water inrush from confined aquifers underlying coal seams, also referred to as floor water inrush, is a major safety and production concern, especially in China, where coal mines have become more vulnerable to water inrush as mining depths and intensity have increased (Surinaidu et al. 2013; Wu et al. 2007a, 2013b). Predicting the potential of water inrush and taking effective measures before mining is essential (Bukowski 2011; Meng et al. 2012). In the 1960s, the water inrush coefficient method was put forward through comprehensive analysis based on existing water inrush accidents in the "Hydrogeology Battle," which had been organized by the Ministry of Coal Industry in the Jiaozuo mining area. Water inrush coefficient (T) refers to the water pressure that a unit thickness of water-resisting layer can withstand, as expressed by the formula $T = P/M$, where P represents water pressure and M represents aquiclude thickness. However, water inrush is a function of many factors, including water pressure, water yield, equivalent thickness of water-resisting layer, faults, and folds, but the water inrush coefficient method only considers the water pressure and thickness of the water-resisting layer.

The vulnerability index (VI) method was developed and used to predict floor water inrush risk in the Gushuyuan Mine, where the upper coal seams are depleted and the lower No. 15 coal seam is the main remaining minable resource. However, as mining gets deeper, the risk of water inrush from the Ordovician aquifer increases greatly because of the thin water-resisting layer and complex hydrogeology.

Another approach, using the analytic hierarchy process (AHP) and fuzzy mathematics, considered factors such as the groundwater level, unfavorable geology, formation lithology, topography, strata inclination, excavation, advanced geological prediction, and monitoring information (Li et al. 2015; Wang et al. 2012). Several factors were selected to help evaluate the risk and these indices were quantitatively assigned to one of four risk levels by expert evaluation (Li et al. 2013). It has been successfully

Electronic supplementary material The online version of this article (doi:10.1007/s10230-016-0410-8) contains supplementary material, which is available to authorized users.

✉ Qiang Wu
wuq@cumtb.edu.cn

1 State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Beijing 100083, China

2 College of Geoscience and Surveying Engineering, China University of Mining and Technology, Beijing, China

applied to predict potential problems at specific working faces and to tunnels in karst environments (Li et al. 2013, 2015; Wang et al. 2012). However, this approach cannot be applied to entire mines or mine districts. Therefore, the VI method was revisited and further developed.

The Study Area

The Gushuyuan coal mine is located approximately 1 km north of Jincheng city, in Shanxi Province in the north-middle Jincheng mining area of the Qinshui coalfield. Most of the mining area is under the jurisdiction of Jincheng city, while a small part lies in the town of Bagong in Zezhou County (Fig. 1). The surface topography consists of low denuded hills with high topography in the northwest and with low topography in the southeast. The study area is located in the inter-mountain basin west of Taihang Mountain and is in the temperate continental climate zone. The average annual precipitation is 686 mm with rainfall mainly concentrated in July, August, and September. The amount of evaporation is commonly 2–3 times the amount of rainfall. There is no perennial runoff in the area and all rivers are seasonal.

Geological Conditions

The stratigraphy in the area from bottom to top consists of an: Ordovician sequence, Carboniferous coal measures sequence, Permian sequence, Triassic sequence, Tertiary sequence, and Quaternary sequence. The stratigraphic dip of strata in the coal mine is 2°–8°, with wide and gentle folds intersected by faults, such as the Baimasi reverse fault in the northwest (Fig. 2). There are two possible faults to the east of the coal field and, in addition, some small faults were discovered during mining. The Erxianzhang syncline and Shichenggou anticline, very wide flat structures with north–south axes, significantly influence groundwater flow. Collapse columns are common in the region but, so far, no collapse columns have been found within the mining area (Fig. 3).

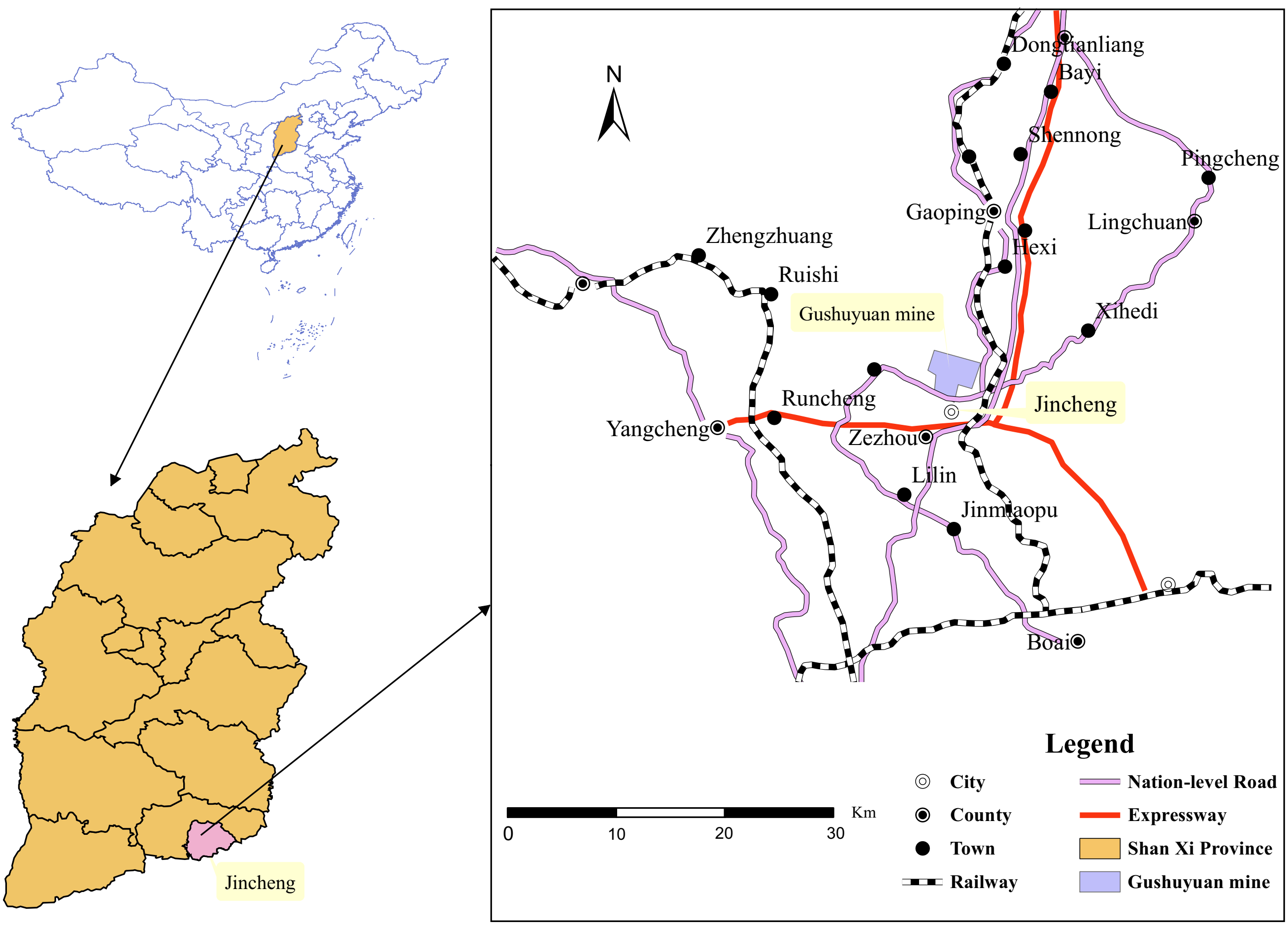

Fig. 1 Location and traffic of the Gushuyuan coal mine

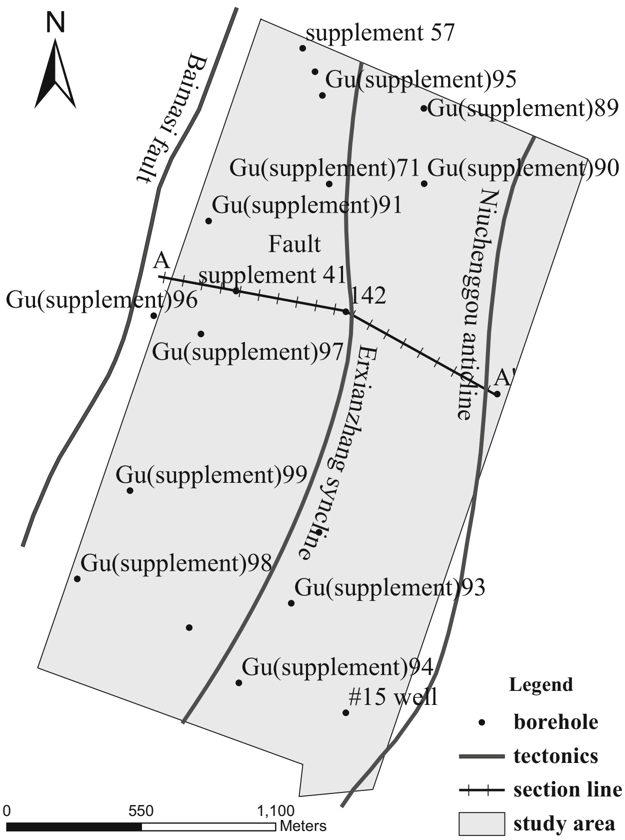

Fig. 2 Geologic structures in the study area

Hydrogeological Conditions

The four aquifers in the mining area are, from bottom to top: (1) the karst fissure aquifer of Middle Ordovician formation, (2) the karst fissure aquifer of Carboniferous limestone, (3) the sandstone fissure aquifer of Permian period, and (4) the alluvial porous aquifer of Quaternary deposits. A typical geologic sequence is shown in Fig. 4.

The water-rich sections of the Middle Ordovician are in the Upper Majiagou and Lower Majiagou formations, which have about 35–40 m of karstic development, were found by drilling. The water level of this strata is about 572 m, based on the hydrological drill hole in the Gushuyuan coal mine. The unit water inflow is 0.0297–0.7660 L/(s m) and the pH of the water is about 7.3–7.9.

Theory

The Vulnerability Index (VI) Method

Vulnerability indexing is a comprehensive evaluation method based on mutual relationships and relative weighting of the major factors controlling floor water inrush (Wu et al. 2007c, 2007d). The multi-factor nonlinear problem (floor inrush) and the geological data are integrated by using the compound superposition and fusion function of the GIS software. The mathematical methods used in information fusion include the artificial neural network method (Wu et al. 2007b), the AHP method (Wu et al. 2009), the weight of evidence method, and the logistic regression method (Wu et al. 2013a). The AHP and associated VI are described briefly below.

The Analytic Hierarchy Process (AHP)

AHP is a multi-scheme and multi-objective decision method. It consists of analyzing the major influencing factors, scoring of the various factors by experts, and combining qualitative and quantitative decisions. The key

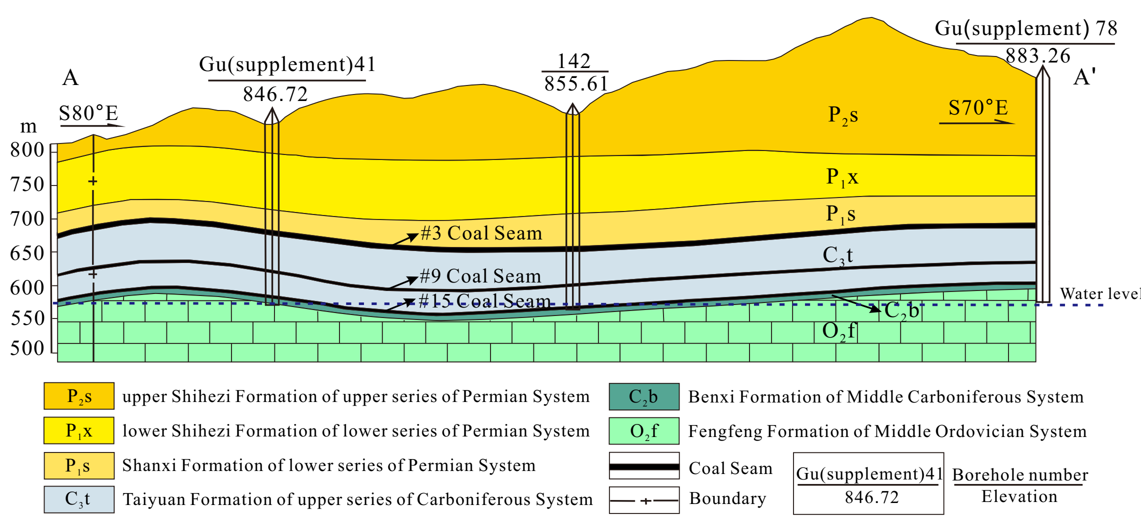

Fig. 3 Geological cross-section A–A′ (location of A–A′ is shown in Fig. 2)

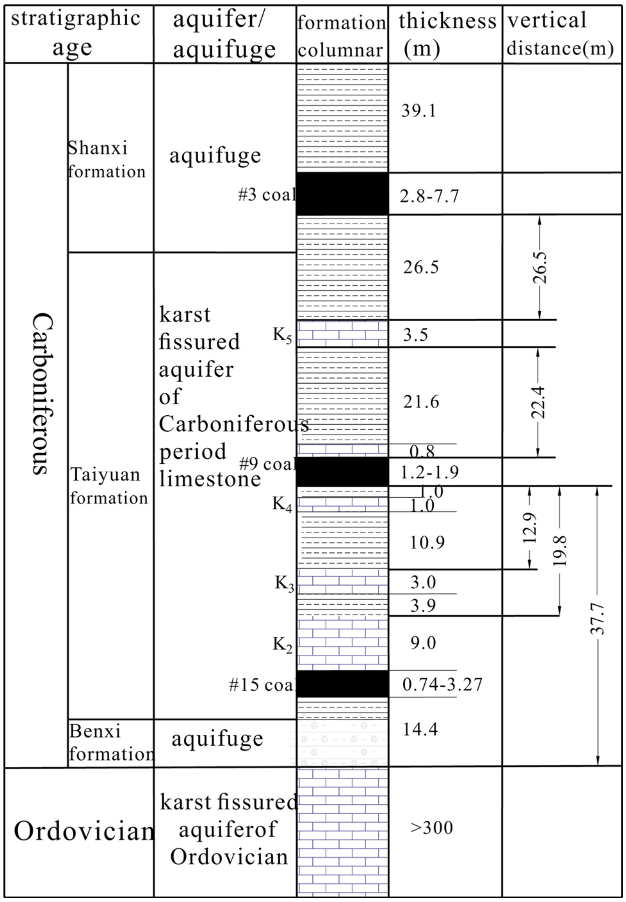

Fig. 4 Relationship between the coal seams and main aquifers

issue of using AHP is to establish a reasonable hierarchical structure and accurate judgment matrix (Xu 1998).

When AHP is used for decisions, the specific calculation processes are:

- Building an analytic hierarchy model;
- Constructing a hierarchical judgment matrix;
- Single sorting and consistency checking; and
- Total sorting and consistency checking.

Consistency checking by single sorting (*C.I.*) adopts the following formula:

$$C.I. = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

Consistency checking of total sorting (*C.R.*) adopts the following formula:

$$C.R. = \frac{\sum_{j=1}^{m} C.I._{j} a_j}{\sum_{j=1}^{m} R.I._{j} a_j} \tag{2}$$

where $\lambda_{\max}$ is the maximum eigenvalue of judgment matrix; m is number of factors in criterion layer; n is number of factors in index layer; j is the jth factor in criterion layer, $j = 1, 2, 3, \ldots$, m; a_j is weight of the jth factor in the criterion layer to the target layer; $C.I._j$ is the consistency index of the judgment matrix in the index layer corresponding with a_j; and $R.I._j$ is the random index of judgment matrix in the index layer corresponding with a_j. The consistency of the judgment matrix is acceptable only when $C.R. < 0.1$; otherwise, the judgment matrix should be revised.

AHP-Type Vulnerability Index Method

The AHP-type VI method uses GIS as an operating platform and relies on the GIS spatial information processing function. This method quantifies the major controlling factors of water inrush and builds the thematic layer map for each factor. The weight of each major controlling factor is determined by model inversion identification and training of the AHP, while the thematic map is developed and superimposed by GIS. Frequency histograms are used to statistically determine the threshold of reasonable water inrush vulnerability partitioning. The partitioning scheme for the vulnerability assessment is then obtained. As an example, a fault scale index, which reflects the geologic fault scale and development degree, is defined by:

$$F = \frac{\sum_{i=1}^{n} L_i H_i}{S} \tag{3}$$

where F is the fault scale index; H_i is throw of the ith fault, m; L_i is strike length of the ith fault in the subarea, m; n is the number of fault in the subarea; and S is the area of subarea, m^2.

With the investigation area discretized, the fault scale index can be calculated for each grid area and contour lines can be generated using the grid center coordinates and index value. The index is a reasonable way to reflect the degree of development of faults in the grid with clear physical meanings. Meanwhile, the index is a comprehensive reflection of the assessment of fault effects, because it comprehensively considers the three elements of fault, strike, and throw. Other major factors used as part of the index are discussed below.

Risk Evaluation of Water Inrush Based on the Vulnerability Index Method

Pressure Areas

Floor water inrush accidents only occur when mining above confined aquifers. The groundwater flow field of the Ordovician limestone aquifer and water level elevation contours were inferred based on the water level measurements in four boreholes within the mining area. The confined and unconfined aquifer areas below the No. 15 coal seam floor, based on the measured pressure heads in Ordovician limestone aquifer, are shown in supplemental Fig. 1.

Determination and Analysis of Major Controlling Factors

Reasonable determination of the major controlling factors decisively controls the reliability of the VI evaluation. Based on a systemic analysis of the major controlling factor system (Wu et al. 2007c, 2007d) and assessment of the hydrogeological conditions, six major controlling factors influence floor water inrush in this mine:

- Water pressure of the Ordovician limestone aquifer;
- Water yield of the Ordovician limestone aquifer;
- Equivalent thickness of the water-resisting layer;
- Fracture zone and effect zone of faults and folds;
- Intersection point and endpoint of faults; and the
- Fault scale index.

Quantification of Major Controlling Factors and Establishment of a Thematic Map

Quantitative analysis of the major controlling factors and calculation of a major controlling factor was based on the available geological and hydrogeological data. GIS was used to generate contour maps by data interpolation and then to build thematic maps of each major controlling factor, showing their distribution and attributes (Fig. 5a–f).

Design of Analytic Hierarchy Process Model

Based on an analysis of the major controlling factors, the model was divided into three levels. Inrush vulnerability assessment is the ultimate goal, or target layer (A level), of the model. The confined aquifer (B_1), geological structure (B_2), and floor water-resisting layer (B_3) were the rule layer (level B). The specific index of the major controlling factors were the decision layer (level C). Based on the hierarchy structure, a judgment matrix was built by the expert scoring method.

$$A = \begin{bmatrix} 1 & 2 & 1 \\ 1/2 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \quad B_1 = \begin{bmatrix} 1 & 6/5 \\ 5/6 & 1 \end{bmatrix}$$

$$B_3 = \begin{bmatrix} 1 & 3 & 4 \\ 1/3 & 1 & 2 \\ 1/4 & 1/2 & 1 \end{bmatrix}$$

Using formulas (1) and (2), each matrix's consistency were checked. All the judgment matrices satisfied the consistency requirement. The weights of each index C_j to the total target A, are the weights of the major controlling factors (Table 1).

Normalization and Superposition of Thematic Maps

Data normalization is required for each thematic map with different dimensions to eliminate the effects of different dimensional data on the evaluation results. The following equation was used for normalization:

$$A_i = a + \frac{(b - a) \times [x_i - \min(\mathrm{x_i})]}{\max(x_i) - \min(x_i)} \quad (4)$$

where A_i is the data after normalization processing; a and b are the lower and upper limits of the normalization range (in this paper, a = 0 and b = 1); x_i is the original data before normalization; $\min(x_i)$ is the minimum of each major controlling factor's quantized value; and $\max(x_i)$ is the maximum of each factor's quantized value. Normalized thematic maps of the six major controlling factors of the Gushuyuan Mine were established based on the above normalization method and principle. Then, the thematic maps were superposed using the GIS layer overlay function.

Establishment of the Vulnerability Assessment Model

The floor water inrush vulnerability of the Gushuyuan coal mine was evaluated using the VI formula (5) shown below. The VI is defined as the superposition total of the various influence factor indices at each position.

$$VI = \sum_{k=1}^{n} W_k \cdot f_k(x, y) \quad (5)$$

where W_k is weight of each major controlling factor; $f_k(x, y)$ is value of each major controlling factor; x, y are geographical coordinates; and n is the number of factors. Based on the weighting of the major controlling factors, the mathematical model of the VI evaluation for the Gushuyuan mine is:

$$\begin{aligned} VI = {} & 0.2269 f_1(x, y) + 0.1857 f_2(x, y) + 0.2599 f_3(x, y) \\ & + 0.2047 f_4(x, y) + 0.0781 f_5(x, y) + 0.0447 f_6(x, y) \end{aligned} \quad (6)$$

Evaluation Partition of Floor Water Inrush Vulnerability

Five risk levels were used to define the vulnerability of the various No. 15 coal seam areas above the confined aquifer based on the VI calculated above. The threshold levels

Fig. 5 Thematic maps of each major influencing factor. **a** water yield of the Ordovician limestone aquifer, **b** Water pressure of the Ordovician limestone aquifer, **c** equivalent thickness of the water-resisting layer, **d** fracture zone and effect zone of faults and folds, **e** intersection point and endpoint of the fault and **f** fault scale index

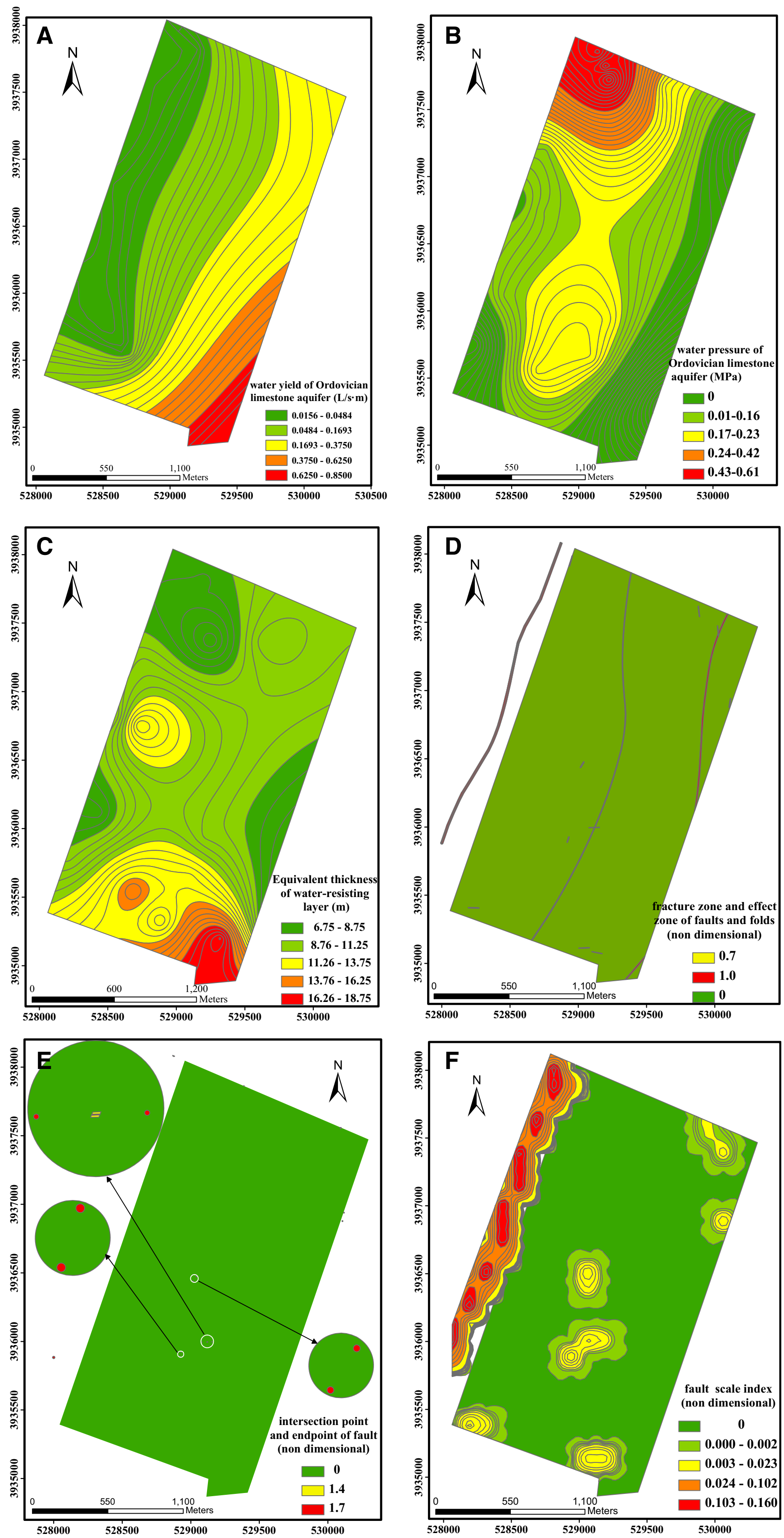

Table 1 Weighting of factors

Factors	Water pressure	Water yield	Equivalent thickness of water-resisting layer	Faults and folds	Fault intersection point and endpoint	Fault scale index
Weight	0.2269	0.1857	0.2599	0.2047	0.0781	0.0447

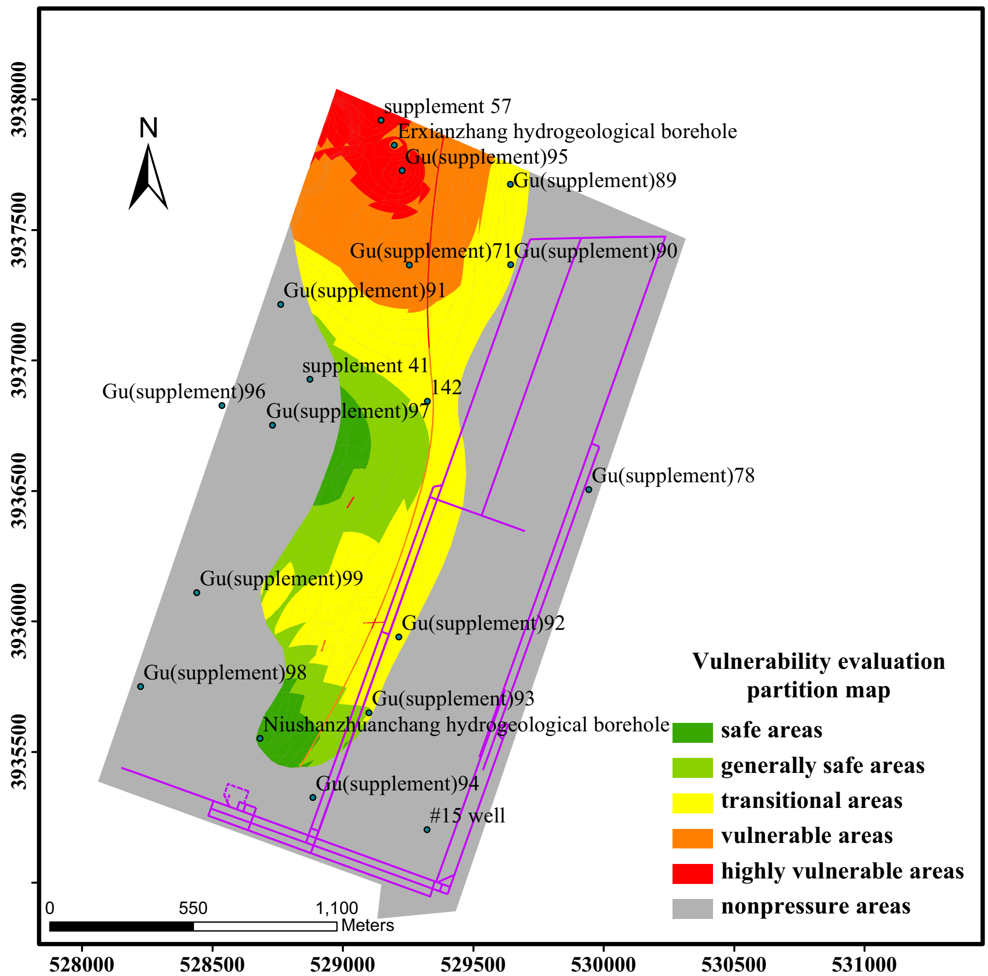

Fig. 6 Vulnerability partition map of floor water inrush for the No. 15 coal seam

selected were 0.208, 0.237, 0.324, and 0.418; the larger values indicates a greater likelihood of water inrush. Word descriptors are noted below.

- Highly vulnerable areas: (VI $>$ 0.418);
- Vulnerable areas: moderate likelihood of floor water inrush (0.324 $<$ VI $\leq$ 0.418);
- Transitional areas: low likelihood of floor water inrush (0.237 $<$ VI $\leq$ 0.324);
- Generally safe areas: (0.208 $<$ VI $\leq$ 0.237);
- Safe areas: (VI $\leq$ 0.208).

Figure 6 shows the different areas of vulnerability for the No. 15 coal seam in the No. 3 panel of the mine.

Comparison of the Vulnerability Index and Water Inrush Coefficient Methods

The water inrush coefficient was defined by *Coal Mine Water Prevention and Control Regulations* (2009), using the mathematical expression:

$$T = \frac{p}{M} \tag{7}$$

where T is the water inrush coefficient, MPa/m; p is water pressure in the floor water-resisting layer, MPa; and M is the thickness of the floor water-resisting layer, m. The water inrush coefficient contour map and the water inrush risk partition map (the critical value of the water inrush coefficient is 0.06 MPa/m) are shown in Fig. 6.

We compared the results of the inrush risk evaluation using the VI method (Fig. 6) to the traditional water inrush coefficient method (supplemental Fig. 2a, supplemental Fig. 2b), and concluded that while the water inrush coefficient method predicts that the coal seam above the confined water is uniformly safe, the VI method predicts that the water inrush risk is divided into five levels. Major factors evaluated by the VI procedure include: the equivalent thickness of the No. 15 coal floor water-resisting layer, the fracture zone and effect zone of faults and folds, the interaction point and endpoint of fault, the water pressure in the aquifer, and the water yield of the aquifer. Compared with the traditional water inrush coefficient method, the VI method provides a more defensible assessment of the variation in inrush risk across the site.

Risk Evaluation Using the Vulnerability Index Method for the Initial Workface

The initial mining workface No. 153302 was next evaluated using a VI analysis of the No. 3 panel in order to better guide actual production (supplemental Fig. 3a $\sim$ supplemental Fig. 3c). From the results, the area of the No. 153302 workface underlain by the pressurized aquifer is small. Because of the thickness of the water-resisting layer and the aquifer water yield, the southwest corner of the workface plots as a transitional area using the VI method. In contrast, the traditional water inrush coefficient evaluation method shows this southwest corner to be a safe area with small water inrush coefficient values. Overall, the water inrush risk at the No. 153302 workface is moderate, but the southwest corner should be carefully examined and monitored during mining.

Conclusions

Geological and hydrogeological conditions were characterized in the Gushuyuan Mine. The water pressure and water yield of the Ordovician limestone aquifer, the equivalent thickness of the water-resisting layer, the fractured zone, the effect of faults and folds, the intersection point and endpoint of the fault, and the fault scale index were the six major controlling factors of the floor water inrush. The mine water inrush vulnerability evaluation was modeled by superposition and quantization of these controlling factors. The water inrush VI risk evaluation of the initial mining workface suggested that this area was in a relatively low risk transition area. The VI evaluation result provided the needed guidance for water inrush prevention and control.

Acknowledgments This research was financially supported by the China National Natural Science Foundation (Grants 41430318, 51174289, and 41272276), China National Scientific and Technical Support Program (Grants 201105060-0 and 2012BAB12B03), National Engineering Research Center for Prevention and Control of Coal Mine Water Disasters (2014FU125Q06), National Geological Survey Program (shui[2012]-01-035-036), Fundamental Research Funds for the Central Universities (2010YD02), Innovation Research Team Program of Ministry of Education (IRT1085), and the State Key Laboratory of Coal Resources and Safe Mining. The authors also thank the editors and reviewers for their constructive suggestions.

References

Bukowski P (2011) Water hazard assessment in active shafts in Upper Silesian coal basin mines. Mine Water Environ 30:302–311

Li SC, Zhou ZQ, Li LP, Xu ZH, Zhang QQ, Shi SS (2013) Risk Assessment of water inrush in karst tunnels based on attribute synthetic evaluation system. Tunn Undergr Space Technol 38:50–58

Li LP, Lei T, Li SC, Zhang QQ, Xu ZH, Shi SS, Zhou ZQ (2015) Risk assessment of water inrush in karst tunnels and software development. Arab J Geosci 8:1843–1854

Meng ZP, Li GQ, Xie XT (2012) A geological assessment method of floor water inrush risk and its application. Eng Geol 143–144:51–60

Surinaidu L, Rao VVSG, Ramesh G (2013) Assessment of groundwater inflows into Kuteshwar limestone mines through flow modeling study, Madhya Pradesh, India. Arab J Geosci 6:1153–1161

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

Wu Q, Dong SN, Zhang ZL (2007a) Mine water inrush disaster prevention and control. China Mining and Technology Univ Press, Xuzhou, pp 3–15

Wu Q, Xie SH, Pei ZJ, Ma JF (2007b) A new practical methodology of the coal floor water bursting evaluation III: the application of ANN Vulnerability Index method based on GIS. J China Coal Soc 32(12):1301–1306

Wu Q, Zhang ZL, Ma JF (2007c) A new practical methodology of the coal floor water bursting evaluation I: the master controlling index system construction. J China Coal Soc 32(1):42–47

Wu Q, Zhang ZL, Zhang SY, Ma JF (2007d) A new practical methodology of the coal floor water bursting evaluation II: the Vulnerability Index method. J China Coal Soc 32(11):1121–1126

Wu Q, Wang JH, Liu DH, Cui FP, Liu SQ (2009) A new practical methodology of the coal floor water bursting evaluation IV: the application of AHP vulnerability index method based on GIS. J China Coal Soc 34(2):233–238

Wu Q, Zhang B, Zhao WD (2013a) A new practical methodology of coal seam floor water burst evaluation V: the comparison study among ANN, the weight of evidence and the logistic regression vulnerability index method based on GIS. J China Coal Soc 38(1):21–26

Wu Q, Zhao SQ, Dong SN, Li JS (2013b) Handbook of mine water inrush prevention and control. Coal Industry Press, Beijing, pp 429–451

Xu SB (1998) Principle of analytic hierarchy process. Tianjin University Press, Tianjin, pp 45–60