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TECHNICAL ARTICLE

Numerical Simulation of the Groundwater System for Mining Shallow Buried Coal Seams in the Ecologically Fragile Areas of Western China

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Abstract

Shallow coal seams are actively excavated in western China, which can adversely affect groundwater availability. We analyzed the failure mode in the mining of a shallow coal seam, and demonstrated that its fracture zone was directly exposed to an unconsolidated aquifer. Two numerical models (steady and unsteady state models) were used in which the fractured overburden was considered as the first boundary and the aquifer-contacting zone was considered as a drainage boundary. We applied this numerical model to analyze the groundwater system of the Daliuta coal mine in the Shendong area of western China. Simulation results showed that the mining cause groundwater level to decline > 50 m in 2012; the groundwater loss amounted to 2.12×10^4 m^3/day.

Keywords Groundwater · Unconsolidated aquifer · Quantitative evaluation · Numerical simulation · Fracture zone

Introduction

Shendong, which is located in the arid northwest area of China, has a fragile ecological environment (Fig. 1). In 2014, Shendong's coal output exceeded 300 million tons, accounting for about 10% of the nation's total coal production, and making it China's main coal mining area. The coal seam at Shendong belongs to the Jurassic Yan'an Formation and is usually less than 150 m deep. Many problems arise during large-scale coal mining there, e.g. subsidence, dried-up springs, reduced river flow, intensified desertification (Chen and Yue 2013; Li et al. 2013; Wang et al. 2008; Zhang et al. 2006, 2011). These problems threaten the sustainable development of western China's industrial coal base.

Differences in the basic energy structure of various countries have led to diverging research directions. In most developed countries, research regarding coal mines is mainly focused on the assessment of water pollution risk as well as mine closure and reclamation, rather than the dynamic disturbance of groundwater (Chugh and Behum 2014; Fu et al. 2009; Skousen and Zipper 2014; Tshivhandekano 2005). In contrast, such studies in China are more concerned with the prevention of water inrush at coal mines and the use of "mining overburden zoning" to prevent water inrush, protect groundwater resources, and predict the impact of coal mines (Qian et al. 2010).

Mining overburden zoning is based on the premise that mine safety and groundwater protection can be ensured if the fractured zone formed by mining does not reach the aquifer or result in excessive groundwater leakage. However, this method does not consider the mechanism of groundwater loss and cannot adequately quantify it. The traditionally used large diameter well method for calculating mine water inflow is based on very simple hydrogeological conditions and therefore is not suitable for coal mines with complex hydrogeological conditions.

Numerical methods have been developed for the quantitative evaluation, prediction, and management of water resources. Zhang and Liu (2002) set mine water inflow as the discharge of pumping wells by assuming a certain amount of pumped water. Li (2008), Liu (2011), and Wu

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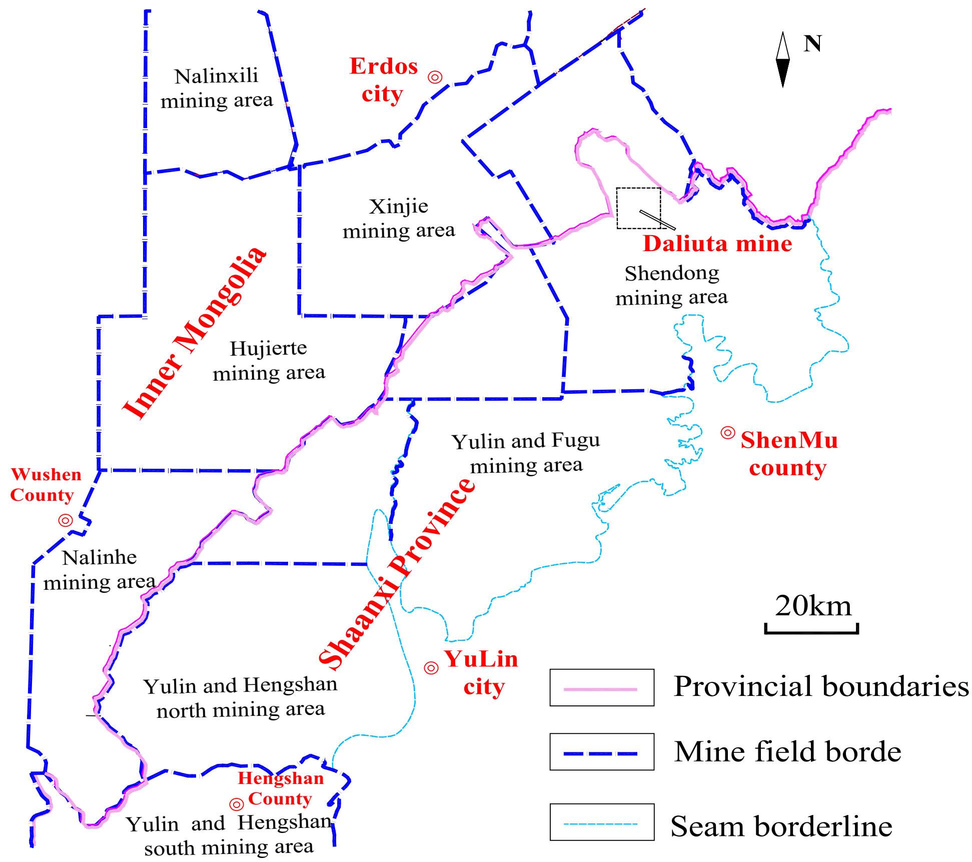

Fig. 1 Distribution of the Shaanxi and Inner Mongolia mining areas in the western arid areas of China

(2013) increased the permeability of the surrounding rock by incorporating a safety factor coefficient (e.g. 1.2× or 1.5×). However, the amount of pumped water or the coefficients were adjusted very subjectively, ignoring the mechanism of mining disturbance.

In this work, we combined the study of overburden failure with the simulation of a groundwater system by analyzing the disturbance mechanism of the surrounding rock and groundwater. We examined two numerical methods to handle the contact zone between the water-conducting fracture and the aquifer as a kind of water head boundary (in the steady-state model) or drainage boundary (in the unsteady-state model), and we used a numerical evaluation model to quantitatively analyze the influence of groundwater. The results provide a basis for the rational development of coal and water resources in the arid area of western China.

Quantitative Evaluation of Groundwater Disturbance

Overburden Failure Characteristics in Mining Shallow Coal Seam

The overlying strata influenced by coal mining are generally divided into three zones from bottom to top, i.e. the caving zone, the fracture zone, and the bending zone (Qian et al. 1996; Xiao et al. 2014). In addition, a subsidence area can develop on the land surface. Because the fracture zone and the caving zone are directly connected and have strong hydraulic conductivity, they are collectively referred to as the “water conducting zone”.

As previously reported (Fan et al. 2012; Yang et al. 2013), the coal seam in the Shendong mining area is shallowly buried (< 150 m) and the bedrock is not thick (< 100 m). As a result, the fracture zone extends directly to the surface, and the typical failure mode in this area involves just “two zones”. Figure 2 shows that the fracture zone directly connects to the unconsolidated aquifer near the surface. Hence, groundwater (and sand) may enter the coal mine via the fracture zone, which can deplete groundwater resources.

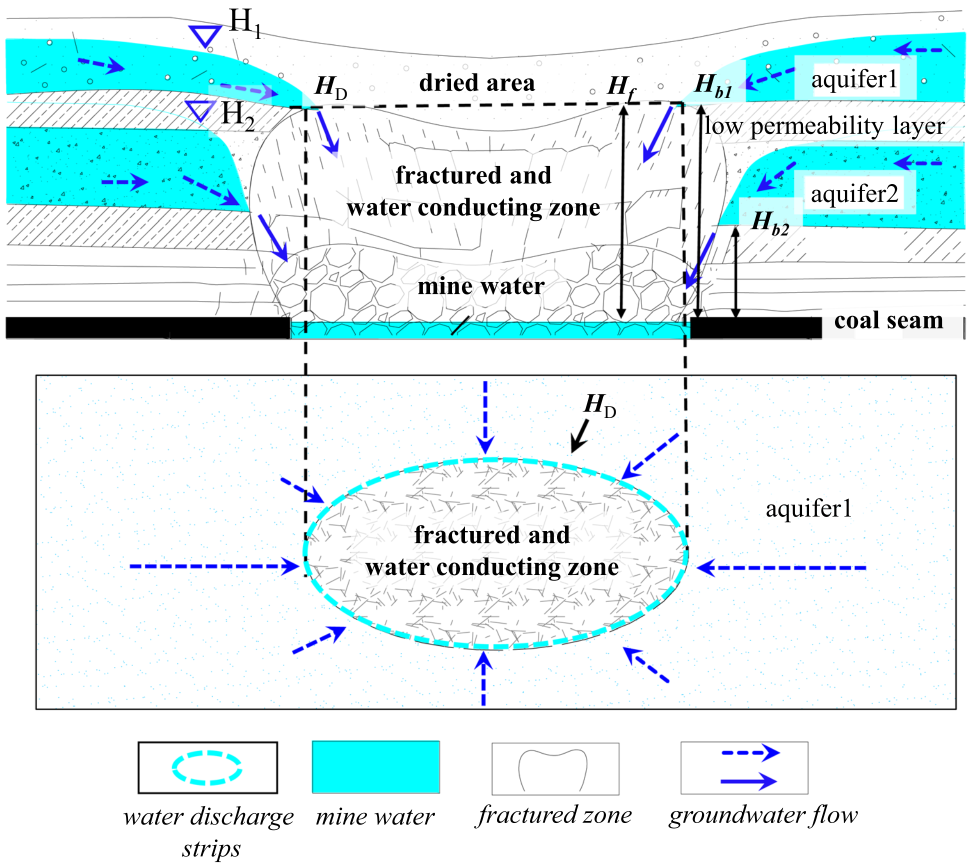

Fig. 2 The relationship between groundwater and the water-flowing fractured zone

In general, the major source of water drainage is the lateral discharge from aquifers in contact with the fracture zone. Mine water inflow can be estimated by the "large diameter well method" based on steady flow analysis (Eq. 1) (Wu 2013):

$$Q = 1.366K\frac{(2H - S)S}{\lg R_0 - \lg r_0}, \tag{1}$$

where K is the permeability coefficient, H is the water head height, S is the groundwater drawdown due to mine drainage, R_0 is the radius of influence, and r_0 is the radius of reference for the mine void space. The aquifer is assumed to be homogeneous and infinite, and the natural water level is approximately horizontal. The radius of influence R_0 can be calculated as follows:

$$R_0 = r_0 + R \tag{2}$$

$$R = 10\mathrm{S}\sqrt{\mathrm{K}} \tag{3}$$

$$r_0 = \sqrt{F/\pi}, \tag{4}$$

where F is the scope of the excavation area. It can be seen from Eq. (1) that the amount of groundwater leakage becomes greater when the water-flowing fractured zone is larger.

Numerical Processing of the "Fracture Zone"

When the fracture zone extends to a certain height, groundwater from the fractured aquifer can enter the mine. As a result, the aquifer's lateral recharge is cut off, and the aquifer above the mine is quickly drained if there is no vertical water supply. The groundwater forms "discharge strips" along the contact zone between the fractured aquifer and the fracture zone. Similarly, groundwater enters the mine e via cracks in the fracture zone, which provides a relatively stable supply of mine water.

1. Constant head boundary: first, the aquifer groundwater level falls to the height of the aquifer floor. The pore water pressure is atmospheric pressure since the cracks are directly connected to the atmosphere. Hence, the groundwater head (Hc) is approximately equal to the elevation (H), which is the height of the highest position of the fracture zone (H_f). With regard to groundwater movement, the contact zone between the fractured

aquifer and the fracture zone can be simplified as a kind of water head boundary condition (Fig. 2), i.e. $Hc = H_f$. This is the numerical treatment of the fracture zone in the steady-state groundwater model. Based on this method, the leakage of groundwater can be calculated accurately at the end of mining activities.

2. Drainage boundary: in the unsteady-state model, in order to numerically derive the lateral discharge, the contact zone or discharge strips between the aquifer and the fracture zone are treated as a "drainage" boundary. The drainage groundwater inflow boundary is calculated as:

$$Q = \begin{cases} C_D(H - H_D) & H > H_D \\ 0 & H \le H_D \end{cases}, \quad (5)$$

where Q is the amount of lateral discharge water that flows from the aquifers into the drainage boundary, H is the water head in a seepage cell, H_D is the water head in a drainage cell, and C_D is the permeability parameter that refers to the aquifer-integrated head loss between a seepage cell and a drainage cell. Chen and Zhou (2016) reported that C_D ranged from 2 to 50 m^2/day. It can be seen from Eq. (5) that the amount of groundwater seepage, Q, is proportional to the head difference between the seepage cell and the drainage cell. Hence, the drainage boundary model can better simulate groundwater loss in unsteady-state during the mining process.

Case Study

General Situation

The case study here considers the Daliuta coal mine in the Shendong region. The surface is completely covered with Quaternary deposits: aeolian sand and the unconsolidated Sara Wusu Formation aquifer. The unconsolidated layer is 15–30 m thick (Fig. 3) and has a permeability of 5≥ m/day. The burial depth of the groundwater level is 2–5 m. A layer of clay (3–15 m thick) in the Quaternary Lishi Formation forms the bottom of the unconsolidated aquifer. The permeability of the sandstone in the Jurassic Zhiluo formation is generally less than 0.04 m/day. The No. 1^{-2} and No. 2^{-2} coal mine seams are in the Yan'an Formation of the Jurassic, and the depth of the coal seam is 150 m on average. Under natural conditions, the unconsolidated aquifer groundwater is mainly recharged by precipitation infiltration. It is exposed at the surface in the valley cutting zone and thus forms perennial or seasonal rivers, e.g. the Muhegou and Huozhutai River. The Wulanmulun and the Beiniuchuan Rivers are the groundwater's final discharge zones (Fig. 4). The upper boundary is described by importing the area elevation data into the model (Fig. 5). The rainfall infiltration coefficient of the aeolian sand layer in this model is 0.27 (He 2014; Zhao 2011). By considering 150 geological drillings in the Daliuta coal mine, the model is mainly divided into four

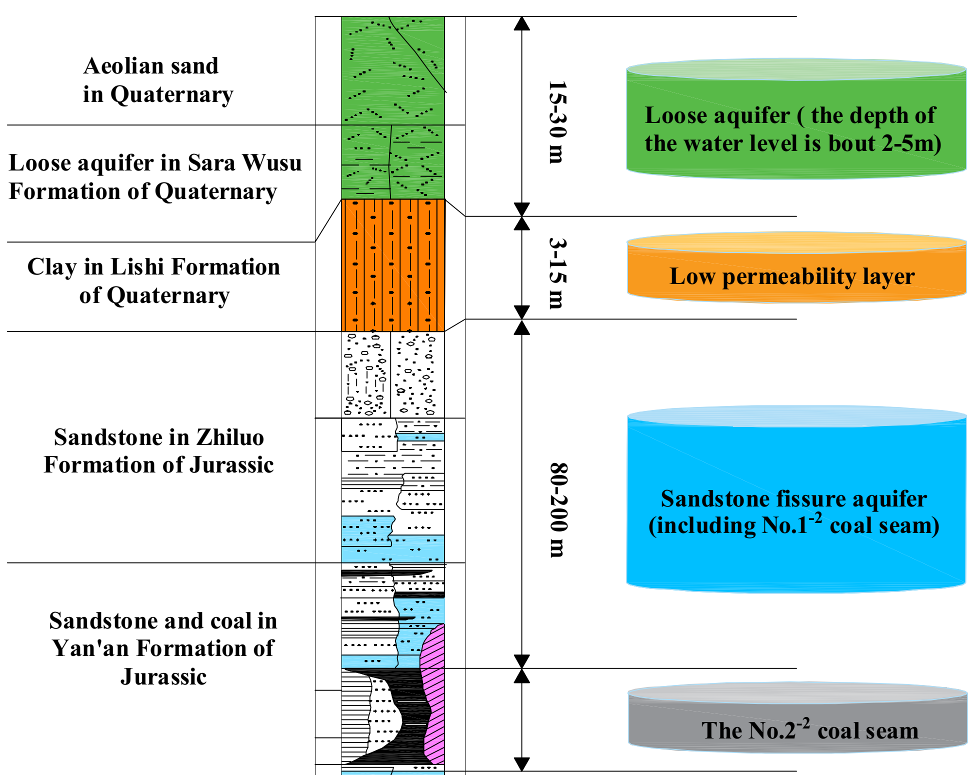

Fig. 3 Schematic diagram of the spatial distribution of aquifers for the Daliuta Coal Mine

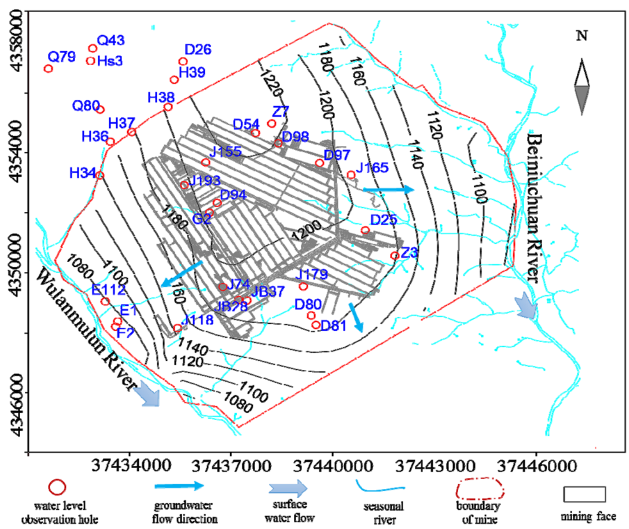

Fig. 4 Groundwater flow (in m) before mining in the year 2000

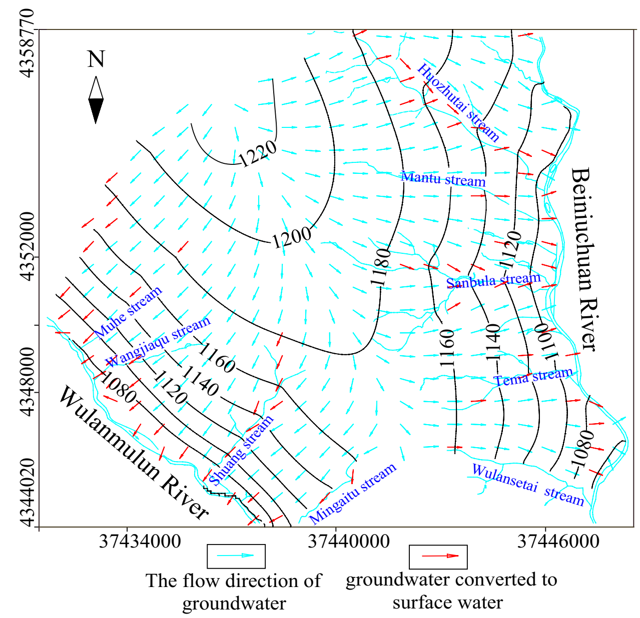

Fig. 6 The calculated groundwater flow (in m) before mining

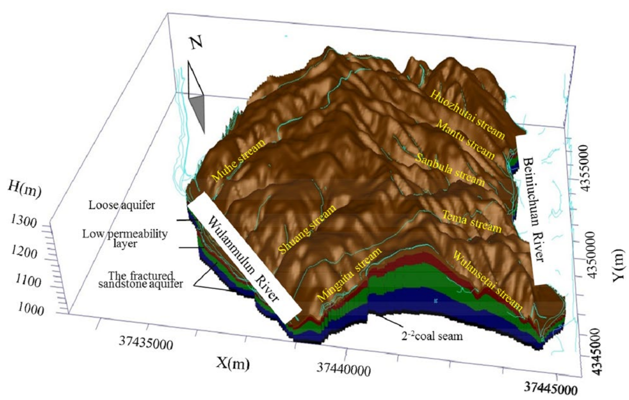

Fig. 5 The geological terrain map of the Daliuta Coal Mine

Table 1 Water balance before mining

Item (× 10^4 m^3/day)		Ratio (%)	Total (× 10^4 m^3/day)
Rainfall	3.86	85.40	4.52
Surface water	0.44	9.73	
Lateral recharge	0.22	4.87	
Evaporation	1.82	40.27	4.52
Drainage to surface water	2.65	58.63	
Lateral discharge	0.05	1.10	

levels vertically, i.e. the unconsolidated aquifer, the low permeability layer, the fractured sandstone, and the No. 2^{-2} coal seam (Fig. 5).

Groundwater Flow Characteristics Before Mining

The underground water flow field before mining in an unconsolidated aquifer was obtained by the steady-state model (Figs. 4, 6) and found to be consistent with the trend of the measured flow field. Hence, the model was in accordance with actual hydrogeological conditions.

Figure 6 shows the groundwater flow characteristics before mining. The blue arrows show the direction of groundwater flow, and the red arrows show the flow of groundwater into surface water. The hydraulic gradient of the groundwater is about 1.3%. Due to the local topography, most of the groundwater discharges into local streams, and the Wulanmulun and Beiniuchuan Rivers. Rainfall and drainage to surface water are the dominant characteristics of the water cycle in this region under natural conditions.

According to the results of the model (Table 1), rainfall accounts for 85% of the groundwater recharge. Lateral recharge from outside of the region accounted for about 5%, and in certain areas, surface water (streams, rivers) contribute the remaining 10%. Drainage to streams and rivers is the main (> 59% of the total) form of discharge. Evaporated discharge accounts for about 40%, and discharge outside of the region is only about 1% because the simulated area is a relatively independent hydrogeological unit.

Groundwater Simulation Under the Influence of Mining

The unsteady-state numerical groundwater model was built based on the actual mining scope of the area in 2000–2012.

The “contact discharge strips” between the fractured aquifer and fracture zone were processed as a drainage boundary in the model, and the amount of rainfall was based on the actual annual rainfall data.

Figure 7 shows the groundwater level contour map during mining from 2002 to 2012. Compared with the situation before mining, the unconsolidated aquifer was obviously affected by coal extraction. The groundwater formed an obvious cone of depression at the center of the mining area, and the water level declined dramatically at the mine, on average by about 50 m. Over the years, as the range of mining was extended, the completely drained area of the aquifer (the yellow section) increased. This, in turn, reduced groundwater discharge to the surface and streams (e.g. the Muhegou) dried up as a result.

Groundwater Balance During Mining

Figure 8 shows how the groundwater balance was changed by mining. The total amount of groundwater is still controlled by rainfall recharge, though lateral recharge from the outside area increased slightly (green area in Fig. 8a) due to the increased hydraulic gradient.

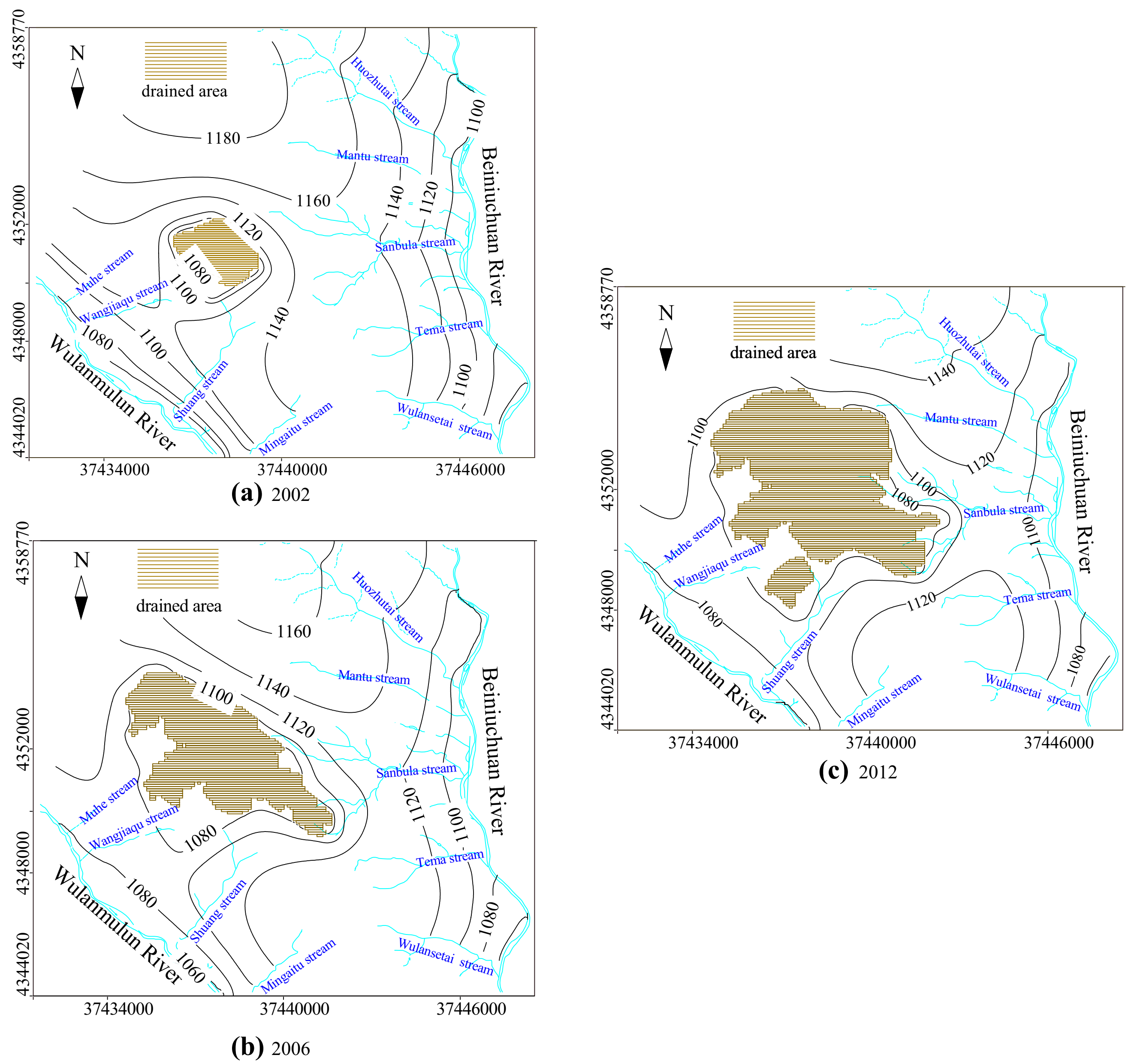

Fig. 7 The groundwater level (in m) of the Daliuta Coal Mine during mining

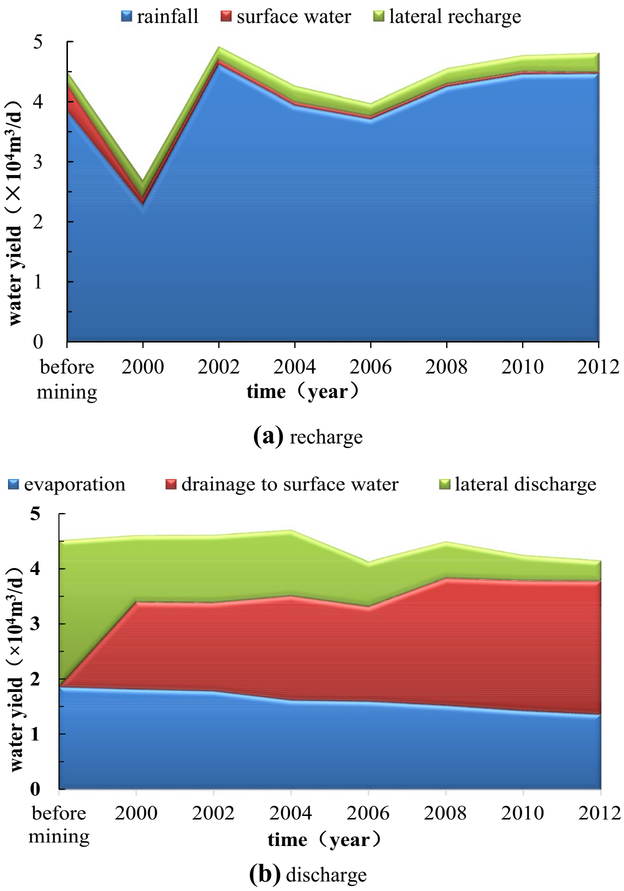

Fig. 8 The water balance in the Daliuta Coal Mine during mining

As the groundwater level in the unconsolidated aquifer declines, the depth to groundwater is increased. Hence, groundwater evaporation readily declines (blue area in Fig. 8b). Within the scope of the mine's influence, the relationship between groundwater and surface water is reversed. The amount of groundwater discharged to the surface drops significantly, from 2.65×10^4 to 0.36×10^4 m^3/day. Meanwhile, the discharge of groundwater from the unconsolidated aquifer into the mined space increased dramatically (green area in Fig. 8b). For example, in 2012, the discharge of groundwater to the mining space (i.e. the amount of groundwater leakage) reached 2.12×10^4 m^3/day. The increased groundwater leakage was mainly balanced from reduced groundwater discharge to the river and evaporation.

Analysis of the Results

The permeability coefficient of the unconsolidated aquifer, K was set at 2.38 m/day, the aquifer water head H and the groundwater drawdown S were both 30 m, and the mining area in 2012 was $F=3.04\times10^7$ m^2. Based on the "large diameter well method", the calculated aquifer groundwater discharge is 4.86×10^4 m^3/day. The groundwater lateral discharge was calculated by the numerical method to be 2.12×10^4 m^3/day (Table 2), which accurately quantified the effect of mining.

Conclusions

As shallow coal seams in western China are mined, the fracture zone caused by mining extends directly to the surface, and the typical failure mode in this area involves the "two zones". Regarding groundwater movement, the contact zone between the fractured aquifer and the fracture zone can be simplified as a kind of water head boundary or drainage boundary. This simplification is reasonable and allows effective numerical treatment of the fracture zone in the groundwater model. Computer model evaluation of groundwater disturbance shows that mining of the shallow coal seam can significant impact the unconsolidated aquifer in the arid regions of western China. According to the simulation, the Daliuta coal mine experienced a decline in groundwater level of > 50 m in 2012 and a groundwater loss of about 2.12×10^4 m^3/day.

Table 2 Comparison of calculation results

Computing method	Water ($\times10^4$ m^3/day)	Problem
Quantitative numerical analysis	2.12	Reasonable: the total loss of groundwater into the mining space
Mine measured drainage	1.32	Too small: does not include the amount of accumulating water in mine and reuse water for coal mining
Large diameter well calculation	4.86	Too large: large diameter well method assumes that the conditions for the four catchment, infinite aquifer, homogeneous, does not conform to the actual hydrogeological conditions

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