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SPECIAL ISSUE

Influence of coal mining on regional karst groundwater system: a case study in West Mountain area of Taiyuan City, northern China

Xiaojuan Qiao · Guomin Li · Ming Li · Jinlong Zhou · Jie Du · Chengyuan Du · Zhonghui Sun

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Abstract Karstic limestone formations in the West Mountain area are important water resources for Taiyuan City in Shanxi Province, northern China, which is also known for its large-scale coal mining production. In this study area, groundwater is not only exploited for water supply purposes but also drained because of coal mining. The process of coal mining changes both the quantity of the karst springs and the quality of karst groundwater system because of overexploitation and overdrainage. In this paper, the influence of coal mining on the groundwater is analyzed from a qualitative and quantitative perspective. The hydrochemical analysis results reflect the relationship of the recharge, runoff, and drainage; the features of the medium; and water-rock interactions. Based on a qualitative understanding of the geological deposition and characteristics of the groundwater flow system, three-dimensional groundwater flow models are established and applied to several scenarios to explore the quantitative influence and allow better protection of the groundwater environment and better utilization of water resources.

Keywords Hydrochemistry · Three-dimensional models · Coal mine · Karst groundwater system · Taiyuan, China

X. Qiao · G. Li (✉) · M. Li · J. Zhou
Key Laboratory of Engineering Geomechanics,
Institute of Geology and Geophysics, Chinese Academy
of Sciences, P.O. Box 9825, Beijing 100029, China
e-mail: guominli@mail.igcas.ac.cn

J. Du · C. Du · Z. Sun
Taiyuan Water Resources Bureau, Taiyuan,
Shanxi Province 030002, China

Introduction

Coal and groundwater are two kinds of natural resources stored in the same subsurface geological media. Taiyuan City in the Shanxi Province of northern China is known for its coal production as well as its many karst springs (Han et al. 1993). In the West Mountain area of Taiyuan City, a wide range of coal-bearing strata overlay the karst groundwater aquifers, which are extensively distributed and come to the surface in the north of Fen River and along the edge of the mountain (The first department of engineering geology and hydrogeology in Shanxi geology survey 1984). The relationship between coal mining and groundwater is complex because of their respective properties. The circulation of groundwater in karstic aquifers, on the one hand, is quite different from water circulation in nonkarstic aquifers (Kacaroglu 1999). Karstic aquifers are mainly determined by their unique geological and hydrogeological features including their lithology, the permeability of limestone formations, the tectonic structure, and the inherent discontinuities (i.e., fault lines, fractures, joints, layering) of the geological structure, as well as the karstic structures such as caves, dolines, channels, and uvala formed during the flow and dissolution process (Sen 1995). The exploitation of coal, on the other hand, is a complex process involving factors such as the natural geological structure, hydrological conditions, and the technological mining methods being used.

The impact of coal extraction on groundwater depends on the location of the mine, the hydrology, and the physical and chemical properties of the coal related to strata and reject materials. In mining operations, water drainage results in lowering of the groundwater table, groundwater depletion, ground subsidence, or cave-ins, and causes losses to livelihood and society (Xu and Shen 2004). Although the drainage differs for different types of coal mines and different steps in the mining process, generally speaking, a large-scale mining operation has the potential for producing adverse environmental effects and may result in changes not only in the hydrodynamic system but also in the chemical composition of the groundwater (Guo and Wang 2006). As coal is a major energy source in China, the problems related to balancing coal exploitation and groundwater protection are difficult to deal with for governors.

Many researchers have focused on the relationship of the coal mining process and groundwater pollution and protection (Wang et al. 2002; Wu et al. 2000, 2002; Yang et al. 2006; Feng 2006; He et al. 2007). Many researchers have also paid more attention to the quantitative influence of the coal mining activity on the water resources (Zhang and Liu 2002; Ren et al. 2000). Han (2008) analyzed the stress changes in the geological formation, deformation of the underground geological structure, and the groundwater decline and pollution during the coal mining. The problem of coal mining and groundwater protection is an international one; in many other countries, numerous studies also have been underaken related to chemical investigation and modeling (e.g., Zipper et al. 1997; Mayo et al. 2000; Brake et al. 2001; Pluta and Trembaczowski 2001; Younger and Wolkersdorfer 2004; Tiwary 2001; Rapantova et al. 2007; Gandy and Younger 2007; Simsek et al. 2008).

In order to make the relationship between coal mining and groundwater exploitation more clear and solve the problems related to the effects of coal extraction on groundwater and environment protection, in this paper, integrated information from many sources is used to undertake analyses considering both quality and quantity. Fourteen representative water samples were collected from the karst water, pore water, and coal mining area. Firstly, many field investigations and a new total analysis of the hydrodynamical elements were done to acquire more hydrochemical information. From the systematic point of view, the elemental composition of the karst groundwater reflects the water's migration as controlled by the geological and hydrogeological background and the physical-chemical balance. The compositions depend on the circulation conditions but can also reflect the basic features of the dynamic flow field (Guo and Wang 2006). The hydrogeochemical method can be used not only to analyze the quality of the water in terms of the regulation of temporal and spatial variation, but also can supply information about the hydrodynamic environment such as the storage conditions, the seepage channel, the circulation depth, and potential resources (Wang et al. 1997, 2001; Mazor et al. 1993). Therefore, the information collected through hydrogeochemical investigation is fundamental and helpful for understanding the karst groundwater system. Secondly, three-dimensional finite difference models were set up to analyze further the quantitative relationship of the drainage and the groundwater system. The model involved taking field data including geological, hydrogeological, and coal mining data, and translating this information into the input model. Several scenarios were defined to evaluate the response in different drainage situations. These scenarios showed that groundwater heads would continue to decrease with the present pumping discharge rates.

The Taiyuan karst groundwater system has a long history of being studied, with many research findings. As early as the 1950s, the department concerned did many investigative works on geology, especially aimed at the coal geology. In 1984, the evaluation of the west karst groundwater resources was launched. During this round of evaluations, the hydrochemical and isotopic method was adopted, but the analysis was not sufficient. Many researchers undertook some chemical analysis in this area (Wang and Wang 1984; Tang et al. 1991; Han et al. 1994, 2006; Wu et al. 2006). Although a great deal of research has been carried out in the past, with steadily expanding economic activities and growth in coal industrial development in this area, the exploitation of groundwater and coal resources has changed the relationships among the area recharge, circulation, and discharge of the groundwater, making the water supply of Taiyuan City an increasingly difficult problem. In particular, water levels of most local springs have been significantly lowered and some have dried up, such as the Jinci spring and Lancun spring, because of the excessive use of surface water and the excessive removal of groundwater. With the increase in the level and depth of coal exploitation, the impact on water resources and the water environment has become worse. This is significant for evaluating the effects of coal mining on groundwater resources using new data and methods.

Description of the study area

Topography and hydrology

Located in the western part of Taiyuan City, Shanxi Province, North China, the study area covers nearly 4,500 km^2 including a large mountain area and a small part of the Taiyuan basin in the west of the Fen River. The altitude of the area ranges from 750 to 2,202 m, with a sharp slope in front of the mountain to the alluvial plain of the Fen River (The first department of engineering geology and hydrogeology in Shanxi geology survey 1984).

The area has a semi-arid continental climate with a mean annual temperature of 9.1°C, with the highest temperatures (mean 39.4°C) in July and lowest (−26.8°C) in January. The average annual precipitation was 449.7 mm during the sampling period (1985–2006), and is distributed unevenly throughout the year with the majority (60%) falling from June to September. Evaporation ranges from 1,045 mm/year in the piedmont to 1,026 mm/year at high altitudes (Taiyuan Water Resources Bureau 2006).

The Fen River is the largest river that originates from the northwestern mountains in the study area, covering an area of 7,705 km^2 (The first department of engineering geology and hydrogeology in Shanxi geology survey 1990). It flows from west to east in the mountain area with many branch rivers, most of which are seasonal, then the direction of the Fen River changes to north to south in Lancun and flows in that direction into the basin, as shown in Fig. 1.

Geology and hydrogeology

The karst water system in the West Mountain area can be divided into two subsystems: the Jinci spring area and the Lancun spring area. They are independent units but together comprise the West Mountain karst water system as a whole.

In the West Mountains, the stratigraphic sequence consists of metamorphite of Archean age, carbonate rocks of Cambrian and Ordovician ages (Є-O), coal measure strata of Carboniferous and Permian ages, detrital formations of Triassic age (C-T), and Cenozoic sediments (Q), with upper Ordovician, Silurian, Devonian, and lower Carbonic rock being absent. Ordovician emerges along the mountain fault, especially near Jinci. The prevailing outcrop strata are Carboniferous and Permian age strata exposed in most of the mountain area. In the basin, loose accumulative formation of Cenozoic occurs widely with a thickness of thousands of meters. The basin bottom slopes down from north to south and sediments gradually change from coarse-grained gravel to medium- and fine-grained sand from north to south.

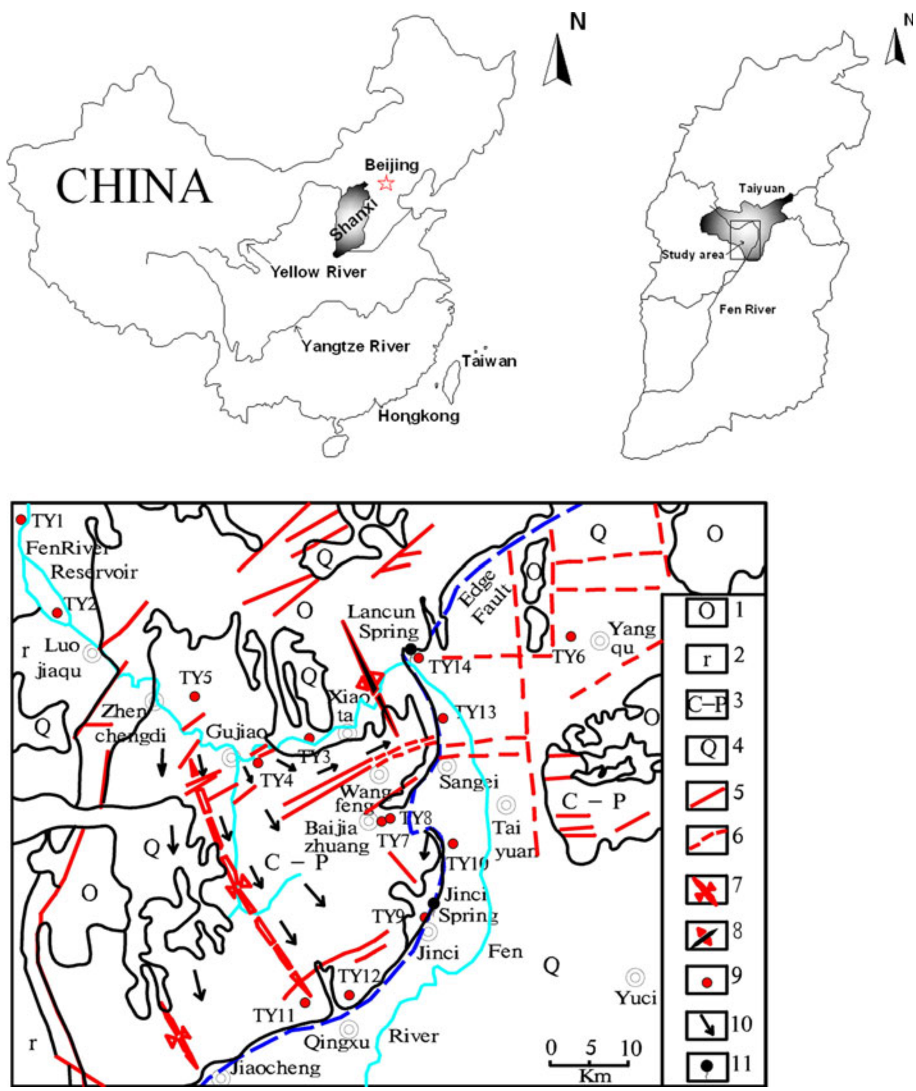

Fig. 1 Location map of the study area and sampling points (*1* carbonatite, *2* metamorphite, *3* clasolite, *4* unconsolidated sediment, *5* fault structure, *6* concealed fault, *7* syncline, *8* anticline, *9* water sampling location, *10* flow direction, *11* springs)

The main aquifer in this region is the stratum of the middle Ordovician, including limestone, dolomite, and marl mingled with gypsum (Ha et al. 1989; Zhang 1990). Ordovician has many outcrops in the domain near the edge of the mountain and the river bed from Gujiao to Lancun. Covered Ordovician is formed by a series of limestones with thickness of 619.4–715.3 m. Shale in the bottom of Xuzhuang group (ϵ_2^{x1}) in the middle Cambrian and Precambrian and metamorphite of the Archean are the main regional aquicludes (The first department of engineering geology and hydrogeology in Shanxi geology survey 1984).

The area mainly gets recharged from precipitation over the carbonate outcropping in the north of the Fen River. A portion of the recharge comes from leakage through surface runoff directly. Groundwater generally flows from north to south and from the mountain towards the piedmont. But a watershed lies along the line from Sangei horst to Wangfeng horst because of the area's low permeability and serves as a boundary between the Lancun spring area and Jinci spring area. In locations where the highly permeable limestone interfaces with the less permeable rocks, the springs discharge groundwater. As the fault along West Mountain acts as a barrier to groundwater flow from the mountain to the basin laterally, springs reach the surface (The first department of engineering geology and hydrogeology in Shanxi geology survey 1984).

Most of the area's coal mines are located in the south along the Fen River from Zhenchengdi to Gujiao, and in the zones of contact between the mountain and basin such as Baijiazhuang. General structures are complicated by horsts and grabens lying in different directions, which play major roles in changing the contact relationship between Ordovician aquifer and coal-bearing strata. According to the investigative data, the amount of water drained to produce 1 ton of coal tends to increase in the places where the geological structures are more developed. There are many synclines, anticlines, and numerous fault lines. The major structure observed in the study area is the fault running north to south along the edge of West Mountain (The first department of engineering geology and hydrogeology in Shanxi geology survey 1984).

The geological and hydrogeological conditions in the study area are shown in Fig. 1.

Sampling and analysis

Groundwater was sampled from 14 representative locations and included karstic and fracture water, coal area groundwater, and surface water collected in August and September 2007. Samples were analyzed for field parameters, and major and minor ions. Cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) were analyzed by inductively coupled plasma (ICP) and anions (HCO_3^-, SO_4^{2-}, Cl^-) through ion chromatography at the Analysis Center of Tsinghua University. Sampling point locations and the chemical results are shown in Fig. 1 and Table 1, respectively.

Samples TY2, TY3, TY4, and TY5 are from the recharge area. Among these samples, TY2 is surface water from the Fen River reservoir, and TY4 is a mixture of karst and coal water from the Dongqu mine area. Samples TY7, TY8, TY9, TY10, TY11, and TY12 are from the discharge area of Jinci spring, and TY13 and TY14 are from the discharge area of Lancun spring. TY13 is from Xizhang catchment area, TY14 is from the water supply point, TY7 and TY8 are coal mine water, TY10 is deep karst thermal water, TY12 is from the fishing area, and TY1 and TY6 are samples from other systems to act as a reference.

Table 1 The hydrochemical and isotopic results of water samples (mg/L)

ID	TDS	HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^+	K^+
TY1	390	286.17	94.43	9.22	81.11	28.01	18.40	1.33
TY2	348	−9.98	101.62	38.91	56.09	20.89	36.91	3.03
TY3	325	−8.28	88.98	9.90	77.36	24.50	16.06	1.33
TY4	882	−9.41	389.88	58.13	121.97	47.17	150.81	4.35
TY5	335	−8.40	34.26	9.16	68.14	18.99	16.65	1.11
TY6	294	−9.21	12.99	4.41	59.75	25.33	13.53	0.84
TY7	1,476	−9.67	632.66	66.22	286.61	65.43	81.97	3.22
TY8	1,504	−9.02	646.87	98.79	284.77	62.77	108.51	3.64
TY9	748	−9.24	396.27	15.54	178.80	50.59	24.80	2.02
TY10	2,218	−9.15	1,392.20	10.10	496.70	98.49	21.75	12.45
TY11	946	−10.48	392.32	21.59	127.73	38.67	129.77	2.83
TY12	3,050	−7.75	2,008.60	35.41	695.25	135.39	46.37	3.97
TY13	961	−9.64	176.49	92.04	159.32	60.08	40.47	2.25
TY14	322	−7.73	32.54	9.85	70.21	27.44	15.67	1.05

Table 2 Total dissolved solids (TDS) data from sample sites (mg/L)

ID	TDS (mg/L)
Recharge area	
TY3	325
TY5	335
TY2	348
TY4	882
Discharge area	
TY14	322
TY9	748
TY11	946
TY13	961
TY7	1,476
TY8	1,504
TY10	2,218
TY12	3,050

Data are arranged from lowest to highest by area

Results and discussion

Distribution of TDS

The total dissolved solids (TDS) can provide important information about the hydrodynamical processes and reflect the regional hydrogeochemical features. TDS data are shown in Table 2 arranged from lowest to highest by area.

From Table 2, it can be seen that in the northern recharge area, the TDS are at a low level, ranging from 325 to 348 mg/L with little variation. It is obvious that TY4 levels are much higher than other points in the recharge area, resulting from its special location in a large coal mining zone in the vicinity of Gujiao, where groundwater is drained heavily during the process of coal exploitation to guarantee the safety of the coal mining. The coal tunnels and the pumping wells drill through the rock, mixing karst water and drained water from coal tunnels.

Most of the high concentration samples were found in the discharge area and the heavily exploited district, where values ranged from 748 to 3,050 mg/L. Sample TY14 has the lowest TDS because it is the nearest discharge point to the north recharge area and has the shortest circulation time and distance. Levels at TY13, a regional water supply center, are a little higher than TY14 due to artificial exploitation. Generally speaking, compared with Jinci spring area, the samples of Lancun spring area remain at a lower levels. The reason for higher TDS in the Jinci spring area, especially in the samples far from the recharged area, is that the water is recharged over a longer flow path, which allows for deep and long circulation in the mountain area. This results in a long retention time, a slower renewal rate, and sufficient water-rock interaction with surrounding strata. For example, sample TY9 near the Jinci spring, which has a shallow depth, has lower TDS than sample TY10 where the water came from a deep source at high temperatures, resulting in sufficient water-rock interaction.

What is most important in the Jinci spring area is that TY7 and TY8 had higher TDS levels than all the others except TY12, a fish farm, and TY10, the thermal water reservoir. Samples TY7 and TY8 are located in the large-scale Baijiazhuang coal fields, which are important for the West Mountain coal industry. Although the separating zone production technique has been used widely, the drainage process in the coal mining area has polluted the water greatly because the karst water and the coal water are drained together and mixed with each other.

Compositions of the major elements

Calcium and magnesium vs. anions

The sources of Ca^{2+} and Mg^{2+} in the groundwater can be determined from the $(Ca^{2+} + Mg^{2+})/HCO_3^-$ ratio. The main weathering process occurs as follows:

$$Ca_xMg_{1-x}CO_3 + H_2CO_3 = xCa^{2+} + (1-x)Mg_2^{2+}HCO_3^- \quad (1)$$

In Fig. 2, most of the samples fall above the equilibrium line between $(Ca^{2+} + Mg^{2+})$ and HCO_3^- (meq/L), indicating that pure carbonates are not the only the source of these samples; there must be additional sources of Ca^{2+} and Mg^{2+}.

As shown in Fig. 3, most of the plots of Ca^{2+} and Mg^{2+} versus $HCO_3^- + SO_4^{2-}$ lie around the 1:1 trend line, indicating that the dissolution weathering of sulfate rocks is also an important factor in addition to carbonates. Taiyuan City is famous as a coal mine center. The process of coal exploitation connects the karst aquifer and the coal lays which is rich in sulfur. The excess of Ca^{2+} and Mg^{2+} over

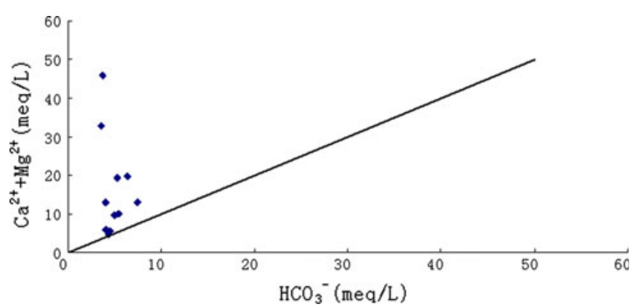

Fig. 2 HCO_3^- vs. Ca^{2+} and Mg^{2+} (meq/L) in the Taiyuan karst groundwater system

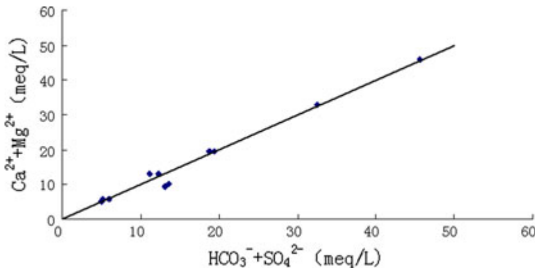

Fig. 3 HCO_3^- and SO_4^{2-} vs. Ca^{2+} and Mg^{2+} (meq/L) in the Taiyuan karst groundwater system

HCO_3^- is balanced by SO_4^{2-}. Consider the oxidation of iron pyrite (FeS_2) as an example:

$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+ \tag{2}$$

Disturbing coal strata during mining operations accelerates sulfidic mineral dissolution resulting from the exposure of these minerals to both oxygen and water; concentrations of chemical constituents in groundwater are affected and SO_4^{2-} increases as a consequence of mining and processing of coal mine drainage. Some samples are also possibly affected by SO_4^{2-} from precipitation or the decay of sulfate-reducing bacteria in soils and HCO_3^- from atmosphere, causing a small deviation from the 1:1 equivalent line.

Water types

The anion and cation piper diagram provides a good way to visualize the hydrochemical characteristics in the groundwater system, as shown in Fig. 4.

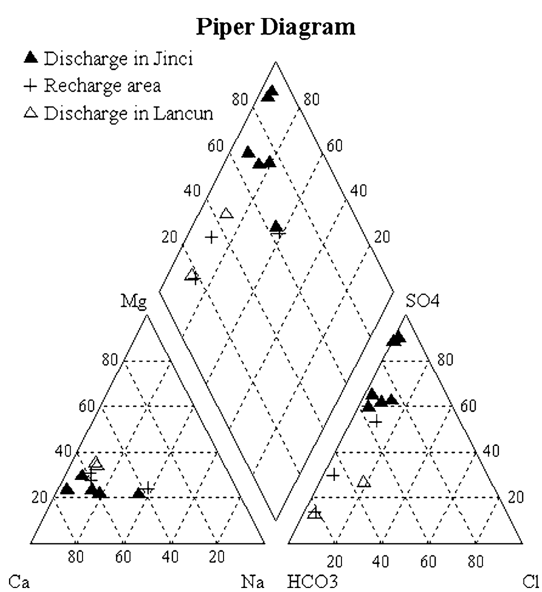

Fig. 4 Piper diagram for the samples taken from the Taiyuan karst groundwater system

From Fig. 4, it can be seen that Ca^{2+} and Mg^{2+} are the main cations, and HCO_3^- and SO_4^{2-} are the major anions. Hydrochemical compositions have two major hydrochemical facies:

1. Ca–Mg–HCO_3: this type is a reflection of the predominant rock in the area, where limestone and dolomite are the dominant formation. The Ca–Mg–HCO_3 facies occur mainly in the recharge areas where carbonate is exposed widely and groundwater eluviation takes place, resulting in low TDS.
2. Ca–Mg–SO_4–HCO_3: This facies is the most abundant type of water in the discharge area. A transition of Ca–Mg–HCO_3–SO_4 type waters to Ca–Mg–SO_4–HCO_3 can be seen from the recharge area to the discharge area.

Hydrochemical facies form through the interaction between rock and water along groundwater flow paths. In the north of the Fen River, there are large carbonate outcrops where the aquifer can receive rainfall directly and rapidly, and then recharge to the south of the Fen River via underground flow where coal-bearing strata are extensively distributed and coal mining is intensive. As the major recharge and run-off area for Jinci spring, water in karst strata circulated deeply and slowly with sufficient time to come in contact with the rock. It is obvious that groundwater in the discharge area of the Jinci Spring is characterized by high TDS with a high concentration of SO_4^{2-} induced by long retention times and interaction between groundwater and coal formations deep in the mountain, which is indicative of a deep circulation and sufficient water-rock interaction compared with the other spots. Acid mine drainage occurs in those mines in which sulphur content is found. The increase in SO_4^{2-} is due to the coal layer rich in sulfur and feldspar, indicating the effects of coal mining.

Modeling methodology

Based on the analysis of the hydrogeological condition in the West Mountain area, the conceptual model and numerical model of the groundwater flow are set up to reflect the hydraulic relationship of the different aquifers and the effect of coal mine drainage on the karst groundwater system.

Hydrostratigraphic area and mesh units

Rectangle hexahedron meshes were created automatically with mesh generation tools in Visual Modflow. The whole West Mountain area extends about 4,539 km^2 according to the surface topography, and the effective area in the model is about 2,580 km^2 in terms of extension of the subsurface

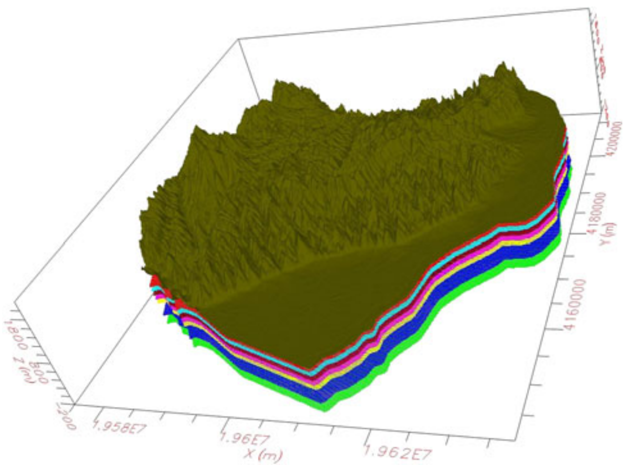

Fig. 5 Vertical layers in the active cells in the study area

geological formations within the modeling domain. The conceptual model is divided into 450 × 450 nodes horizontally and seven layers vertically, as shown in Fig. 5.

Boundaries

The model area including most of the mountain area and a small part of Taiyuan basin is located along the Fen River, which acts as the north and east physical boundaries in the first layer with the head set to the river elevation. Due to exposure of the Ordovician, the leakage from the surface water is calculated according to the observation river flux data in several hydrological stations along the Fen River. The west boundary is defined as a no-flow boundary based on the assumption that the metamorphite of the Archean age has very low permeability and allows minimal flow. The south boundary is an artificial drain boundary that allows discharge to the cell when head values are higher than the head in the cell. The surface topography serves as the precipitation boundary and is based on accurate surface elevation data. The bottom is defined as a no-flow boundary with the same assumptions as with the west boundary.

Recharge and discharge

The main aquifer in this region is the stratum of the middle Ordovician. In the north of the Fen River, there are large carbonate outcrops where the aquifer can receive rainfall directly and rapidly, then recharge to the south of the Fen River through underground flow. In the sector from Gujiao to Lancun along the Fen River, recharge depends on direct surface leakage. Jinci and Lancun springs are the two main discharge points obstructed by the fault along the mountain with low permeability. Groundwater was withdrawn from the aquifer through drilled and dug wells for water supply and coal mining drainage.

Modeling approach

Transient models were developed because the amount of precipitation, and consequently recharge, differs significantly between the wet and dry seasons as well as from year to year. Before transient models were constructed, a steady-state model was developed to study the regional and general response of the groundwater flow system, as well as to examine flow patterns in the aquifer and to calibrate and verify the model's initial flow head, which is difficult to generate over the whole area due to the lack of observation wells in the mountain area. Starting parameters were estimated from test results and historical records from past related work, recharge zones were divided according to the distribution of rainfall stations, and the precipitation in each sub-zone was calculated during the calibration procedure within reasonable bounds. Through steady state flow simulation analysis, the parameters including the hydraulic permeability, storage, and recharge percentages could be estimated and improved using investigated values from the field. As steady state models cannot account for the above variations, the steady-state model was calibrated using mean annual data from several years including precipitation, surface leakage, well pumping rates, and coal mining drainage, which were input as initial conditions.

This model was verified by simulating the 2005–2006 field data using the same set of calibrated parameter values and the precipitation and pumping values estimated for this time period. From January 2005 to December 2006, the observed head data in Gujiao and Baijiazhuang were compared with the calculated values as identification periods. The results showed a good flow head consistency, as shown in Fig. 6a, b. This model also represents the basic scenario, called scenario 0, which will be used to analyze the follow-up scenarios.

Based on the steady state analysis, transient state models were developed to study the cyclic fluctuations in the water table and the coal mining drainage effects on the flow patterns and the karst springs flux. Several scenarios were defined to explore the quantitative effects on the karst groundwater levels. Results from the following five different scenarios are reported:

1. Steady state: doubled and trebled based on present pumping rate
2. Steady state: coal mining continued at a fixed depth
3. Transient state: spring fluctuation over 10 years under the present conditions
4. Transient state: spring fluctuation over 10 years for a drainage situation reduced by half
5. Transient state: spring fluctuation over 10 years if drainage were completely halted

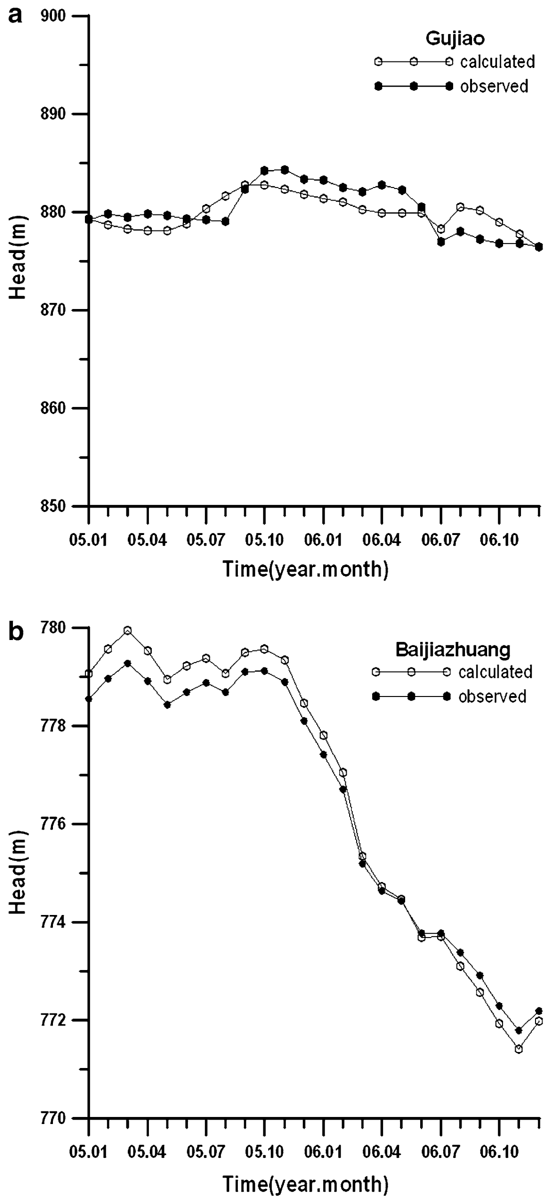

Fig. 6 Calculated vs. observed hydraulic heads in **a** Gujiao well and **b** Baijiazhuang well

The first scenario was developed to compare the hydraulic head fluctuation under different coal mining pumping conditions on the assumption that other recharge and discharge conditions would remain unchanged for the next 2 years and to analyze the effects of the coal mining drainage on the whole flow field. The second scenario focused on Baijiazhuang, one of the major coal mines in the West Mountain area. Under the assumption that the coal exploitation would remain at a fixed depth, the model was used to understand the effects of water drawdown. The purpose of scenarios 3, 4, and 5 was to study the cyclic fluctuations in the karst springs water table and to analyze the effects of changes in groundwater extraction and coal mining drainage. Conductivities and recharge percentages determined during the steady-state calibration were used to simulate the transient state response, and average monthly precipitation values (expressed in millimeters per year) were calculated using precipitation records. Recharge was estimated using a series of values monitored at the precipitation station.

Scenario 1: the effects of changes in coal mining quantity and pumping rates on water head

Based on scenario 0, which showed the quantity of mined coal at about 40,630,000 tons per year and the drained groundwater at about 35,660,000 tons per year, we calculated the ratio of groundwater drainage to quantity of mined coal at about 0.88. Holding the ratio constant, we varied the quantity of mined coal in two different sub-scenarios shown in Table 3. We then compared the groundwater head distribution and fluctuation in the study area, as shown in Fig. 7. It can be seen from the Fig. 7 that the hydraulic heads declined with the increase in the coal mining levels. In some locations in the vicinity of the mining center such as Baijiazhuang, the drop in the head was more obvious. Comparing the three scenarios, the differences reflect a declining trend of the head with an increase in drainage; the effect becomes greater in the area in the north where there is a higher concentration of mines and where the recharge area is closer.

Scenario 2: the effects of mining at a fixed depth

Holding the drainage rate of coal mining constant at the same level as scenario 0, the influence of coal mining depth on the systemic flow field was analyzed. Taking the biggest coal mining point, Baijiazhuang, as an example, if the mining depth is held at 770 m, drainage during coal mining would transform the area into a major discharge point and the center of a groundwater depression cone. The head in the whole flow field was lowered by different levels, as shown in Fig. 8.

Table 3 Quantity of coal mined and water discharged in different scenarios (mg/L)

Scenarios	Scenario assumption	Quantity of coal mined (10,000 tons/year)	Quantity of water drained (10,000 tons/year)
Scenario 0	Present situation	4,063	3,566
Scenario 1-a	Doubled	8,126	7,132
Scenario 1-b	Trebled	12,189	10,698

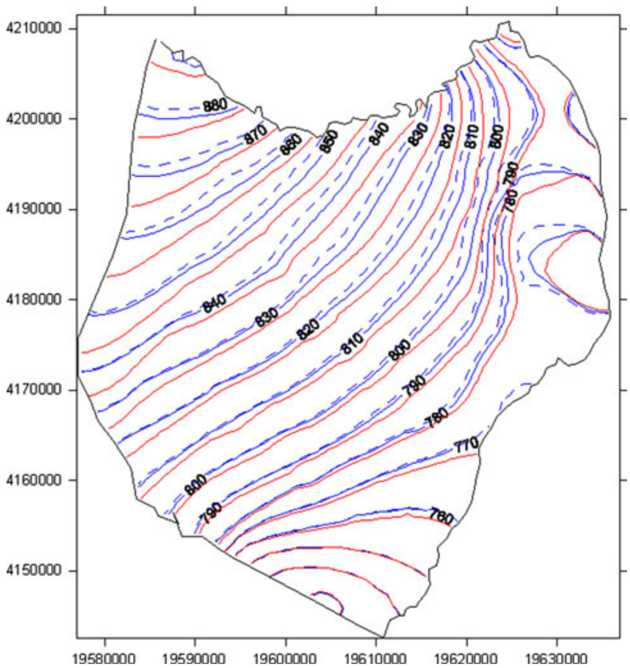

Fig. 7 Calculated hydraulic heads (m) under three scenarios (*red line* scenario 0, *solid blue line* scenario 1-a, *dashed blue line* scenario 1-b)

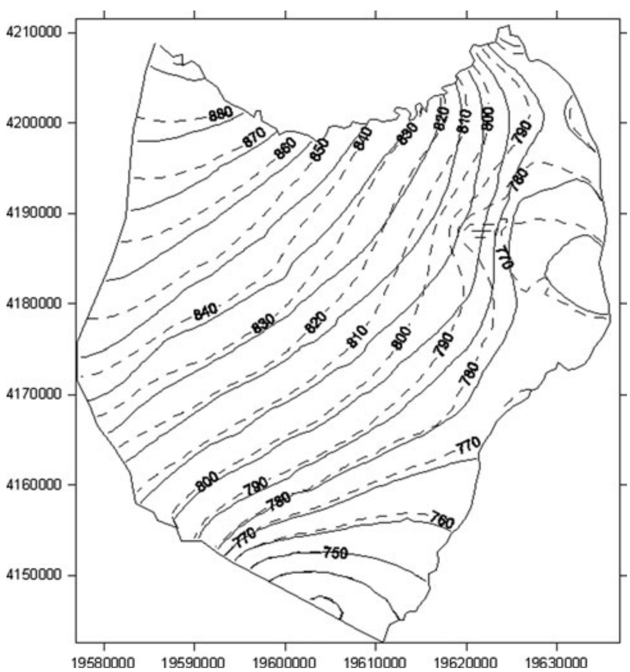

Fig. 8 Calculated hydraulic heads (m) at a fixed mining depth (*solid black line* scenario 0, *dashed black line* scenario 2)

Scenario 3–5: spring flux fluctuation

Based on the steady state models, a transient model was developed to forecast the fluctuation of Jinci spring for 10 years after 2006 on the assumption that the drainage rate remained unchanged. Two other models were set up to compare the spring response under different drainage levels, as shown in Fig. 9.

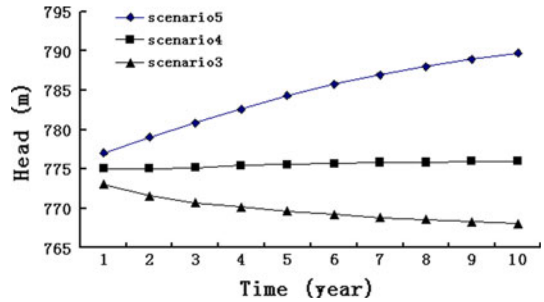

Fig. 9 Head fluctuation of the Jinci spring for the 10 years starting with 2006 (scenarios 3, 4, 5)

From Fig. 9, it can be seen that over 10 years, the head of Jinci spring would keep dropping down to 768 m with little fluctuation if the present pumping rate is maintained. Scenario 4, the middle level condition, in which drainage is reduced by half of the total quantity, showed a small rise in the head of the spring, to nearly 776 m 10 years later, while demonstrating that it is very hard to make the spring recover its flux. Scenario 5 was an extreme scenario in which coal mining drainage is reduced to zero in keeping with the ratio of groundwater drainage to coal mining. The result showed that the spring level rose gradually over the 10 years to nearly 790 m at the end of study time, but it still showed the difficult trend of flux recovery. All of these scenarios showed that the groundwater system has a slow and hysteretic response to stimulus from outside no matter whether extraction or injection is occurring. Once the groundwater has declined or become polluted, it is more difficult to reverse its condition compared with other water systems such as surface water.

The special properties of groundwater make it more difficult to address the problems between groundwater utilization and coal mine development. The present models demonstrate that numerical techniques can be successfully used to study the relationship between karst groundwater system and coal mining drainage. In the five different scenarios, the influence of the quantity of mined coal on head fluctuation in the West Mountain area could be estimated. It is obvious that fluctuations in the karst groundwater were restrained by the coal mining quantity and the site of the exploitation. The models not only provide a management platform upon which the head distribution could be determined according to the mining quantity and the exploitation location, but they also offer an effective method for protecting the spring from declining. The newest recharge and discharge data can be calculated on the platform based on the observation results, and the quantity of coal mining and the drainage of groundwater in a real time series could be altered and input directly. The models could be used to simulate and quantify the effects of different coal mining parameters on the groundwater head under different scenarios. Future karst groundwater management activities should consider the effects of both the quantity of coal mining and the characteristics of the groundwater system.

Summary

The karst groundwater system in the West Mountain area in Taiyuan City is mainly associated with limestone-dolomite rocks and coal seams. The relationship between coal mining and groundwater protection was analyzed through qualitative and quantitative methods.

From the qualitative point of view, the distribution of TDS and the concentration of the main cations (Ca^{2+}, Mg^{2+}, and Na^{+}) and anions (HCO_3^{-}, SO_4^{2-}, and Cl^{-}) revealed the effect of the coal mine operation on the composition of groundwater and the characteristics of the groundwater flow system in the West Mountain area. The results showed that TDS increased with the runoff distance and depth. The samples located in the coal mine areas exceeded the normal values and had been polluted when the drainage process mixed the fresh groundwater and the coal mine water, which kept the TDS high. Most of the samples fell above the equilibrium between ($Ca^{2+} + Mg^{2+}$) and HCO_3^{-} but lay around the 1:1 trend line of (Ca^{2+} and Mg^{2+}) versus (HCO_3^{-} and SO_4^{2-}), indicating that carbonates are not the only source of these samples, but the dissolution-weathering of sulfate rocks is also an important factor. The water chemistry changed from HCO_3 type to HCO_3–SO_4 type, SO_4–HCO_3 type, and SO_4 type from the recharge areas to the discharge areas along the flow path. The increase in SO_4^{2-} is due to the dissolving of sulfate as a result of the coal mining. In fact, human activities have a great influence on the hydrogeochemistry of groundwater, for example, the water from the supply center and the fishing grounds had high TDS and SO_4^{2-}, indicating an open environment which is more easily polluted. More attention should be paid to groundwater protection in such areas.

As the primary source of energy, coal is essential to meet the energy demands of China. Underground coal mining methods affect the environment, especially water resources, by discharging huge amounts of mine water. Groundwater modeling is an important tool for a quantitative understanding of hydrogeological systems and for finding a balance between drainage of coal mining and karst groundwater resources using currently available data.

Our research results can be summarized as follows. The steady-state model was used to identify the most critical parameters and the initial head, although the scenario is limited in the practical sense because it makes use of the mean values. Other models in this study were defined to create five different scenarios for understanding the quantitative link between groundwater and coal mining. The simulations indicated that increased drainage of coal mining critically affects the water table near the coal mine and slightly affects the water table far from the coal exploitation center. Specifically, the five scenarios revealed the relationships from different perspectives:

1. Scenarios 0, 1a, and 1b showed that as coal extraction proceeds, the groundwater head should gradually drop down. Comparing the three different scenarios, it was very clear that the more coal was exploited, the deeper the groundwater dropped.
2. According to scenario 2, if intensive extraction happened at a certain site, such as Baijiazhuang in this case study, this point would eventually develop into a depression, indicating that pollutants would be transported with the groundwater flow and ultimately concentrate at this point.
3. The results in scenarios 3, 4, and 5 showed a high correlation between the groundwater table and the drainage of coal mining. In the West Mountain area in Taiyuan City, Jinci is a famous spring where drainage has been affected by coal mining. If coal extraction levels remain at the current rate, the head of the spring will continue to decrease. If the coal mining discharge is halved or shut down entirely, the declining trend in the groundwater head would be changed, but it is still not easy for the spring flux to recover. It is clear that coal mining plays an important role in protecting the spring from decreasing. Through the models, it becomes easy to estimate the spring flux under some kind of coal mining plan.

This study extends the evaluation from a single analysis to a multi-aspect analysis of the groundwater system. In coal mining areas in particular, more information from different points of views brings many benefits to understanding the complex relationship between coal mining and groundwater utilization. This case study sets an example of how to use numerical modeling methods to perform a quantitative analysis together with a qualitative analysis of changes in chemical components. The models supply us with a scientific platform on which many other scenarios can be realized. As a reference, this method may be helpful to other similar sites in China and many other countries to analyze similar problems of karst groundwater in coal mine areas. For future karst groundwater management in coal mine areas, both the quantity and quality of the karst groundwater should be taken into consideration when developing a coal mining management plan. The characteristics of the groundwater and coal system, such as special distribution of coal strata and aquifer, the recharge pattern, the discharge points, extraction depth, exploiting site, and pumping rate, should be considered.

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