

# Impacts of Yuyang Coal Mine on Groundwater Quality in Hongshixia Water Source, Northwest China: A Physicochemical and Modeling Research

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**Abstract** The Yuyang Coal mine drainage can potentially have a negative impact on the surrounding drinking water, including the Hongshixia water source, causing detrimental effects to the environment and on human health. Here, contamination from the coal mine was analyzed by physicochemical interpretation and numerical simulation. We constructed two sampling profiles along the groundwater flow and transverse directions, and collected twenty-six groundwater samples near the drainage ponds from the Yuyang coal mine for physicochemical analysis and interpretation. And in terms of the numerical simulations, we chose the MODFLOW software to describe river, drainage ponds and reservoir and establish the flow model. We chose the MT3DMS modular software to build a solute transport model, and established a three-dimensional transient numerical model to predict the migration of total Fe and  $\text{SO}_4^{2-}$ . The physicochemical analytical results indicate the groundwater quality degrades as we approach the drainage ponds. The variations of ion concentrations in the eastward and northward directions show the migration distance of the contaminants in the eastward direction (e.g., the direction of groundwater flow) is much greater to that in the northward direction (e.g., perpendicular to the groundwater flow direction). Numerical simulation results suggest within the predicted days, the concentrations of Fe and  $\text{SO}_4^{2-}$  in the

mine drainage ponds will be higher to that of the acceptable levels recommended by the national groundwater quality guidelines, imposing serious risks to the surrounding groundwater and human health. The pollution plumes of the contaminants migrate closer to the groundwater source governed by groundwater flow, suggesting the mine drainage may pose a risk to the groundwater quality of the Hongshixia water source.

**Keywords** Groundwater quality · Physicochemical analysis · Solute transport · Numerical simulation · Water pollution · Mine water

## Introduction

The demand for natural resources, such as water and fossil fuel has been increasing since the 1980s because of the rapid development of the global economy and population. For instance, the technological development and demand for coal mining have increased over the years, further accelerating the industrial development in many countries, particularly in developing countries such as China. Several programs, such as the Western Development Program, have been greatly beneficial to the local population. The Silk Road economic belt proposed by China in 2013 had enormous commercial benefits for Central Asia (Li et al. 2015). However, serious negative impacts on the groundwater have occurred within these developing regions. For example, the land creation projects underway in the loess region of China is questioned for its influences on hydrogeological structures and groundwater preservation (Li et al. 2014a), and groundwater pollution and overexploitation have also been reported in many parts of China and the world (Esmaeili et al. 2014; Li et al. 2014b, c; Li

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et al. 2016a; Wu and Sun 2015; Wu et al. 2015; Sacchi et al. 2013).

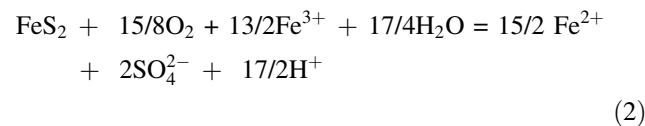
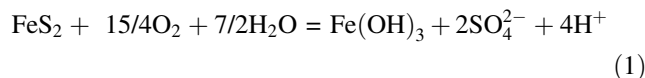
Large scale development of coal resources has great influence on the water sources and environment. For example, the coal development within a region can induce surface water and groundwater pollution and decrease groundwater levels which results in groundwater depletion and an extinct spring. It can even cause ground subsidence, ecosystem degradation and biodiversity loss. This makes the task of protecting the environment very arduous yet greatly important in terms of preserving the environment and maintaining human health.

Coal mining is closely linked to the groundwater environment because coal mines are often adjacent to water-bearing formations, and water drainage from the mine can have a direct impact on the groundwater quantity and quality. Furthermore, coal mining may also destroy the ecological balance of the groundwater system, triggering a series of unexpected consequences.

Several decades earlier, many scholars have noted these problems and have conducted many essential studies on groundwater problems related to water drainage from mines and the environment. For example, Stoner (1983), Booth (1986), (Britton et al. 1989) and Lines (1985) studied the impact of mining on the regional aquifers. Recently, Li et al. (2013) assessed the shallow groundwater quality in Dongsheng Coal field before the start of production. Younger et al. (2014) studied the synergistic wetland treatment of sewage and mine water. Our research provides a baseline of groundwater quality and is helpful to assess the impact of mine development on groundwater quality within the area. Acid mine drainage (AMD) appears to be significantly influenced by seasonal fluctuations (Kim and Kim 2004; Olías et al. 2004; Cánovas et al. 2008). It was recognized as one of the most serious environmental problems in the mining industry (Akciil and Koldas 2006), and brings the most serious obstacles for gold mining in South Africa, affecting the lives of many South Africans (Durand 2012), Durand (2012) mentioned the most consistent and pressing problems caused by mining were their impacts on water bodies in and adjacent to the Witwatersrand. Caraballo et al. (2016) studied typical AMD groundwater from a sulfide mining district with a dry Mediterranean climate (Iberian Pyrite Belt, SW Spain). The investigation determined the effect of long term weather changes on water flow rate and concentrations of metal contaminants. There are even more researches that have been conducted on AMD groundwater in coal mining districts (Jarvis et al. 2006; Lambert et al. 2004; Younger 1997; Younger 2000; Younger et al. 2002).

Our study area is principally a desert so after viewing historical data, the background values of both Fe and sulphates were deemed very low. There were many reactions of Fe in contaminated water or industrial waste water, such as

some reaction in boiler corrosion, which had significant implications for our study (Jami et al. 2013). The main chemical equations using FeS<sub>2</sub> are (Akciil and Koldas 2006):



Yulin City is an exceptional city located in northern Shaanxi, China with an economy based on energy and chemical industries. The Quaternary Salawusu unit is the main aquifer in this area. This water-bearing formation directly overlies the coal-bearing strata, and coal mining has disturbed this aquifer, causing infiltration into the mine and inducing a series of problems, such as groundwater depletion, environmental pollution and ecological degradation. Yuyang coal mine drainage is discharged into low-lying areas of the sandy desert without any treatment. This has led to significant pollution of the water-bearing units, imposing health risks to the residents around this drainage area. Therefore, it is necessary to assess the hydrogeochemical characteristics of the groundwater in and around the drainage area and predict the groundwater quality variations in the Hongshixia water source. For environmental issues due to coal mining, other research groups usually have studied falling water, aquifer destruction, ground fissures, and ground subsidence, etc. However, the focus of our work is on groundwater pollution problems caused by direct discharge of untreated mine drainage in the desert; a problem posing potential threats to the Hongshixia reservoir (e.g., the water source downstream) and water safety, which is very different from other studies.

## Study Area

The study site is the Yuyang Coal Mine and its surrounding area. The Yuyang coal mine is located west of the Yuxi River and north of Yulin city. It is situated four kilometers from the Hongshixia reservoir, which is the source of drinking water in the region. The region enjoys an arid or semi-arid continental climate, a scarce water resource, a relatively fragile ecological environment and abundant coal resources. Coal and water resources are extremely unbalanced.

The Yuyang Coal Mine is located in the eastern extension of the Maowusu desert, which is characterized by the accumulation of aeolian sediments. The Quaternary sand aquifer mainly includes valley alluvium unconfined water, lake sediments unconfined water, rock weathering unconfined water, and pore and fissure confined water in clastic rock. According to the existing borehole data, the main

sedimentary formations in this area are Jurassic (J), Cretaceous (K) and Quaternary (Q) in age. The Jurassic strata are subdivided into several units including the Yan'an ( $J_{2y}$ ), Zhiluo ( $J_{2z}$ ) and An'ding ( $J_{2a}$ ) formations. The Yan'an ( $J_{2y}$ ) Fm is a clastic fluvial formation which contains coal. The Zhiluo ( $J_{2z}$ ) Fm outcrops in the southeast area of the study site with a thickness increasing gradually from east to west (20.94–50.73 m). The An'ding ( $J_{2a}$ ) Fm is exposed along the White River Valley, which is 50–80 m-thick. The only Cretaceous (K) Fm of the area is the Luohe ( $K_{1l}$ ) Fm which gradually thickens from east to west (0–260 m). The unconsolidated Quaternary deposits are widely distributed across the region. Holocene ( $Q_h$ ) sedimentary deposits include early alluvium ( $Q_h^{1al}$ ), early lacustrine layer ( $Q_h^{1l}$ ), late alluvium ( $Q_h^{2al}$ ), and a late aeolian layer ( $Q_p^{2eol}$ ). The thickness of each layer is generally 3–20 m, but locally greater than 20 m.

The Yuyang Coal Mine was founded in 1993. Its designed annual production capacity at that time was only 0.3 Mt/a, while the actual production capacity is 0.15 Mt/a. After an expansion in 2007, the designed production capacity increased to 3 Mt/a. The principal mined coal seam is the third Yuyang coal seam situated at a depth of 166–230 m. Vertical and inclined shafts were developed in the mine. Owing to geological structures, a longwall mining method was used in the western mining area and a room and pillar mining in the eastern mining area.

The Hongshixia reservoir is the main water supply of the region and is located to the southeast of the Yuyang coal mine. Deserts are mainly located upstream of the Hongshixia reservoir. Numerous mine drainage ponds have been established surrounding the Yuyang coal mine, with drainage pond 1 located 4.5 km northwest of the Hongshixia reservoir. Drainage pond 2 is located at the Xiaojihan forestry farm. These drainage ponds have to some extent polluted the local groundwater. According to the physicochemical analyses of the drainage water of the Yuyang coal mine, the concentrations of the total dissolved solids (TDS) can reach 1.8 g/L, and the concentrations of total Fe and  $SO_4^{2-}$  are higher than the acceptable limits for drinking purposes. Mine water discharge infiltrates the Quaternary sand aquifer, deteriorating the quality of groundwater in the area. Pollutants will further migrate during groundwater runoff, and cause serious environmental pollution to the surrounding groundwater. If the Hongshixia reservoir is contaminated by mine water, the water supply will not be potable, which may pose threat to human and environment health.

## Materials and Methods

### Water Sampling and Analyses

The regional hydrogeological conditions including the types of aquifer, direction of groundwater flows, position

and characteristics of the pollution source, has guided us during our sampling procedures. We constructed two sampling profiles along the groundwater flow and transverse directions. We constructed 26 monitoring wells exposing the Quaternary aquifer. We collected water samples from these wells. The distance intervals will be shorter when the wells are bored close to pollution sources; longer when they are away from pollution sources. The positions of the monitoring wells were adjusted according to the specific conditions of the construction site.

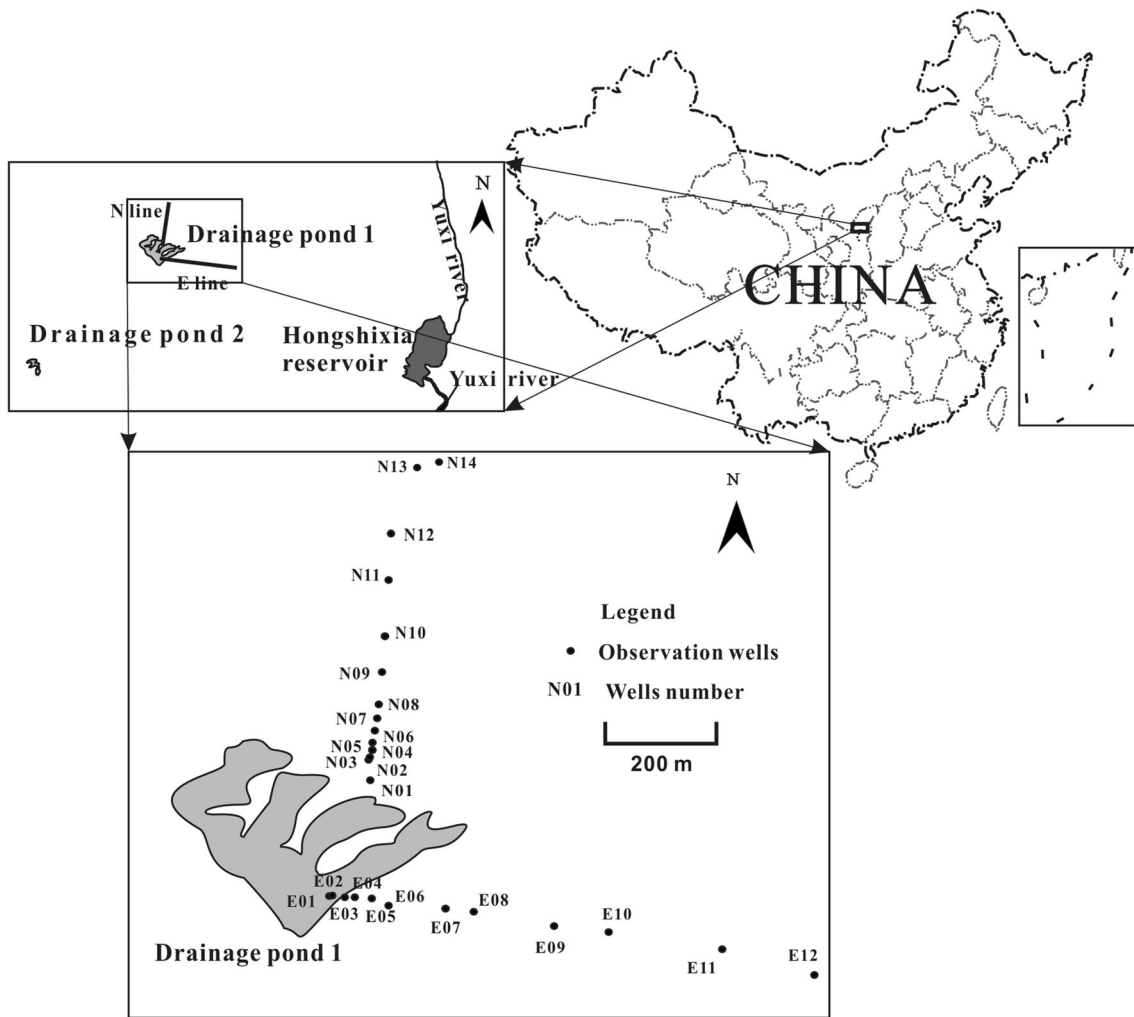
According to the national standard for underground water quality testing method (Ministry of Land and Resources of the P.R. China 1993), we need to add different protective agent to prevent oxidation, reduction, adsorption and other physical and chemical changes. For example, for analyzing total Fe, we added sulfuric acid (2.5 mL) and ammonium sulfate (0.5–1.0 g) to a water sample (250 mL).

To determine the effects of mine drainage on the surrounding groundwater, 26 monitoring wells were constructed on the northern and eastern sides of drainage pond 1 (Fig. 1): 14 oriented north–south (line N), and 12 east–west (line E). Groundwater samples were collected from the wells in September 2013 for physicochemical analyses. Water samples collected along the line E were labeled E01–E12 and N01–N14 along the line N, respectively. The samples were analyzed for major ions, pH, TDS, Fe,  $NH_4^+$ ,  $NO_3^-$ ,  $NO_2^-$ ,  $F^-$  and  $PO_4^{3-}$  to measure the changes in ion concentration with the distance from the drainage ponds.

### Numerical Model

First, we determined a simulation range based on the comprehensive analysis of the hydrogeological conditions in the simulation area. A hydrogeological conceptual model was then established through the conceptualization of boundary conditions, groundwater flow characteristics and structure of the aquifer system (Li et al. 2016b). The numerical model was further built through space discretization, elevation interpolation and boundary condition settings. Subsequently, model recognition and correction were completed by matching the existing water level observations and regional groundwater movements. Finally, according to the mine water quality analytical results, we designed pollution scenarios using two pollutants in the drainage pools, and established a groundwater solute transport model to predict the impacts of the Yuyang Coal mine drainage on the surrounding groundwater quality.

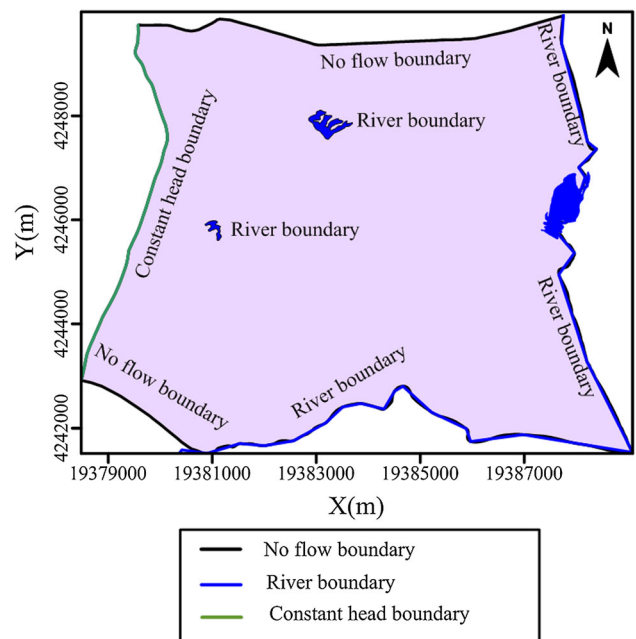
In terms of the method applied to the numerical simulations, we chose MODFLOW to describe river, drainage ponds and reservoir and establish the flow model. We chose the modular MT3DMS to build a solute transport model. The model forecasting time was 30 years and the



**Fig. 1** Location of the study area and sampling locations

maximum time intervals were 100 days. The main simulation range covered the Yuxi River basin and Qinhe River basin, including part of the Mahe water source, the Niujawan water source and Qinhe water source. The Yuxi River and Qinhe River were set as the eastern and southern boundaries, respectively. Based on the flow field under natural conditions, the north and southwest boundaries of the simulation range were set as the flowline boundary, while the northwest boundary was treated as a constant head boundary.

Groundwater recharge sources before coal mine discharges in the simulation area are mainly atmospheric precipitation, desert condensate, agricultural irrigation return flow and groundwater recharge from the northwest. The principal runoff direction of the groundwater was from the northwest to the southeast, and groundwater discharges into the rivers. The groundwater movement conforms to Darcy's law and shows the characteristics of three-dimensional flow. The hydrogeological conceptual model of the study site is shown in Fig. 2.



**Fig. 2** Analog hydrogeological conceptual model diagram

According to the hydrogeological conceptual model, the three-dimensional mathematical model describing the groundwater transient flow (Guo et al. 1994) can be written as:

$$\left\{ \begin{array}{l} \frac{\partial}{\partial x} \left( K \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( K \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( K \frac{\partial H}{\partial z} \right) = S_s \frac{\partial H}{\partial t} \quad (x, y, z) \in D, t > 0 \\ H(x, y, z, 0) = H_0(x, y, z) \quad (x, y, z) \in D, t = 0 \\ \left. \begin{array}{l} \frac{\partial H}{\partial n_1} \Big|_{\text{no flow boundary}} = 0 \quad t > 0 \\ H(x, y, z, t) \Big|_{\text{constant head}} = f(x, y, z) \quad t > 0 \\ \frac{K_r}{M_r} (H_r - H) \Big|_{\text{river}} = q_r \quad t > 0 \\ H = z \\ -(K + W) \frac{\partial H}{\partial z} + W = \mu \frac{\partial H}{\partial t} \end{array} \right\} \quad \text{water table } t > 0 \tag{3}$$

where  $H$  is the water head (m);  $K$  is the hydraulic conductivity (m/d);  $t$  is time (d);  $x, y, z$  are coordinate variables (m);  $K_r$  is the river bed alluvium vertical hydraulic conductivity (m/d);  $M_r$  is the hyporheic zone thickness (m);  $H_r$  is the river stage (m);  $q_r$  is the exchange quantity per unit area of the river (m/d);  $W$  is the areal recharge and discharge rates (m/d);  $\mu$  is the specific yield; and  $S_s$  is the specific storage (1/m).

For the migration of contaminants in groundwater, considering the convection, dispersion, areal recharges and discharges, and equilibrium adsorption of pollutants in aquifers, the three-dimensional migration mathematical model of the contaminants in the groundwater (Guo and Zhang 1994) can be expressed as:

$$\left\{ \begin{array}{l} nR \frac{\partial c}{\partial t} = \frac{\partial}{\partial x_j} \left( nD_{ij} \frac{\partial c}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (nCv_i) - C'W \\ D_{ij} = \alpha_{ijmn} \frac{V_m V_n}{|V|} \end{array} \right. \tag{4}$$

where  $D_{ij}$  is the dispersion coefficient of an aquifer;  $\alpha_{ijmn}$  is the dispersivity of a groundwater aquifer;  $V_m, V_n$  are the velocity components in m and n directions, respectively (m/d);  $C$  is the concentration of contaminants in the aquifer (mg/L);  $n$  is the effective porosity of the aquifer;  $x_i$  is coordinate variable (m);  $t$  is time (d);  $C'$  is the concentration of pollutants in areal recharges and discharges (mg/L);  $W$  is the rate of areal recharges and discharges (m/d);  $V_i$  is

the groundwater seepage velocity (m/d);  $R$  is the retardation factor. The change of water density was ignored in this study. we ignored the inflow and outflow of solutes when determining boundary conditions, and only considered the

constant concentration infiltration of mine drainage. We just simulated the migration of total Fe and  $SO_4^{2-}$  caused by the infiltration of mine drainage.

The No. 1 and the No. 2 drainage ponds in the simulation area contained a variety of chemicals, and we selected the iron and sulfate ions which were mainly introduced into waste water by coal mining as the typical pollutants. At the same time, we used the maximum concentration value obtained at the water samples collected from the 26 wells as the pollutant concentration (Table 1). The unsteady flow migration trend forecasting models were established.

We used the dispersivity regression equation established by Cheng (2002) and written as:

$$\log \alpha_L = 0.408 \log L_s - 0.0495 \tag{5}$$

where  $\alpha_L$  is the longitudinal dispersivity of a porous media; and  $L_s$  is the field scale of solute transport. The relationship of  $\alpha_L$  and  $L_s$  can be plotted in logarithmic coordinates, and the function of  $\lg \alpha_L$  and  $\lg L_s$  are determined by the least sum of squares.

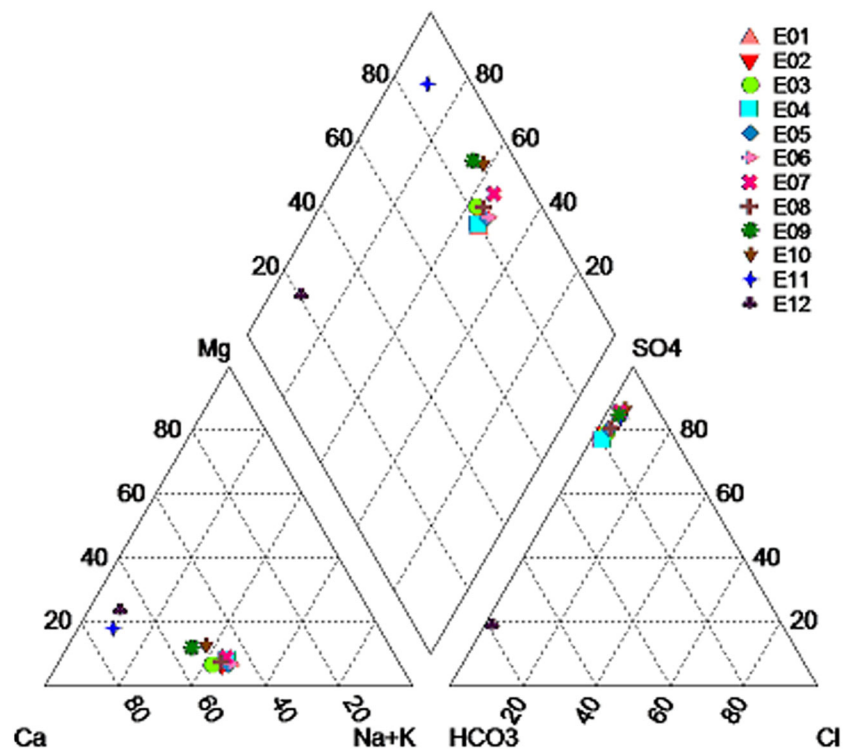
Taking into account the distance between the pollution source (drainage ponds 1 and 2) and the Hongshixia reservoir being 4254 m, we set the longitudinal dispersivity at 27 m. Based on experience, for horizontal transverse dispersivity and vertical transverse dispersivity, we chose  $\alpha_L : \alpha_H : \alpha_V = 100 : 10 : 1$ .

**Table 1** Pollutant concentrations in the simulation area

Typical pollutants	Source of pollution	Pollutant concentration (mg/L)	Aquifer
$SO_4^{2-}$	Pond 1, pond 2	1300.5	Unconfined water
Fe	Pond 1, pond 2	1.99	Unconfined water

**Table 2** Water analysis results of observation wells

Water quality indexes	Min	Max	Mean	Acceptable limit	Rate exceeding the standard
Cation (mg/L)					
Na <sup>+</sup>	6.94	302.83	200.28	200	73.08 %
Ca <sup>2+</sup>	44.89	312.3	202.25	200	73.08 %
Mg <sup>2+</sup>	8.29	46.16	20.62	150	00.00 %
Fe	0.05	2.13	0.53	0.3	57.69 %
NH <sup>4+</sup>	<0.02	0.8	0.17	0.5	3.85 %
Mn <sup>2+</sup>	<0.05	0.64	0.32	0.1	26.92 %
Anion (mg/L)					
Cl <sup>-</sup>	3.58	51.92	26.99	250	00.00 %
SO <sub>4</sub> <sup>2-</sup>	18.71	1300.52	811.38	250	80.77 %
HCO <sub>3</sub> <sup>-</sup>	155.3	326.12	222.36	600	00.00 %
NO <sub>3</sub> <sup>-</sup>	0.1	10.5	2.23	20	00.00 %
NO <sub>2</sub> <sup>-</sup>	<0.002	4.67	1.16	0.02	30.77 %
F <sup>-</sup>	0.05	0.68	0.35	1	00.00 %
PO <sub>4</sub> <sup>3-</sup>	0.01	0.4	0.15	0.1	69.23 %
PH	7.1	7.6	7.33	6.5–8.5	00.00 %
TDS (g/L)	0.19	1.79	1.30	1	76.92 %

**Fig. 3** Piper three-line diagram of E line

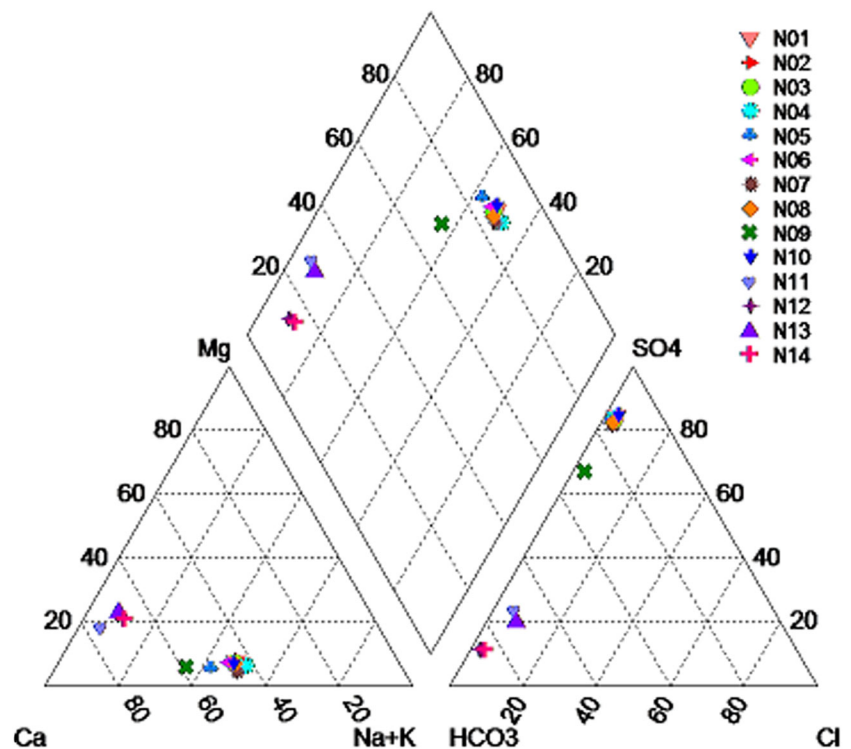
## Results and Discussions

### Water Quality Analysis at the Sampling Wells

Under the natural state, the chemical characteristics of groundwater and surface water are not only related to its recharge, runoff and discharge conditions, but also

controlled by the aquifer lithology (Wu et al. 2014). Overall, hydrogeochemical facies are relatively simple in desert and valley environments such as those covered by the study, while sand-covered hilly regions and loess hilly regions have relatively complex facies. Specifically, according to daily monitoring, the Yuyang coal mine drainage is about 16,400–24,000 m<sup>3</sup>/d, and is greater than

**Fig. 4** Piper three-line diagram of N line



25,000 m<sup>3</sup>/d from July to September. The maximum drainage during the monitoring period was 39,096 m<sup>3</sup>/d.

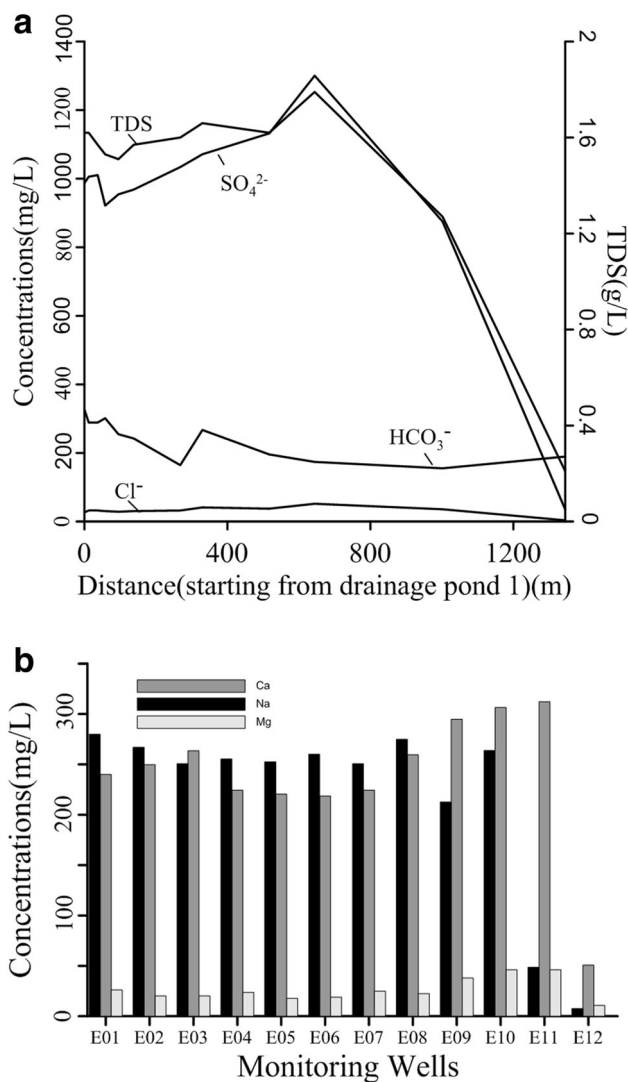
According to the physicochemical analytical results, the concentrations of TDS varied from 0.19 to 1.79 g/L with an average value of 1.30 g/L, indicating brackish water. In AMD area, Fe and SO<sub>4</sub><sup>2+</sup> are typical pollutants from the mine drainage (Akcil and Koldas 2006). The acceptable limit of total Fe for drinking water is 0.3 mg/L, according to the national standard for groundwater quality (Ministry of Land and Resources of the P.R. China 2015), with the highest and average concentrations of total Fe in the study area being 2.13 and 0.53 mg/L, respectively. Our study area is mainly a desert, so after viewing the historical data, the background values of total Fe and sulphates were deemed very low, which hardly interfere with the contents of these critical parameters from sources other than the coal mine. The concentration of total Fe in over half of the samples (57.69 %) exceeds the acceptable limit of total Fe for drinking water. The acceptable limit of SO<sub>4</sub><sup>2+</sup> for drinking water is 250 mg/L as the national standard for groundwater quality (Ministry of Land and Resources of the P.R. China 2015). The highest SO<sub>4</sub><sup>2+</sup> concentration measured in this study is 1,300.52 mg/L, with an average value of 811.38 mg/L. 80.77 % of the samples have SO<sub>4</sub><sup>2+</sup> concentrations over the standard value (Table 2).

After coal mining, drainage can greatly impact the shallow groundwater quality (Li et al. 2013). In this study, the Piper diagram (Piper 1944) was used to delineate the

hydrochemical characteristics of groundwater. The results from the 26 monitoring points in line E and line N (E01—E12, N01—N1) are plotted in Figs. 3 and 4.

The major soluble ions in the aquifer which was 1000 m away from the drainage ponds were almost identical to the natural background conditions. The cation distributions are mainly concentrated at one end of Ca<sup>2+</sup> side, and the anion distributions are mainly concentrated at one end of HCO<sub>3</sub><sup>-</sup> side (Figs. 3 and 4). In contrast, the major ion concentrations near the drainage ponds are clearly different. The cations slightly shift toward Na<sup>+</sup> + K<sup>+</sup>, with the percentage of Na<sup>+</sup> + K<sup>+</sup> ion concentration being 25 to 40 %. The anions changed significantly, from HCO<sub>3</sub><sup>-</sup> to SO<sub>4</sub><sup>2-</sup> and converged principally at one end of the SO<sub>4</sub><sup>2-</sup> plot (Figs. 3 and 4). The anion composition of the samples gradually becomes identical to the coal mine drainage composition as it approaches the drainage ponds. In conclusion, coal mine drainage water appears to have infiltrated the unconfined aquifer, which mixes and changes its hydrogeochemical characteristics.

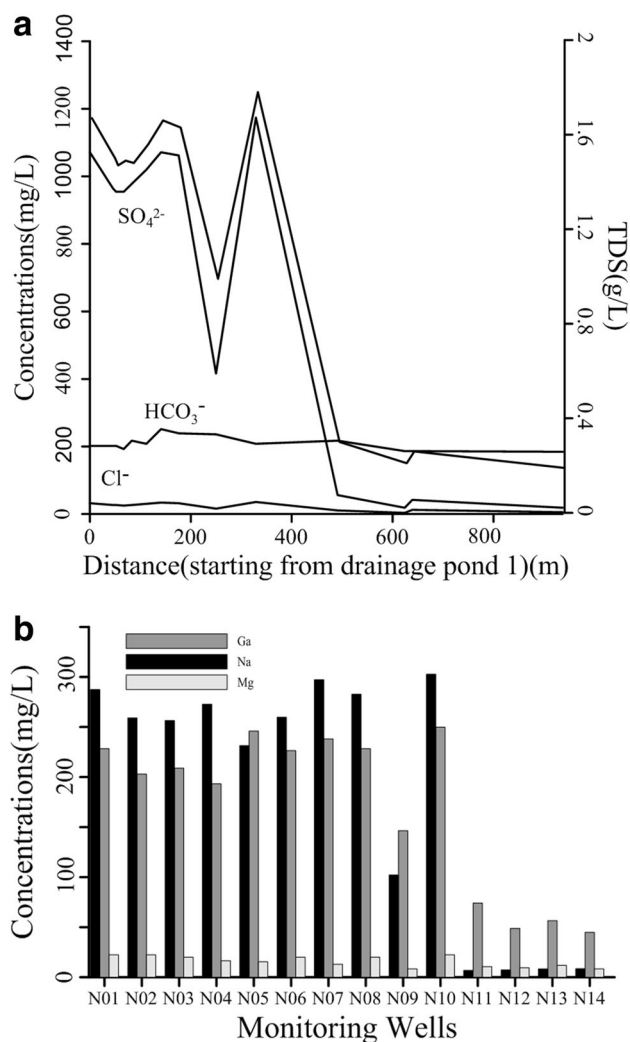
The change in ion concentrations and total dissolved solids with the distance from the drainage ponds along lines E and N were then plotted. Along the groundwater flow direction (line E), the ion concentrations decreased, and the concentration of pollutants also decreased with increasing distance from the drainage ponds. Along the transverse direction (line N), ion concentrations decreased with distance, and the concentration of pollutants also



**Fig. 5** The change patterns of each ion’s concentration and the TDS with line E

decreased with increasing distance from the holding ponds. Through comparative analysis of concentration changes in lines E and N, we found the contaminants traveled much further along the groundwater flow direction (line E) relative to that the perpendicular to the groundwater flow direction (line N). Content of total dissolved solids (TDS) content was high in the water samples in the vicinity of the drainage pond (<1000 m). Similar to the ion concentrations, TDS concentrations decreased with increasing distance from the drainage ponds along both transects (Figs. 5a, b, 6a, b).

Because the total Fe concentrations were relatively low, their variations with the distance along lines E and N are shown in Fig. 7. They show the total Fe concentrations do not have a clear decreasing trend with distance from the ponds for both lines E and N.



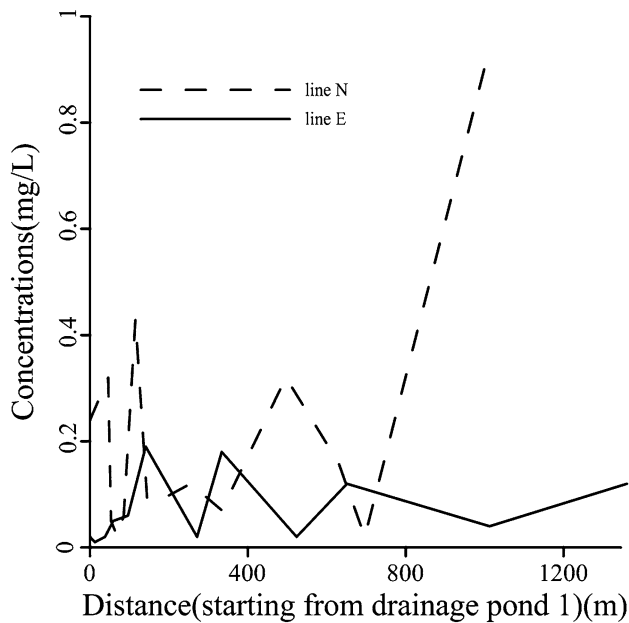
**Fig. 6** The change patterns of each ion’s concentration and the TDS with line N

**Potential Impacts of Fe From Mine Drainage on Water Quality**

According to the national standard for groundwater quality, groundwater quality can be classified into five ranks. Rank III is based on benchmarks for human health, and is mainly used as acceptable limits for drinking water as well as in industrial and agricultural water. The acceptable limit of total Fe is 0.3 mg/L under Rank III, and this limit was used to predict the potential impacts of Fe in mine drainage on the groundwater quality of the Hongshixia water source through modeling.

Fe is one of the two pollutants input in the model and the two drainage ponds were considered as the two sources of pollutants within the model domain. The influencing areas where Fe exceeding the detection limit, the areas with Fe exceeding the acceptable limit, and the distance of the plumes to the Hongshixia reservoir are listed in Table 3.





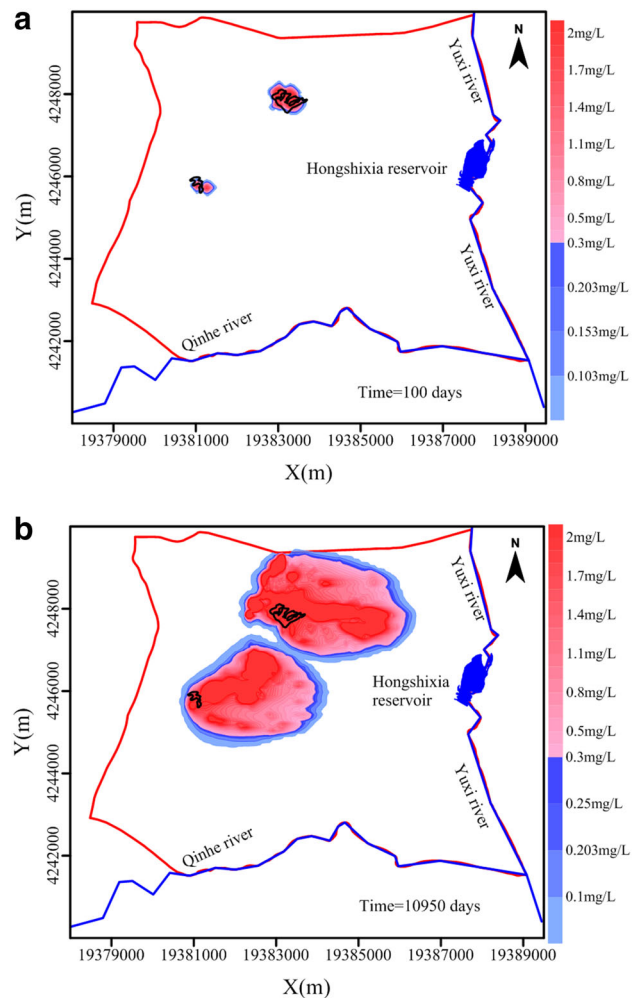
**Fig. 7** The change patterns of Fe's concentration with line E and line N

After running the model for 100 days, the influencing area of pond 1 and the area with Fe exceeding the acceptable limit are 0.53 and 0.36 km<sup>2</sup>, respectively, and the distance from the pollution plumes to the Hongshixia reservoir is 4069 m. Relative to drainage pond 2, the influencing area of the pond and the area with Fe exceeding the acceptable limit after 100 days are 0.17 and 0.08 km<sup>2</sup>, respectively, and the distance from pollution plumes to the Hongshixia reservoir is 5811 m.

Fe is transported farther over time. After 10,950 days, the influencing area of pond 1 and the area with Fe exceeding the acceptable limit are 8.70 and 6.76 km<sup>2</sup>, respectively, and the distance from pollution plumes to the Hongshixia reservoir is reduced to 1516 m. Fe from drainage pond 2 does not travel as extensively relative to that of drainage pond 1. The influencing area is 6.96 km<sup>2</sup>, the area with Fe exceeding the acceptable limit is 5.01 km<sup>2</sup>, and the distance from pollution plumes to the Hongshixia reservoir is 3022 m (Fig. 8). This indicates the area with Fe exceeding the limit is increasing with time, and the distance from the plume to the reservoir is shortened. With the pollution plumes gradually approaching the water sources, the drainage ponds will have negative impacts on the suitability of water in the reservoir for drinking purposes, posing a potential threat to the water supply and human health.

**Potential Impacts of SO<sub>4</sub><sup>2-</sup> From Mine Drainage on Water Quality**

SO<sub>4</sub><sup>2-</sup> was considered another contaminant in the model. The acceptable limit of SO<sub>4</sub><sup>2-</sup> is 250 mg/L according to the Chinese Standard for groundwater quality (Ministry of



**Fig. 8** Potential impacts of Fe from mine drainage in 100 days and 10950 days

Land and Resources of the P.R. China 2015). The minimum of SO<sub>4</sub><sup>2-</sup> concentration in the samples collected from the wells was taken as a background value and we set the acceptable limit as 250 mg/L in the simulation.

The pollutants from the two drainage ponds migrate over time. The influencing areas, the areas with SO<sub>4</sub><sup>2-</sup> exceeding the acceptable limit, and the distance of the plumes to the Hongshixia reservoir are shown in Table 4. After migrating for 100 days, the influencing area of pond 1 and the areas with SO<sub>4</sub><sup>2-</sup> exceeding the acceptable limit are 0.68 and 0.32 km<sup>2</sup>, respectively, and the distance from the pollution plumes to the Hongshixia reservoir is 3952 m. The influencing area of pond 2 and the area with SO<sub>4</sub><sup>2-</sup> exceeding the acceptable limit after 100 days are 0.24 and 0.06 km<sup>2</sup>, respectively, while the distance from the pollution plume to the Hongshixia reservoir is 5713 m.

After 10,950 days, the influencing area of pond 1 and the area with SO<sub>4</sub><sup>2-</sup> exceeding the acceptable limit increase to 10.59 and 5.03 km<sup>2</sup>, respectively with the distance from the

**Table 3** Potential impacts of Fe from drainage ponds on water quality

Time (d)	Drainage pond 1			Drainage pond 2		
	Influencing area (km <sup>2</sup> )	Area with Fe exceeding the acceptable limit (km <sup>2</sup> )	Distance to the reservoir (m)	Influencing area (km <sup>2</sup> )	Area with Fe exceeding the acceptable limit (km <sup>2</sup> )	Distance to the reservoir (m)
100	0.53	0.36	4069	0.17	0.08	5811
365	0.93	0.66	3833	0.40	0.22	5625
1000	1.62	1.18	3588	0.79	0.51	5331
3650	3.93	3.06	2796	2.39	1.65	4584
7300	6.52	5.12	2000	4.72	3.39	3768
10,950	8.70	6.76	1516	6.96	5.01	3022

**Table 4** Potential impacts of SO<sub>4</sub><sup>2-</sup> from drainage ponds on water quality

Time (d)	Drainage pond 1			Drainage pond 2		
	Influencing area (km <sup>2</sup> )	Area with SO <sub>4</sub> <sup>2-</sup> exceeding the acceptable limit (km <sup>2</sup> )	Distance to the reservoir (m)	Influencing area (km <sup>2</sup> )	Area with SO <sub>4</sub> <sup>2-</sup> exceeding the acceptable limit (km <sup>2</sup> )	Distance to the reservoir (m)
100	0.68	0.32	3952	0.24	0.06	5713
365	1.28	0.54	3698	0.61	0.16	5456
1000	2.37	0.92	3324	1.30	0.36	5068
3650	5.19	2.18	2432	3.74	1.14	4261
7300	8.00	3.80	1777	6.63	2.26	3392
10,950	10.59	5.03	1329	8.83	3.30	2576

pollution plume to the Hongshixia reservoir being 1516 m. Similar to the situation of Fe, the distance of transported SO<sub>4</sub><sup>2-</sup> from the drainage pond 2 is shorter to that from drainage pond 1. The influencing area of pond 2 is 8.83 km<sup>2</sup>, the areas with SO<sub>4</sub><sup>2-</sup> exceeding the acceptable limit is 3.30 km<sup>2</sup>, and the distance from the pollution plumes to the Hongshixia reservoir is 2576 m (Fig. 9).

Within the predicted days, the concentrations of SO<sub>4</sub><sup>2-</sup> in the mine drainage ponds are higher to that of the acceptable limit recommended by the Chinese standard for groundwater quality, which indicates that serious pollution may affect the groundwater surrounding the ponds. Controlled by the groundwater flow, the pollution plumes will gradually approach the water sources, posing a potential threat to the Hongshixia reservoir water and the health of humans who drink the reservoir water.

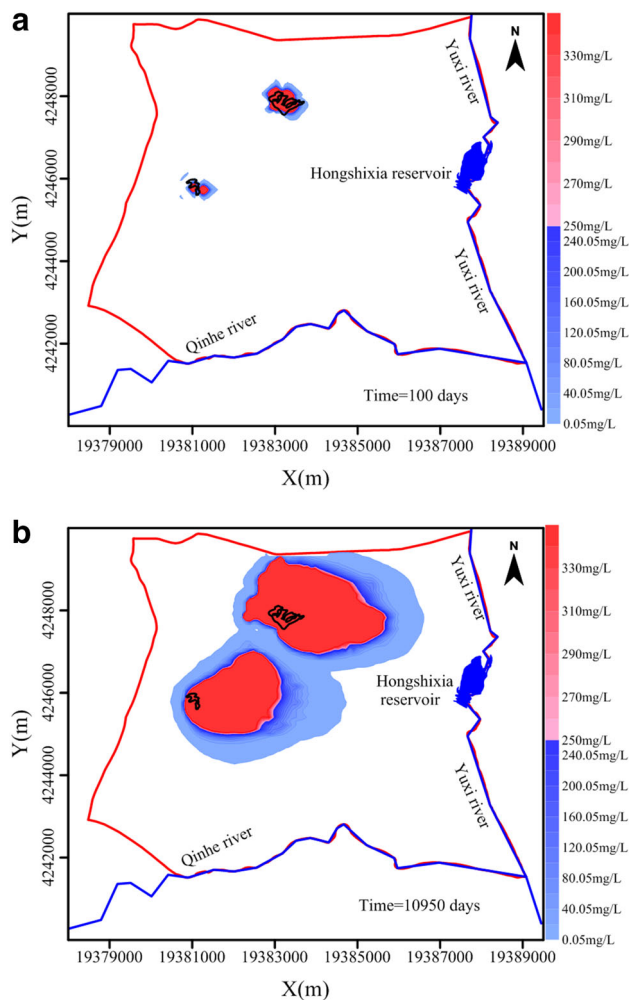
## Conclusions

In this study, physicochemical analyses were used to quantify the quality and characteristics of groundwater affected by Yuyang coal mine drainage. The mean

concentration of TDS is 1.30 g/L, indicating brackish water. The mean pH value of the groundwater samples is 7.33, indicating the water in the study area is slightly alkaline. Fe and SO<sub>4</sub><sup>2+</sup> are considered as the representative pollutants. The concentrations of Fe and SO<sub>4</sub><sup>2-</sup> in the majority of water samples exceed the acceptable limits set by the Chinese national standard.

According to the Piper diagrams, major ion concentrations near the drainage ponds of Yuyang coal mine are clearly different from that under natural conditions. The cation compositions are slightly shifted towards the Na<sup>+</sup> + K<sup>+</sup> apex, and the anion was mainly SO<sub>4</sub><sup>2-</sup>. Coal mine drainage water has infiltrated the unconfined aquifer and affected the hydrochemical characteristics of groundwater.

Ion concentrations increase along both lines E and N as we approach the ponds. The closer the water samples are to the drainage pond, the higher the concentrations and the more serious the pollution. In particular, the distance of migration of all solute contaminants except Fe along the groundwater flow direction (line E) are much farther to that along the direction perpendicular to the groundwater (N line). However, the Fe concentrations do not show a decreasing trend in either direction from the drainage pond.



**Fig. 9** Potential impacts of  $\text{SO}_4^{2-}$  from mine drainage in 100 days and 10950 days

The simulation results by Modflow and MT3DMS indicate the drainage ponds have a potential influence on the groundwater quality near the Hongshixia reservoir. Within the predicted days, the concentrations of Fe and  $\text{SO}_4^{2-}$  in the mine drainage ponds are higher to that of the acceptable limits established by the national standard for groundwater quality, generating serious potential pollution problems to the groundwater around the ponds. Controlled by the groundwater flow, the pollution plumes gradually approach the nearby water sources, posing potential threats to the Hongshixia reservoir and the human health.

Based on the prediction results, unprocessed discharge of mine water posed a potential threat to the Hongshixia reservoir. These issues presented should be treated as soon as possible. First, the Yuyang coal mine company should stop the unprocessed discharge and treat the existed coal mine drainage appropriately; Second, monitoring wells should be set on the contamination migration path to the water source

upstream and observe continuously the migration of the contaminants so that we could provide a basis for the prevention of water pollution. The contaminant transport equation is complex, including hydrodynamic dispersion, exchange adsorption and chemical reactions, etc. We considered the concentrations of  $\text{SO}_4^{2-}$  and total Fe in the study area were mainly affected by the infiltration of mine water. So we selected a relatively simple transport equation, which ignored some secondary variables, like exchange adsorption, chemical reactions, etc. Certainly, the basic characteristics reflected the migration of the contaminated water, so our model was feasible.

The impacts of coal mining on the groundwater quality are also very important. The following protection measures are proposed: 1. To cut off the sources of pollution, stopping the discharge of sewage is a urgent request; 2. It is highly recommended that regular groundwater quality monitoring be undertaken and focus on the migration of pollutants by observing monitoring wells; 3. water pollution treatment projects must be implemented, such as boring wells to pump contaminated water, and then put in place injection wells to recharge the groundwater after being treated.

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