A GIS-based Model of Potential Groundwater Yeld Zonation for A Sandstone Aquifer based on the EWM and TOPSIS Methods

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Abstract

Resolving the potential groundwater yield zonation of sandstone aquifers is an important task for prevention of flood hazards from coal roof in coal mines. Based on the accessible geological exploration data, we presents a method of predicting the potential groundwater yield zone in sandstone aquifers based on entropy weight method (EWM) and the technique for order performance by similarity to ideal solution (TOPSIS). The relationships between the factors and groundwater yield in sandstone aquifers were discussed and determined by EWM. And finally, a potential groundwater yield contour map was constructed by PGYI values using TOPSIS method. And the field data were used to test the accuracy of the prediction model.

Keywords: potential groundwater yield zonation, sandstone aquifers, coalmine, China

Introduction

Coal mining activities will inevitably damage or disturb the roof aquifers (Wu et al. 2017). It is more possible to cause serious water inrush in the rich water abundance zone during mining. So it is one of the most important tasks to explore the potential sandstone aquifers situated in the proximity of active mine sectors, which could contribute to the prevention of flood hazards in coal mines. Predicting the potential groundwater yield zonation of sandstone aquifers has been an important and challenging objective of the hydrogeological research focused on the prevention of the flood hazards (Yin et al. 2018). And several methods have also been used to estimate the groundwater potential zonation in sandstone aquifers, such as analytic hierarchy process (AHP) method (Wu et al. 2017) , fuzzy analytic hierarchy process index (Han et al. 2012), and trapezoidal fuzzy number (TFN) method (Yin et al. 2018). These methods provide a powerful tool for estimating the groundwater potential zonation in sandstone aquifers, but the weights of the factors are obtained based on expert analysis in these methods which are of relatively subjective. In addition, it is relatively rare that hydrogeological studies exceed the geological exploration during mining activities especially in new coal mines. So it is important to accurately estimate the potential groundwater yield zone of the sandstone aquifers by using data acquired during geological exploration.

Accordingly, a method was proposed for predicting the groundwater potential zone in sandstone aquifers based on the entropy weight method (EWM) and the technique for order performance by similarity to ideal solution (TOPSIS) by using data collected from coal mine. EWM was applied to discuss and determine the relationship between the factors and the groundwater yield zone in sandstone aquifers, decreasing the subjectivity of traditional expert analysis. And finally, a potential groundwater yield contour map was constructed based on data of conditioning factors by using the TOPSIS method. The field data were used to test the accuracy of the prediction model.

Study area and data

Study area

The No. 1 mine field of Changcheng coalmine belongs to the Otog Front Banner, Erdos City, Inner Mongolia, China, which covers an area of 6.65 km^2, extending between 106°32′40″-106°37′04″E and 38°14′26″-38°17′16″N. It has a typical characteristic of desert steppe and the surface is almost covered by wind-deposited sands of quaternary with sparse vegetation. The mean annual rainfall of the area is about 270.4 mm, and the mean annual

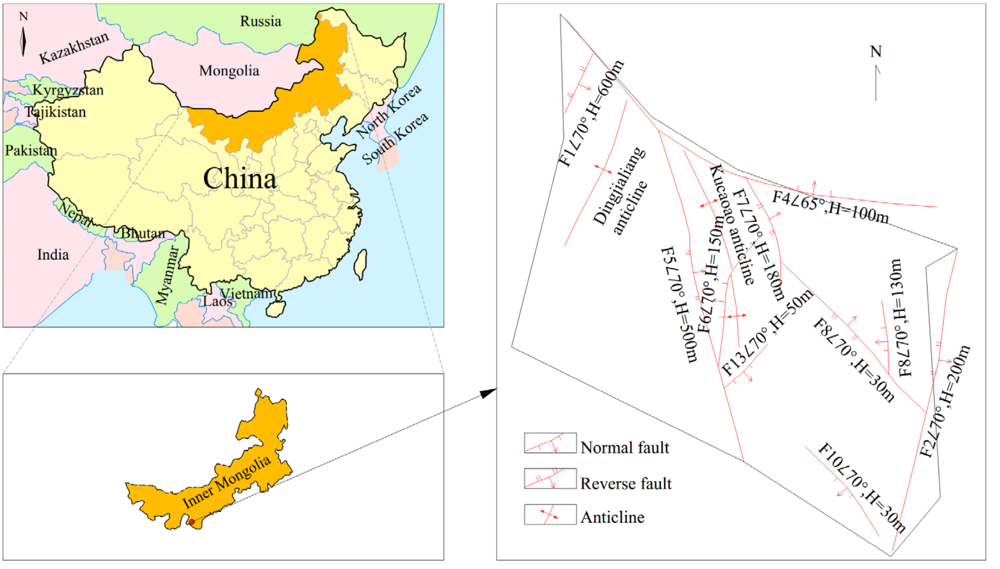


Figure 1 Location of the study area in Inner Mongolia, China, and geological structure of No. 1 mine field of Changcheng coalmine

temperature is 7.3°C. Generally, the area is a monocline with a south-north strike and dipping east, where faults and anticlines are well developed (Fig. 1).

The No. 1 mine field of Changcheng coalmine is a North China coalfield of Permo-Carboniferous age. The main coal-bearing strata are Taiyuan Formation (F) and Shanxi F of the Permo-Carboniferous system, including seven minable seams, i.e. No. 1, 31, 32, 5, 8, 91, 92. One of the mining activities is No. 3 coal seam, which is 0.63-5.72 m thick, extensive and of high quality. The lithology of the main aquifers overlying the No. 3 coal seam are mainly sand and gravel at the Quaternary and Neogene, and sandstone within the Permo-Carboniferous deposits. The main aquitards overlying the No. 3 coal seam include clay beds in Quaternary and Neogene, and mudstone and siltstone in Permo-Carboniferous, which cut off the hydraulic connecting between groundwater in sandstone aquifers and surface water and rainfall. When mining the No. 3 coal seam, water flows into the work-face are from the roof sandstone in the Shanxi F. The study focuses on the sandstone occurring on the roof of the No. 3 coal seam, which is the fractured confined aquifer with a thickness and depth ranging between 0 m and 74.1 m,and 214.79 m and 1046.3 m below the surface, respectively. In this study, only two well pumping tests on the roof sandstone aquifers of the No. 3 coal seam were carried out in the No. S01 and No. XJ3, and the results showed that the aquifer had a low

Table 1 Pumping test on the roof sandstone aquifers of the No. 3 coal seam

Hydrologic well	Water level (m)	Water yield per unit of drawdown (L/s.m)	Permeability coefficient (m/d)	Actual yield description
No. S01	+1192.5	0.0339	0.10477	low
No. XJ3	+1203.82	0.032277	0.297847	low

Table 2 Pumping test on the roof sandstone aquifers of the No. 3 coal seam

Work-face	Actual yield(m^3/h)	Work-face	Actual yield(m^3/h)	Work-face	Actual yield(m^3/h)
1301N	30	1302S	24	1304N	126
1301S	25	1303N1	160	1304S	33
1302N	126	1303N2	160		

water yield (Table 1). However, eight water inrushes ocured from the roof sandstone aquifers during mining the No. 3 coal seam, and the maximum water yield ranges from 24 to 160 m^3/h (Table 2).

The existence and abundance of groundwater in a given aquifer is controlled by many factors. Six main potential groundwater yield conditioning factors selected in this study are thickness of sandstone, lithological composition index, depth of sandstone, fault intensity index, density of fault intersections and endpoints, and fold axis length density, which were collected mainly from boreholes and 3D-seismic exploration throughout the mine field.

- Thickness of sandstone (TS)
  The thickness of sandstone is the basis of determining the potential groundwater yield, which was acquired from the geo-exploration data. The thicker the sandstone layer, the greater the yield in a aquifer when all the other factors are the same (Yin et al. 2018). The sandstone overlying the No. 3 coal seam in the study area varies from 0 m to 74.1 m, shown in Fig. 2 a.
- Lithological composition index (LCI)
  Different types of lithology affect groundwater storage. The layers overlying the No. 3 coal seam are sandstone of all grain sizes, siltstone, and mudstone. The coarser the sandstone, the greater is the water storage capacity (Zhang 2008). Due to brittle and susceptible to fracturing, sandstone thus increases porosity and permeability. The sandstone with bigger grain size would have greater influence on the groundwater storage capacity than the soft rock with small grain size. The lithological composition index is calculated by the following Equation:
  $$LCI=(a\times1+b\times0.8+c\times0.6+d\times0.4+e\times0.2+f\times1)\times g \quad (1)$$
  Where LCI is the lithological composition index; *a, b, c, d, e, f* are the thickness of the conglomerate, coarse sandstone, medium-grained sandstone, fine-grained sandstone, siltstone, and limestone, respectively; *g* is the structure coefficient, and 0.2, 0.4, 0.6, 0.8, and 1 are the equivalent coefficient for different rock types. when the sandstone thickness represents more than 80% of the total thickness, *g* is 1; when the proportion is between 60% and 80%, *g* is 0.8; when the proportion is between 40% and 60%, *g* is 0.6; when the proportion is between 20% and 40%, *g* is 0.4; when the proportion is less than 20%, *g* is 0.2. Lithological composition index was shown in Fig. 2 b.
- Depth of sandstone (DS)
  With the increase of depth, the lithostatic pressure increases, which decreases secondary porosity slightly by possibly closing the fractures present. The depth of sandstone is one of the factors affecting the groundwater storage. The depth of sandstone was acquired from 3D-seismic exploration, geoexploration, and roadway and workface constructions, ranging from 124.79 m to 1046.3 m below the ground surface, as shown in Fig. 2 c.
- Fault intensity index (FII)
  Faults have a great influence on groundwater potential and especially on groundwater storage and migration, which have usually been used as an indicative tool for locating potential groundwater yield zones (Dar et al. 2010; Sander et al. 1997). The fault intensity index is the sum of the fault throws multiplied by their corresponding fault length divided by the grid cell area:
  $$FII = \frac{\sum_i^n l_i h_i}{S} \quad (2)$$
  Where *H is* the fault throw and *L* is the corresponding strike length; *S* is the area of the grid cell; and *n* is the number of faults in the grid cell. In general, FII is directly correlated with the groundwater potential, as shown in Fig. 2 d.
- Density of fault intersections and endpoints (DFIE)
  More fault intersections and endpoints will weaken the integrity of the rock and increase sandstone permeability and water storing capacity. The density of fault intersections and endpoints is expressed by Eq. (3) and shown in Fig. 2 e.
  $$\mathrm{DFIE} = \frac{n}{S} \quad (3)$$
  Where *n* is the total number of fault intersections and endpoints of all faults in

each grid unit, and S is the area of the grid unit.

- Fold axis length density (FALD)
  For folds, the fold axis is the main factor describing the fold distribution, along which fractures are well developed which are destructive to the integrity and continuity of the strata, thus increasing sandstone permeability and water storing capacity. the fold axis length density is expressed by Eq. (4) and shown in Fig. 2 f.

$$\mathrm{FALD} = \frac{\sum_t^r L_t^2}{S} \tag{4}$$

where FALD is the fold axis density; Lt is the tth fold's axis length; S is the area of the grid unit; and t =1, 2, …, r, where r is the total number of folds in each grid unit.

Methodology

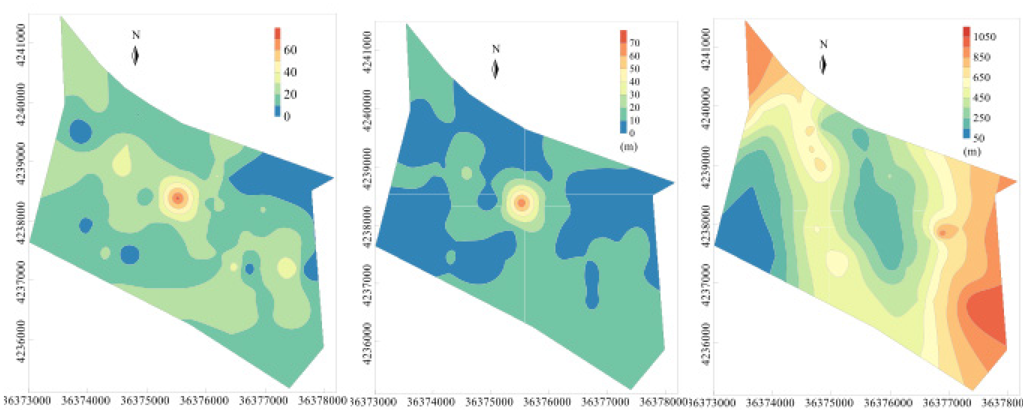
Determination of the factors weights

Entropy weight method is a measure of the degree of uncertainty represented by a discrete probability distribution, which can objectively weights factors as a feasible scientific method. Three steps were followed to calculate the weights of the six assessment factors (Wang et al. 2018):

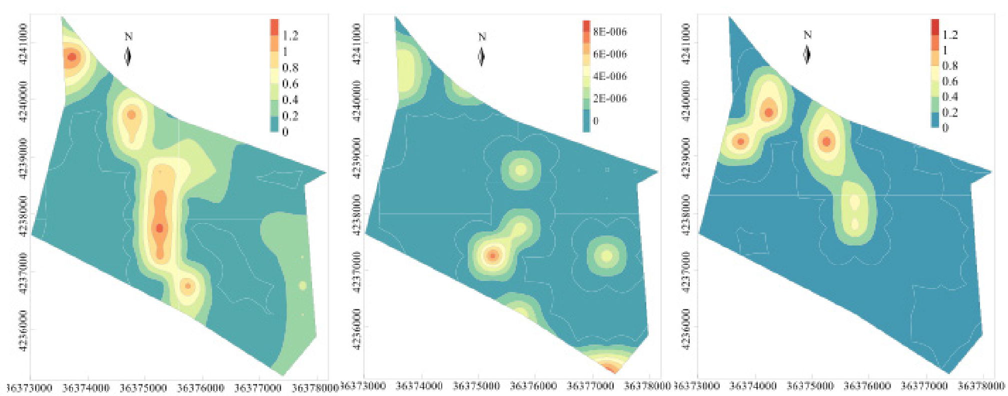
(a) Constructing the decision matrix as follows (Wang et al. 2018):

$$R = \begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix} \tag{5}$$

where x_{ij} is the value of the ith sample jth factor; i = 1, 2, …, 76; j = 1, 2, …, 6; and m and n are the total number of the samples and factors respectively.



(a) Thickness of sandstone aquifers (b) Lithological composition index (c) Depth of sandstone



(d) Fault intensity index (e) Density of fault intersections and endpoints (f) Fold axis length density

Figure 2 *Assessment factors of the potential groundwater yeld*

(b) Calculating the entropy of the jth factor (Wu et al. 2015):

$$E_j = -\frac{1}{\ln m}\sum_{i=1}^{m}\frac{x_{ij}}{\sum_{i=1}^{m}x_{ij}}\ln\frac{x_{ij}}{\sum_{i=1}^{m}x_{ij}} \quad (6)$$

(c) Establishing the entropy weight of the jth factor (Huang et al. 2017):

$$\omega_j = \frac{1-E_j}{\sum_{j=1}^{n}(1-E_j)} \quad (7)$$

Following the above steps, a 76×6 decision matrix was established, and the entropy E and entropy weights of the factors were calculated as shown in Table 3. The weights of TS, LCI, DS, FII, DFIE, and FALD were 0.043, 0.059, 0.242, 0.192, 0.220, and 0.244, respectively.

The TOPSIS method is a multiple-attribute decision making techniques applied to wide variety of decision problems (Ataei et al. 2012; Baykasoğlu and Gölcük 2017; Sepehr and Zucca 2012). In this paper, the TOPSIS method was used to determine the final ranking of the potential groundwater yeld, and three steps were followed.

(1) Constructing the weighted standardized matrix based on the original data and the weights calculated by EWM by using the following Eq. (7):

$$V = (v_{pi})_{l\times n} = \begin{bmatrix} W_1c_{11} & W_2c_{12} & \cdots & W_nc_{1n} \\ W_1c_{21} & W_2c_{22} & \cdots & W_nc_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ W_1c_{l1} & W_2c_{l2} & \cdots & W_nc_{ln} \end{bmatrix} \quad (7)$$

Where V is the weighted standardized matrix; vpi is the weighted standardized value of the pth sample's ith factor; Wi is the weight of the ith factor derived by EWM, i∈[1, n]; c_{pi} is the standardized value of the p^{th} sample's i^{th} factor, which is normalized by the following Equation:

$$c_{pi} = b_{pi}/\sqrt{\sum_{p=1}^{l} b_{pi}^2}$$

i = 1, 2, ⋯, n, where b_{pi} is the observed value of the p^{th} sample's i^{th} factor.

(2) Determinating the ideal solutions. During determination of the ideal solutions, the potential negative and positive related factors of the potential groundwater yield had to be considered separately. If J_1 and J_2 indicate the set of negative factors and positive factors, respectively, the negative ideal solution and the positive ideal solution are determined by Equations 8 and 9:

$$V^- = \left\{(\max_{1\le p\le l} v_{pi} \mid i \in J_1),\ (\min_{1\le p\le l} v_{pi} \mid i \in J_2)\right\} \quad (8)$$

$$V^+ = \left\{(\min_{1\le p\le l} v_{pi} \mid i \in J_1),\ (\max_{1\le p\le l} v_{pi} \mid i \in J_2)\right\} \quad (9)$$

Where V^- and V^+ are the negative ideal solution and positive ideal solution, respectively.

(3) Determinng the final ranking of the potential groundwater yeld for each sample, which is expressed by a potential groundwater yield index (PGYI) calculated using Equation 10:

$$\text{PGYI} = \frac{D_p^-}{D_p^+ + D_p^-},\ (p = 1,\ 2,\ \cdots, l) \quad (10)$$

Where D^-_p and D^+_p indicate the distance between the p^{th} sample and the negative ideal solution, and the positive ideal solution respectively, which were calculated by Equations 11 and 12, respectively:

$$D_p^- = \sqrt{\sum_{i=1}^{n}(v_{pi} - v_i^-)^2} \quad (11)$$

$$D_p^+ = \sqrt{\sum_{i=1}^{n}(v_{pi} - v_i^+)^2} \quad (12)$$

The larger the PGYI value, the greater the potential groundwater yeld is. The ranking of the potential groundwater yeld can be determined by arranging the PGYI value in descending order.

Results

The PGYI value was calculated for each 500 m × 500 m grid unit, and all grid data was then processed by using Surfer and MapGis software and interpolated with the Kriging function interpolation technique to create the PGYI contour model map as shown in Fig. 3. According to the contour map, the potential groundwater yeld which is expressed by PGYI value ranges in the study area from 0.032 to

Table 3 *Values of entropy E and entropy weights of the assessment factors of the potential groundwater yeld*

Factor	TS	LCI	DS	FII	DFIE	FALD
entropy E	0.984	0.978	0.911	0.930	0.920	0.911
entropy weight ω	0.043	0.059	0.242	0.192	0.220	0.244

0.497. Thus, the area was divided into three water abundance zones: low (<0.07), medium (0.07-0.12), and high (≥0.12). The prediction result shows that the details of the distribution of the potential groundwater yeld: the areas with the highest groundwater potential are mainly located in the central and northwest parts of the mine field whereas the low and medium potential areas are mainly located in the southwest and northeast parts of the mine field. The results of the study can be applied to guiding dewatering the sandstone aquifers during the mining of No. 3 coal seam using boreholes, which also can be used to provide water for mining activities for other mines with sandstone aquifers.

Conclusions

To prevent coal mine flooding from coal seam floor, it is essential to determine the distribution of groundwater in sandstone aquifers. In this study, a PGYI model was successfully applied to predict the potential groundwater yeld zonation in the sandstone aquifers overlying No. 3 coal seam in the No. 1 mine field of Changcheng coalmine, China. The PGYI model integrated six factors consisting of thickness of sandstone, lithological composition index, depth of sandstone, fault intensity index, density of fault intersections and endpoints, and fold axis length density. The weights of the six factors were determined by EWM, which were 0.043, 0.059, 0.242, 0.192, 0.220, and 0.244, respectively. And potential groundwater yield contour map was builtd by the PGYI values using the Kriging function interpolation technique. The area was divided into three water abundance zones: low (<0.07), medium (0.07-0.12), and high (≥0.12).

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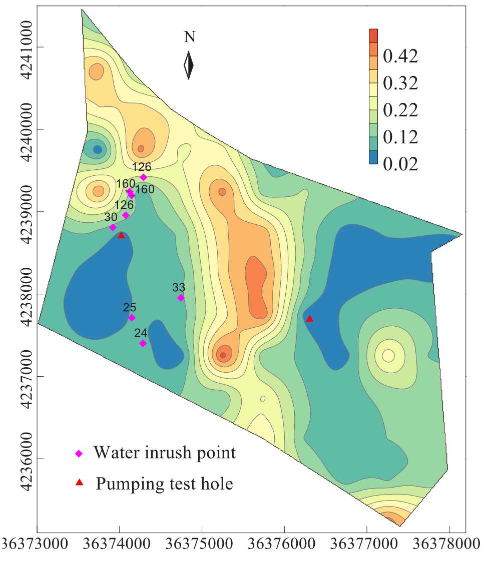

Figure 3 *Potential groundwater yeld zonation by PGYI*

References

Han C, Ban X, Li G (2012) The Fuzzy analytic hierarchy process of water abundance of an aquifer based on GIS and multi-source information fusion techniques. Hydrogeology & Engineering Geology 39: 19-25

Wu Q, Xu K, Zhang W, Wei Z (2017) Roof aquifer water abundance evaluation: a case study in Taigemiao, China. Arab J Geosci 37(1): 174-184, doi: 10.1007/s12517-017-3048-3

Yin H, Shi Y, Niu H, Xie D, Wei J, Lefticariu L, Xu S (2018) A GIS-based model of potential groundwater yield zonation for a sandstone aquifer in the Juye Coalfield, Shangdong, China. Journal of Hydrology 557: 434-447, doi: 10.1016/j.jhydrol.2017.12.043

Zhang Y (2008) Investigation on predicting water inrush under complicated water– filling condition in the coal mines -for example the Longgu Coal Mine. College of Geological Science and Engineering, Qingdao, Shandong (in Chinese).

Dar IA, Sankar K, Dar MA (2010) Remote sensing technology and geographic information system modeling: an integrated approach towards the mapping of groundwater potential zones in hard rock terrain, Mamundiyar basin. J. Hydrol 394: 285–295.

Sander P, Minor TM, Chesley MM (1997) Groundwater exploration based on lineament analysis and reproductivity tests. Ground Water 35 (5): 888–894.

Ataei M, Mikaeil R, Hoseinie SH, Hosseini SM (2012) Fuzzy analytical hierarchy process approach for ranking the sawability of carbonate rock. International Journal of Rock Mechanics and Mining Sciences, 50: 83-93.

Baykasoğlu A, Gölcük İ (2017) Development of an interval type-2 fuzzy sets based hierarchical MADM model by combining DEMATEL and TOPSIS. Expert Systems With Applications, 70: 37-51.

Sepehr A, Zucca C (2012) Ranking desertification indicators using TOPSIS algorithm. Natural Hazards, 62: 1137-1153.

Wang Z, Wang C, Wang Z (2018) The Hazard Analysis of Water Inrush of Mining of Thick Coal Seam Under Reservoir Based on Entropy Weight Evaluation Method, Geotech Geol Eng. doi: 10.1007/s10706-018-0520-0