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Combination of GIS and AHP Methods to Predict Water Abundance of Sandstone Aquifer in Coal Seam Roof

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Abstract

During coal mining, the water of sandstone aquifer in the coal seam roof is the direct water source. Accurate prediction of the water abundance of the aquifer is the precondition and guarantee for the safe production and the maximum exploitation of coal resources. Therefore, a suitable prediction method is important for the control of water hazards. However, no unified and accurate prediction method and system are available for the prediction of water abundance in all of coal mining areas. A multi-source information integration model of geographic information system (GIS) was proposed after using analytic hierarchy process (AHP) to determine the weights of indicators and thus establish an integrated prediction model and study the regularity of water abundance. Wolong Lake coal mine, which is located in Huaibei coalfield of China, was taken as an example, and a case study was conducted to verify the correctness of the prediction results by using hydro-geological information, such as the maximum mud leakage and the core recovery percentage. The prediction and zoning of the water abundance were ultimately completed. Results demonstrate that the water abundance of sandstone aquifer is strong in the northeast of the mining area. The area of strong water abundance is mainly in the north of line 5 and east of the AB exploration line (the geological exploration line from the North A point to the South B point). The area of strong water abundance accounts for 72% of the entire mining area. The thicknesses of the sandstone aquifer and coalfield structure are the main factors that greatly affect the water abundance. Combination of GIS and AHP methods is reasonable and feasible to predict the water abundance. The proposed model can provide a good reference to the prediction of the water abundance of sandstone aquifer and can guide safe production of the coal mine, especially in coal mining areas that are affected by water of sandstone aquifer in the coal seam roof.

Keywords: Sandstone aquifer, Water abundance, Analytic hierarchy process, Geographic information system, Multi-source information

1. Introduction

Mine water inrush from the roof of the coal seam is a major water hazard, and the water abundance of aquifer is the key factor for water inrush. The water of sandstone aquifer in the coal seam roof is the direct water source. The rich water source in the aquifer restricts the safe production of coal mine [1]. Furthermore, water inrush brings large economic losses. Water abundance of aquifer in the coal seam roof has repeatedly caused incidents of water burst, flooding of wells, halted production, and even casualties because of its insufficient understanding [2]. However, for areas with poor water abundance of aquifer, excessive measures of prevention and control result in the increase in waterproof pillars and the waste of mine resources. Thus, a reasonable prediction method should be selected to accurately predict and evaluate the water abundance of sandstone aquifer. The method can guarantee the subsequent analysis of water inrush condition and prevent and control the aquifer condition in the coal seam roof [3].

Many factors control the water abundance of sandstone aquifer, and the controlling mechanisms and combination types of controlling factors vary in different coal mining areas. A suitable prediction model of water abundance based on the characteristics of different coal mines is necessary to describe the relationship between the water abundance of aquifer and the main controlling factors and conduct quantitative expression [4-9]. The main controlling factors of water abundance present two characteristics: (1) the controlling factors vary in different coal mining areas; (2) the factors exhibit different influence degrees on controlling water abundance under different hydro-geological conditions. Thus, the key point is to choose an appropriate method of determining weights to quantitatively confirm the "contribution" of main factors. Many factors affect the water abundance of the mine area with complex geological and hydro-geological conditions. The second key point is to complete multi-factor weighted integration analysis and quantitatively predict the water abundance with the spatial transferring of main controlling factors in different mines. Thus, considering the coupling of the two key points, this study establishes a prediction model of geographic information system (GIS) by integrating multi-source information. Ultimately, the quantitative prediction model of the water abundance of sandstone aquifer in coal seam roof is established on the basis of analytic hierarchy process (AHP) and GIS.

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2. State of the art

Under complicated geological conditions in the deeper mining area, the regularity of water abundance is controlled mainly by lithology, fissure rate, structure, and crustal stress. Medici G. et al. studied the types of sandstone aquifer on the basis of the heterogeneity study of the sediments and structures in the basin of East Irish. Then, they discussed the relationship among sedimentary environment, joints and faults, permeability coefficient, and water abundance of sandstone aquifer [10]. Zhao B. F. et al. studied the water abundance of sandstone aquifer through sedimentary environment of the aquifer and its tectonic characteristics, such as sand–mud ratio, sandstone thickness, and fault and fold spatial distribution [11]. Wu Q. et al. completed the quantitative expression by qualitatively analyzing aquifer thickness, specific discharge of a well, rock quality, faults, folds, and other indicators [4,12,13]. Wu X. R. et al. used Longgu minefield as an example to predict the water abundance of sandstone aquifer in coal seam roof by using fuzzy clustering method [5]. Wu Q. et al. constructed an index model of water abundance utilizing GIS and AHP to obtain a zoning map of water abundance [6]. Simultaneously, the height of the mining fissure zone was calculated by numerical simulation to study whether the fissure zone communicated with the aquifer, which can indicate the spatial connection between the fissure zone and the aquifer. Geo-stress controls the development and closure of porosity and fissure. Qiao W. concluded that the increase in geo-stress plays a role in the reduction of permeability coefficient and the opening degree of original fissures with the increase in buried depth [7]. The study of water abundance of sandstone aquifer in coal seam roof has yielded many results, and the influence indicators of water abundance in each coal mine differ. Therefore, for safe mining of coal mine, the geology and hydro-geological indicators of coal mine are used to study the controlling mechanisms of the water abundance, and appropriate prediction and evaluation methods are needed to provide appropriate guidance to a given coal mine.

In the research field of water abundance of sandstone aquifer, many prediction methods are proposed, such as hydro-geological analysis, multi-factor comprehensive method, GIS multi-source integration method [14], and fuzzy clustering method [15]. Wang H. et al. finally achieved the integrated zoning map of water inrush in No. 3 coal seam of the test area through analyzing the characteristics of faults, fissure structure fractal dimension, rock mass fragmentation, and water conductivity [16]. GIS technology has been widely used to predict the water abundance of sandstone aquifer since it was introduced by Professor Sun Y. J. from China University of Mining and Technology. After the introduction of prediction models such as AHP and Artificial Neural Network (ANN) by Professor Wu Q., GIS has been used in prediction and zoning of water abundance [17]. Mohamed M. Y. completed the prediction and zoning of groundwater resources by using DEM data and GIS technology [18]. However, AHP in GIS is a method to solve the qualitative problem quantitatively. The progress of qualitative research on the water abundance of coal mine roof has required further verification of the accuracy of the quantitative research in practice.

To obtain the accurate zoning regularity of water abundance of sandstone aquifer in coal seam roof, suitable prediction indicators and methods to a given coal mining area need to be selected. The prediction results vary greatly when only using single index threshold method or fuzzy integrated clustering method [8, 9]. A reasonable prediction method is the premise to accurately predict the water abundance of sandstone aquifer. For a given coal mining area of complex geological conditions, many controlling indicators of water abundance exist. To determine the "contribution" of each indicator and comprehensively predict water abundance, this study proposes a quantitative prediction model using AHP method and multi-source information integration of GIS. The AHP method has the advantages of the comparability of control indicators and comprehensive evaluation of the hierarchical structure problem, and GIS has the advantages of visualized function and spatial comprehensive integration analysis of multi-source information. This study takes Wolong Lake coal mine in Huaibei coalfield, China, as a test area to complete the prediction of water abundance of sandstone aquifer and thus verify the accuracy of the proposed prediction model. The prediction result is verified by the data of geological logging in exploration and production, and the accuracy and applicability of the prediction model are evaluated.

The remainder of the study is organized as follows. Section 3 introduces the characteristics of indicators, the determination of the weights, and the multi-source information integration of GIS. Section 4 discusses the results of multi-source information integration of GIS and the conduct of the prediction zoning. Section 5 summarizes the conclusions.

3. Methodology

3.1 Test area

Wolong Lake coal mine is located in Huaibei coalfield, and its sandstone aquifers in coal seam roof are composed of four aquifers, which are divided into 4–8 aquifers, respectively. The fifth aquifer is the roof of No. 3 coal seam consisting of K_1, K_2, K_3, K_4, and K_5 aquifers with strong water abundance, especially in the K_3 aquifer. The K_3 aquifer is the most obvious aquifer due to its transition strata between the upper and lower Shihezi Formation of the Permian. For example, the total thickness of the fifth aquifer sandstone is 17.10–59.30 m in Liuqiao coal mine, which is adjacent to the test area, and the water inrush of 254 m^3/h occurs when the shaft passes through the strata.

In August 2012, when the 8101 first mining working face pushed through $1^{\#}$ gas drilling by 20 m, the drilling bushing was broken under mining stress, and then the water of K_3 sandstone aquifer flowed into the working surface along the fissure of the bushing, with the maximum inrush of 400 m^3/h. Although the accident has been controlled in time, it was still a continuous threat to the safe production. Subsequently, the results of hydro-geological monitoring and hydro-chemical analysis show that direct water source is the water of K_3 aquifer that is supplied from sandstone aquifer of northern adjacent coalfield [8, 9].

3.1.1 K_3 sandstone aquifer of Wolong Lake coal mine

The large thickness of K_3 aquifer provides a large bearing space for water. The spatial distribution of thickness, lithology, and the fissure structure of K_3 aquifer are uneven because of the difference in sedimentary environment and multi-period geological tectonic movement. The K_3 sandstone contour map is drawn by the statistics of the 85 boreholes of K_3 aquifer. The results are obtained as follows: (1) the thickness of K_3 aquifer in the entire coal mining area is relatively thick at mostly between 20 and 30 m. (2) The thickness in the west side of the north area of the fifth line is small, and the east side is thick. The thickness of the K_3 aquifer in the south is relatively thin and is even lacking because of the effect of F_5 and F_6 fault uplifts. (3) The statistical results of 14 boreholes from north to south on the AB exploration line (the geological exploration line from the North A point to the South B point) show that the thickness varies; the thickness presents a decreasing tendency from north to south. The thickness of K_3 aquifer on B2-5 borehole is the largest at 38.91 m (Fig. 1).

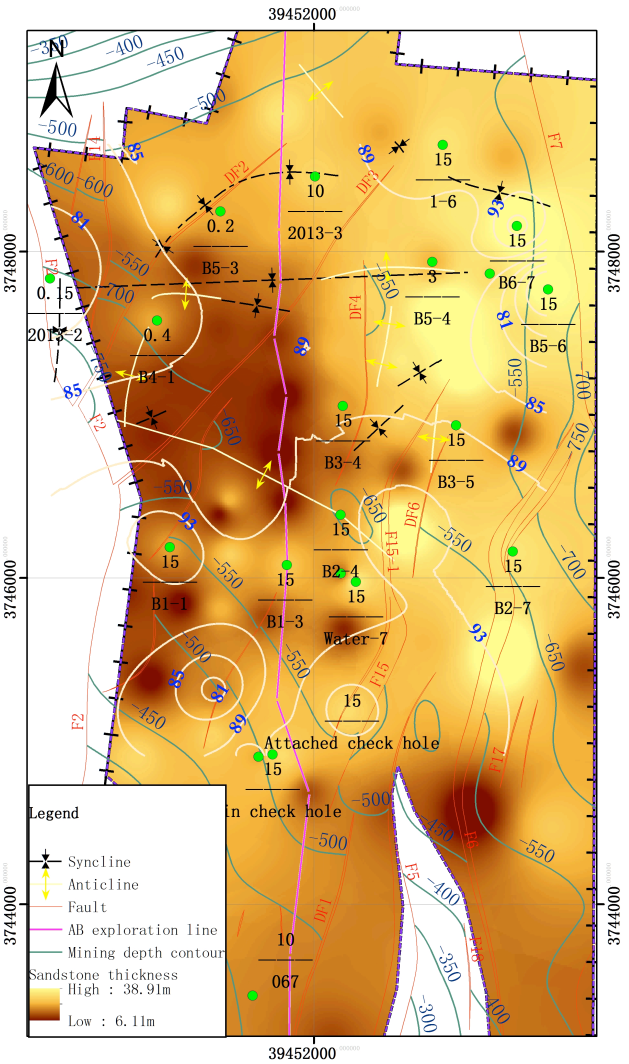

Fig. 1. Spatial thickness distribution of K_3 aquifer

3.1.2 Regional structure of Wolong Lake coal mine

Wolong Lake coal mine is located in the eastern side of the Yongcheng anticline, connected with the Cheji coal mine belonging to the Yongxia coalfield in Henan Province of China. The main strata trend of the eastern side is NNE oriented, and followed by EW oriented and NW oriented. Wolong Lake coal mine is located in the northern side of Zhaozhuang anticline, and the eastern and western boundary of the coal mine are Fengguo fault and Xu-Su arc nappe structure, respectively. The main fold structures in the mining area are the Mengzhuang syncline and the Zhangdazhuang anticline, both of which are located in north of the fourth line with gentle dips of the strata. Wolong Lake coal mine has seven faults with a drop of more than 100 m, six faults with a drop between 30—100 m, and 30 faults with a drop of less than 30 m. Four large fold structures, namely, Mengzhuang syncline, Zhangdazhuang anticline, SF_7 syncline, and SF_6 anticline, are present in the mining area. S_1, S_3, S_5, and S_7 synclines and S_2, S_4, S_6, and S_8 anticlines also exist, and all of them are distributed in the north of the mining area. Mengzhuang syncline and Zhangdazhuang anticline are cut off by DF_4 and F_2 faults, respectively. The NE folds occur earlier than near NS faults. The coal strata in the north of the mining area are lightly affected by magmatic erosion and present a relatively high recoverable area ratio.

3.2 Prediction of water abundance of K_3 aquifer based on AHP and GIS

3.2.1 Prediction indicators

The prediction indicators of water abundance includes sandstone aquifer thickness (A_1), sandstone structure index (A_2), fractal dimension value (B_1), deformation coefficient of fold plane (B_2), distance from fold (B_3), distance from fault (B_4), fissure (C), and buried deep stress (D).

The thickness of aquifer determines the container space of water. A large thickness indicates a strong water abundance. A large sandstone structure index indicates a strong water abundance. A high fractal dimension value indicates a large number of faults that increase the storage space of water and a strong water abundance. Conversely, the water abundance in the aquifer is weak [19, 20].

The pumping test result of the K_3 aquifer shows that the influence radius of the bearing water pressure of the aquifer is 183.5 m. As the buried depth of the mining strata increases, the geo-stress exerted on the rock in the vertical direction intensifies. This condition is beneficial to the closure of the fissure of the rock. Thus, the depth contour of the strata is selected as the indicator to predict the water abundance.

3.2.2 Determination of weights

AHP is used to establish the weight model of the indicators to predict water abundance of K_3 aquifer. The first-level indicators include sandstone types (A), regional structure (B), fissure (C), and buried depth stress (D). The second-level indicators include sandstone thickness (A_1), sandstone structure index (A_2), fractal dimension value (B_1), deformation coefficient of fold plane (B_2), distance from fold (B_3), distance from fault (B_4), fissure (C), and buried depth stress (D). According to experts, lithology is the main indicator followed by regional structure, and the effect of fissure rate is small. The influence of buried depth stress on water abundance of the aquifer remains to be further studied, and its weight is set to the minimum. The criteria layer expert judgment matrix is established and shown in Table 1 [21].

Table. 1. Expert judgment matrix of AHP

First-level indicators	A	B	C	D
Sandstone types (A)	1	2	3	5
Regional structure (B)	1/2	1	3	4
Fissure (C)	1/3	1/3	1	3
Buried depth stress (D)	1/5	1/4	1/3	1
λ_{max} =4.108 CR=0.0399<0.1				

The effect of fault on water abundance of sandstone aquifer is larger than that of fold. On the basis of the distance of the influence radius, the above-mentioned two indicators are used to construct second-level indicators, namely, the distance from fold and the distance from fault (Tables 2 and 3).

Table. 2. Expert judgment matrix of regional structure

Second level indicators	B_1	B_2	B_3	B_4
Fractal dimension value (B_1)	1	3/2	2	2
Deformation coefficient of fold plane (B_2)	2/3	1	3/2	3/2
Distance from fold (B_3)	1/2	2/3	1	1
Distance from fault (B_4)	1/2	2/3	1	1
λ_{max} =4.002 CR=0.0006<0.1				

Table. 3. Weights of the indicators

Indicators	A	B	C	D	W_i
Sandstone thickness (A_1)	0.50				0.231
Sandstone structure index (A_2)	0.50				0.231
Fractal dimension value (B_1)		0.374			0.117
Deformation coefficient of fold plane (B_2)		0.273			0.086
Distance from fold (B_3)		0.181			0.056
Distance from fault (B_4)		0.181			0.056
Fissure (C)					0.152
Buried depth stress (D)					0.071

3.2.3 Normalization data of the indicators

To eliminate the influence of the dimensional difference of indicators [22], linear normalization is applied before the multi-source information integration of GIS. Thus, the data value of each prediction indicators is normalized to 0–1. In the influence radius of 185 m and using the GIS buffer analysis function, the value is assigned to 1 when the distance from the axis of fault or fold is less than 25 m, whereas the value is assigned to 0 when the distance is more than 185 m. Using the linear normalization method, the distance between 25–185 m is assigned to 0–1. The normalized formula (1) is:

$$X_i' = \frac{X_i - \min(X_i)}{\max(X_i) - \min(X_i)} \quad (1)$$

The prediction results A of water abundance is acquired using weighted integration method of GIS [23, 24]. The rationality of prediction results is judged and approved using the maximum drilling mud leakage and core recovery percentage. The weighted integration formula (2) is:

$$A = \sum_{1}^{i} X'_i \times W_i \times 10 \quad (2)$$

Where X_i', $\max(X_i)$, and $\min(X_i)$ are seperately the linear normalized data, the maximum and the minimum data of *i*th prediction indicator, and X_i is the original value of the *i*th indicator. W_i is the weight of the *i*th indicator.

4. Result Analysis and Discussion

The fractal dimension value of K_3 aquifer is high in the east and low in the west. The area with large value is distributed around the F_2, F_5, and F_6 faults. In the south of the lines 4 and 5, the fractal dimension value is less than 1. The minimum value is close to the industrial square area, where water abundance of the K_3 aquifer is weak.

The dips of the strata in the coal mining area are gentle between 5° and 20°. The deformation coefficient of fold plane is below 0.25, and its variance is small. In the intersection of two large faults F_6 and F_7 in the southeastern corner of the coal mining, the coefficient is large. The coefficient is generally large in the integration zone of the east side of the AB exploration line and the south side of the B_4 line. The coefficient is generally small in the west side of the AB exploration line except the northwest corner and near the 067 borehole. The northwest corner of the west side of the AB exploration line presents the major folds and some superior faults (such as F_2, DF_2, and F_{14}). A large coefficient indicates a strong water abundance of aquifer. Conversely, the water abundance is weak in the southwestern area of the coal mining area with the lowest coefficient.

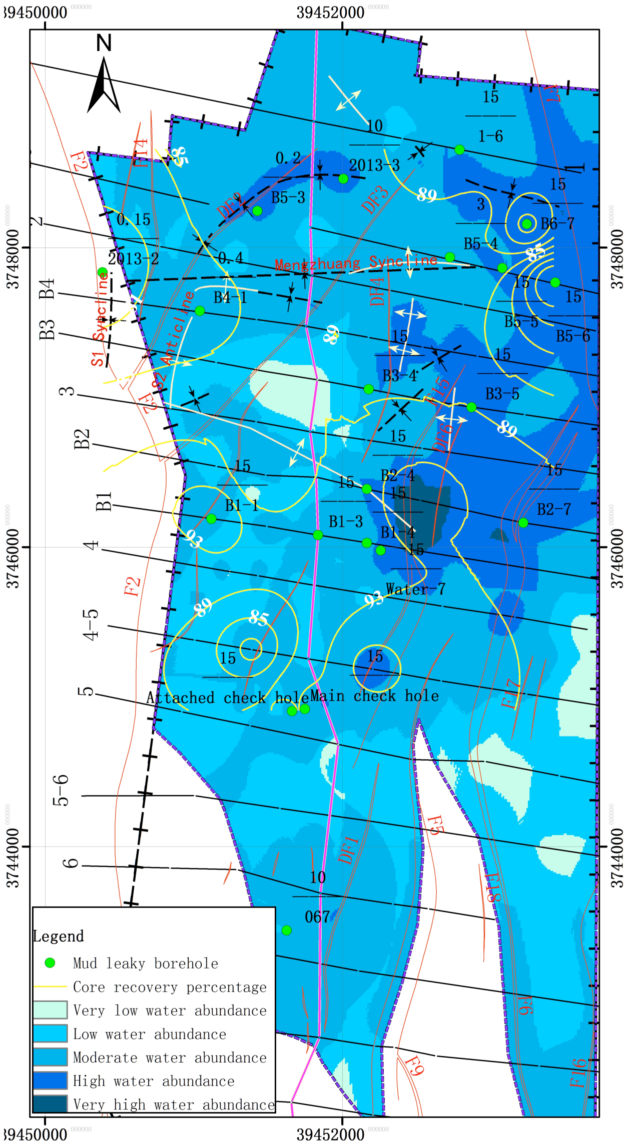

Fig. 2. GIS multi-source integration prediction and zoning result

The K_3 sandstone has a broken core and many fissures with high angle and filled by calcite, and a few fissures open up to 5 mm. Obviously, the sandstone is eroded by water because it is rusty red, which indicates that the water abundance of K_3 aquifer in study area is rich. The microscopic identification results of K_3 sandstone slice show that K_3 sandstone fissure develops in many directions and cuts off the quartz particles. The statistical results of the fissure characteristics of 61 K_3 boreholes show that the fissures are concentrated in the vicinity of the axis of fault or fold, but the development degree is extremely uneven. For example, near the fault in the north side of the line 4 or the disappearing region of the north of the F_{16} fault, the development degree of fissures shows a strip distribution regularity in spatial direction, where the fissure of sandstone is very remarkable. Moreover, the water abundance of K_3 aquifer in this area is very strong.

Among the 85 boreholes, 20 boreholes exhibit leaking with a mud leakage between 0.15 and 15 m^3/h. The mud leakage over the 15 m^3/h is unified as the complete leakage boreholes. Most of the leaky boreholes are distributed in the northern side of the line 4, and mostly locates in the axis and east side of the Mengzhuang syncline or the axis and the south side of the Zhangdazhuang anticline. Near the F_2, DF_5, F_7, and F_{15} faults, the spatial distribution of the leaky boreholes presents a north-east stripe in spatial direction. The leaky boreholes in other areas are few.

For the leaky boreholes, the buried depth of floor of working face is between −779.8 and −149.3 m. The boreholes mainly appear from −710.8 m to −411.8 m, and the average depth is −559.3 m. Therefore, the influence of the geo-stress to fissure closure is not obvious. The thickness of K_3 aquifer in Wolong Lake mine is between 6.11 and 38.91 m with an average thickness of 18.32 m. Twenty leaky boreholes appear with a thickness from 13.12 m to 34.70 m and an average thickness of 21.99 m. Fifteen leaky boreholes among the 20 boreholes present a thickness larger than the average of 18.32 m. Ten leaky boreholes appear among the 15 boreholes and present a thickness of over 21.99 m and a mud leakage greater than or equal to 15 m^3/h. The thickness of the five other boreholes is less than 21.99 m, and the mud leakage is less than 10 m^3/h. Therefore, the thickness of sandstone exerts a relatively large impact on the water abundance of K_3 aquifer [25].

With regard to region structure, 20 mud leaky boreholes appear, of which 14 boreholes are in the influence radius of fold or fault, especially the B_3−5, B_5−3, and 2013-2 boreholes affected by fold and fault synchronously. Obviously, the region structure plays a major role in the water abundance.

The average core recovery percentage is 88% by statistics of the data of 18 core boreholes. The maximum core recovery percentage in Wolong Lake mining area is 99%, and the borehole is near the 4-5-6 borehole. The core recovery percentage in the south is generally above 95%, which is higher than that in other regions. The core recovery percentage in the central regions is generally around 90%. A NE-oriented strip region with a core recovery percentage between 85% and 95% is found in the north.

The comprehensive prediction value A of 20 leaky boreholes ranges from 3.21 to 6.08 with an average of 4.82. If the A value exceeds 3.20, then the area is considered a water abundance region of K_3 aquifer that accounts for 72% of the entire mine area. When A value is more than 4.80 of the average, the proportion of the total mine area is 19.58%, which is defined as high or very high water abundance.

Table. 4. Prediction result of the aquifer water abundance

Prediction result	A value	Proportion (%)
Very low water abundance	1.79–2.50	3.52
Low water abundance	2.50–3.20	24.31
Moderate water abundance	3.20–4.80	52.60
High water abundance	4.80–6.40	18.73
Very high water abundance	6.40–7.56	0.86

5. Conclusions

To solve the problem of inconsistent prediction results by using the single index threshold method, weighted integration prediction model based on AHP method and GIS technology is proposed. First, the study determines the primary and secondary control indicators of water abundance of K_3 aquifer and achieves the weight of each indicator by AHP. Then, the prediction and zoning of the water abundance in the test area are completed using multi-source information integration of GIS. Finally, the prediction results are verified mainly by the maximum mud leakage and the core recovery percentage. The conclusions are obtained as follows:

(1) The prediction results of water abundance of sandstone aquifers with single index threshold method quite differ. The thickness of sandstone aquifer in the test area varies from north to south and exhibits a tendency to be slightly small from the north to south. The thickness in middle-east is thicker than that in the west. The region with large deformation coefficient of fold plane is mainly distributed near the northwest corner of the mining area or several large faults in the east. The region with large fractal dimension values is concentrated near several major faults such as F_2, F_5, and F_6. The trends of the faults are uniform in the NS oriented, especially in the north of the mining area. Multi-source integration prediction of GIS can solve the inconsistency of the results by using single index threshold method.

(2) The prediction results of combination of GIS and AHP methods show that the region with high water abundance is mainly located in the northeastern part of the coalfield, and the region with low water abundance is mainly located in the southern part of the coalfield. The water abundance of the aquifer is dominated by medium water abundance, followed by low water abundance. The region of high water abundance is consistent with the locations of the boreholes with small core recovery percentage or high mud leakage. This finding confirms the reliability of the results obtained from the AHP–GIS integration prediction model.

(3) The regions with strong water abundance are located in the overlapping region with thick sandstone aquifers and high development degree of region structure. The region with very high water abundance is located at the central location of several complete leakage boreholes, where the core recovery percentage reaches up to 95%. Therefore, the model used in this study is practical and accurate in predicting the water abundance of sandstone aquifer.

The multi-source information integration of GIS in this study can provide a reference for the prediction and evaluation of sandstone aquifer water abundance of sandstone aquifer for the coal mining areas under hydro-geological conditions. The study can also provide a theoretical basis for comparing different prediction methods.

The study can guide the safe production of coal mines affected by the roof water.

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