Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22376

121 (2018) 126–133
July

Hydrogeological changes caused by opencast coal mining in steppe zone: a case study of Shengli 1 open-pit coal mine

Zhenguo Xing[a,b], Suping Peng[a,b,*], Wenfeng Du[a,b], Yunlan He[a], Shan Chong[a], Feisheng Feng[a,b], Peng Yu[c], Changchao She[c], Dongjing Xu[d]

[a]*State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology (Beijing), Beijing, China, Tel. +86 010 62331305; emails: psp@cumtb.edu.cn (S. Peng), TSP1600201046@student.cumtb.edu.cn (Z. Xing), duwf66@126.com (W. Du), 55069008@qq.com (Y. He), 396185870@qq.com (S. Chong), fengfeisheng21@163.com (F. Feng)*
[b]*College of Geoscience and Surveying Engineering, China University of Mining and Technology (Beijing), Beijing, China*
[c]*Shenhua Beidian Shengli Energy Co., Ltd., Xilinhot, China, emails: cumt-05052287@163.com (P. Yu), 11610720@shenhua.cc (C. She)*
[d]*College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao, China, email: xudongjinggg@126.com*

Received 24 February 2018; Accepted 16 April 2018

ABSTRACT

The exploitation of coal resources can lead to change of regional environment, and open-pit mining makes even more direct impact on vegetation, topsoil, surface water and underground water in grass area. Studying the change of hydrogeological condition caused by open-pit mining is beneficial for rational utilization of water resource in grass area and guaranteeing normal exploitation of open-pit mine. In this study, the Shengli 1 open-pit coal mine with typical hydrogeographical features, locating in typical meadow steppe area, was taken as researched area. Through collecting basic mine production data, such as annual output, drainage quantity, water inflow, the water inflow (including static-storage and recharge rate) of mine was predicted and calculated by horizontal catchment channel method, big well method and replenishment quantity method, respectively. This study investigates the hydrogeological condition changes of open-pit coal mine in grass area during production process. Results show that the static storage of hydrogeological unit exerts great impact to coal mine exploitation and production in early stage, while recharge rate exerts continuous influence to the whole mining process. As the quarternary loess in earth surface of steppe area is thick, and phreatic layer has a direct association with mining pit, the replenishment quantity method can achieve the most accurate calculation; the influence of open-pit mining to geohydrologic condition is mainly determined by aquifer hydraulic conductivity and mining depth.

Keywords: Groundwater; Hydrological change; Open-pit coal mine; Water inflow; Eastern grassland, China

1. Introduction

Coal resource is one of key energy consumptions of China. Open-pit coal mining, as a type of mining, has gained an annually increasing proportion. According to statistics research by Zhao et al. [1], China has a total of over 400 open-pit coal mines, including open-pit coal mines on-production and under-construction, with total capacity of 0.65 billion t/a, in particular the coal yield of 2013 was 0.52 billion t. Of all open-pit coal mines, the number of large-scale ones is over 30, with designed capacity of 0.36 million t as of July 2014. Of large-scale open-pit coal mines, there are

* Corresponding author.

Presented at the 3rd International Conference on Recent Advancements in Chemical, Environmental and Energy Engineering, 15–16 February, Chennai, India, 2018.

1944-3994/1944-3986

15 super-huge type ones (with capacity over 10 Mt/a), including 12 ones locating in Inner Mongolia, as shown in Fig. 1(a), which belongs to eco-fragile region where the grassland is largely distributed and evaporation capacity exceeds precipitation [1,2]. Large-scale high-intensity open-pit mining will bring negative impacts to surrounding ecological environment (especially for eco-fragile region), including pumping and drainage of groundwater, mining the boundary of mining, land occupied by the waste-dump, closed pit, etc. [3,4]. Groundwater has an influence on slope stability, vegetation abundance, etc. [5–7]. The hydraulic connection complex is not conducive to the surrounding engineering [8,9].

The effect of open-pit mining on underground water is mainly due to pumping and water burst. Pumping underground water refers to pumping the underground water above mining level to earth's surface via dredging dried well for further processing, so as to guarantee normal production [10,11]. Water burst is caused due to that aquifer is revealed or overland runoff burst into working level or pit via underground watercourse [12–14].

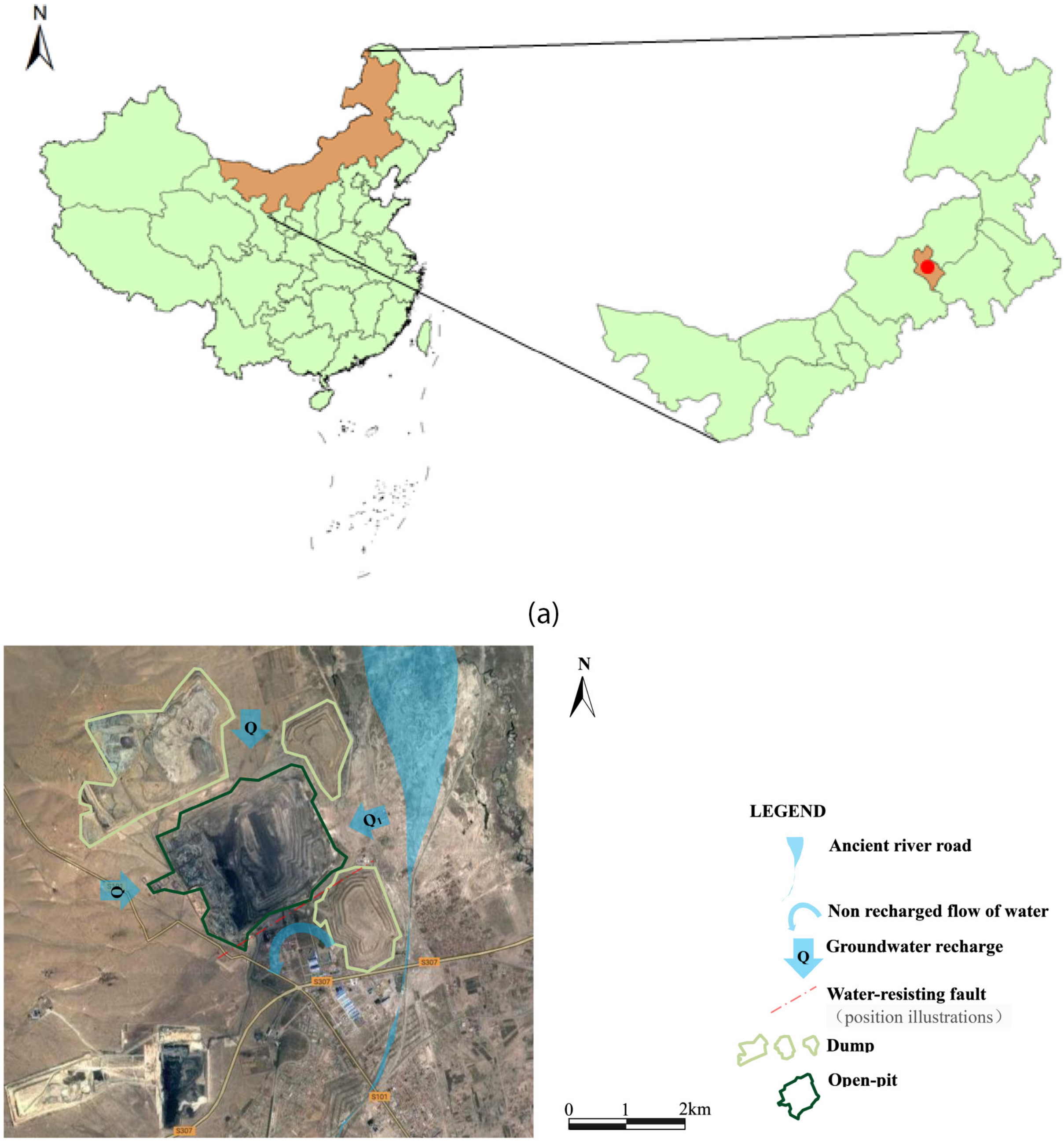

Fig. 1. Geographical location of researched area. (a) Administrative region of researched area (red point represents open-pit mine) and (b) geographic map of open-pit mine.

Currently, the prediction methods of coal mine water inflow are mainly concentrated on underground mine rather than on open-pit coal mine. Consensus on prediction model of water inflow for coal mines in steppe area has not been reached [15–20]. In this paper, Shengli 1 large-scale open-pit coal mine in steppe area (Fig. 1(b)), with diversified forms of underground water and complete mining cycle, is selected as researched area. Through collecting data on water inflow, exploitation quantity, drainage quantity over the years, this study investigates the existing forms of underground water, calculates static storage and water inflow, predicts stable water inflow, providing reference for production planning of mine and water resource protection.

In this paper, based on water inflow of mine as basic research object, we analyzed hydrogeological condition changes of coal mine area by comparing prediction values of water inflow with actual values, and discussed the influence of open-pit mining to water resource of mine area. The remainder of this paper is organized as follows: Section 2 describes the background, including study area and hydrological boundary. Section 3 analyzes four calculation methods for water inflow for the study area. Section 4 discusses the results of hydrogeological condition changes of coal mine area in steppe region. Finally, Section 5 summarizes the conclusions from this study.

2. Background

2.1. Study area

2.1.1. Hydrology and climate

Built in 1958, Xilinhot reservoir locates in 9 km south of Xilinhot City, with total sink capacity of 19.0 Mm^3, and water level elevation of 1,011.87 m.

Xinlin River is the largest rive within such coal field, with total length of 268 km. This river flows past Xilinhot reservoir and then flows through the midwestern coal field. The annual mean runoff is 19.22 Mm^3, largest peak discharge upon spring flood is recorded to be 57.4 m^3/s (April 7th, 1987), the water depth varies within 0.5–1.00 m. In each year, January and February are the blanking period.

This area has semiarid prairie climate, with large annual temperature difference. Rainy season lasts from June to August, account for 71% of annual precipitation. The maximum annual precipitation is recorded to be 481.0 mm (1974), while the minimum annual precipitation is 146.7 mm (1980), the annual mean evaporation is 1,794.64 mm.

2.1.2. Strata and faults

The stratum of Shengli coal field include (from the old to the new) paleozoic erathem-devonian system, lower permian system; mesozoic erathem-jurassic upper series Xing'anling group, cretaceous system lower series Bayinhua group; cenozoic erathem-tertiary upper series, quaternary pleistocene series and holocene series.

There are three layer sections containing coal, including lower coal-bearing section of Xilin group, coal-bearing section of mudstone section, and upper coal-bearing section of Shengli group.

As shown in Fig. 2, several normal faults exist near the southern border of open-pit area, wherein the faults within area include F_1, F_{25}, F_{27}, F_{29} and F_{30}, all are normal faults (Table 1). Fault zone has a significant impact on hydraulic connection of underground water.

2.1.3. Aquifer

In this area, the aquifers that are influential to open-pit mining include quaternary pore-phreatic aquifer, coal-series top-conglomerate pore-fissure confined aquifer group, No. 5 coal seam fracture confined aquifer group, and No. 6 coal seam fracture confined aquifer group.

The quaternary pore-phreatic aquifers are widely distributed in this area, belonging to medium water-rich aquifer, with thickness of 0–40.7 m.

The coal-series top-conglomerate pore-fissure confined aquifer group is distributed in the west of mine area, belonging to medium water-rich aquifer, with large variation in thickness.

No. 5 coal seam fracture confined aquifer group is dominated by No. 5 coal seam and distributed in the whole region, belong to medium water-rich aquifer, with average thickness of 16.34 m.

No. 6 coal seam fracture confined aquifer group is dominated by No. 6 coal seam and roughly distributed in the whole region, belonging to poor-extremely poor aqueous aquifer, with extremely non-uniform water yield property.

2.1.4. Aquiclude

Stable water-resisting layers exist among above four aquifers, which mainly consist of mudstone, sandy mudstone and silty-sandstone.

Drilling data show that at alluvial plain area of Xilin river valley, there is a stable water-resisting layer between quaternary pore-phreatic aquifer and lower aquifer. The water-resisting layer is normally 2–25 m in thickness, and mainly consists of mudstone and sandy mudstone, will less water abundance in local areas.

Among No. 5 coal seam fracture confined top aquifer, quaternary pore-phreatic upper aquifer and top-conglomerate pore-fissure confined aquifer, there are stable water-resisting layers, except for individual area. The water-resisting layer mainly consists of mudstone, sandy mudstone and siltstone, with thickness of 5–25 cm. There is no water-resisting layer in local area.

Stable water-resisting layers exist in the whole area between No. 5 coal seam fracture confined bottom aquifer and No. 6 coal seam fracture confined aquifer. The water-resisting layer mainly consists of mudstone, sandy mudstone and siltstone, with thickness of 1.9–36 m.

2.2. Hydrological boundary

The groundwater recharge, runoff, discharge conditions of open-pit coal mine as well as its hydrogeological unit determine the water filling avenue, water filling way and water filling scale of future open-pit.

Currently, unveiled aquifers include quaternary pore-phreatic aquifer and cretaceous No. 6 coal seam

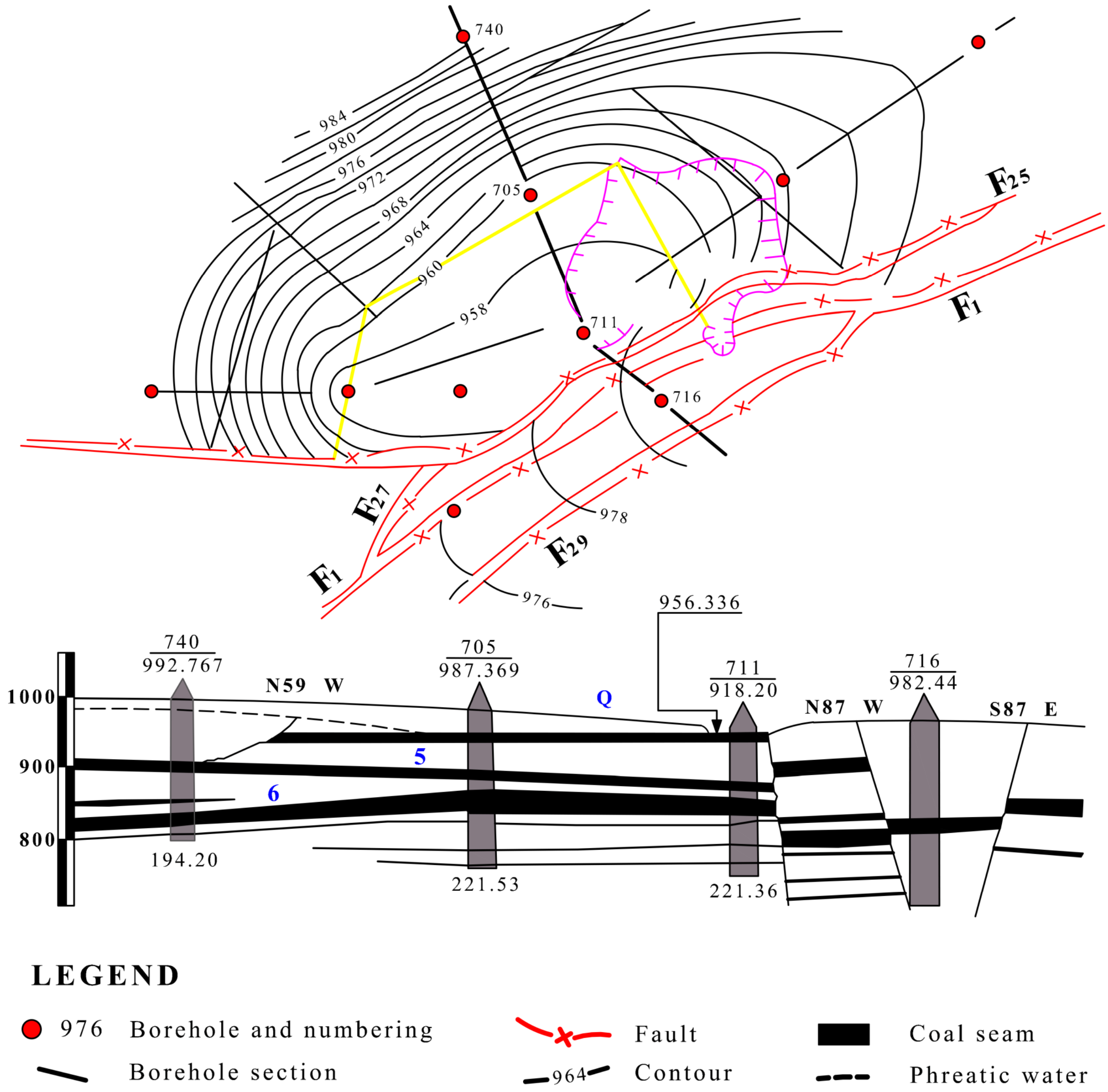

Fig. 2. Hydrogeological profile of mining area.

fracture confined aquifer and pore-fissure confined aquifer above. Among them, quaternary pore-phreatic aquifer is the dominant one (Table 2).

2.2.1. Recharge boundary

The mine area located at 650–1,050 m west of Xilin river, 600–1,250 m east of valley plain west boundary. The west of coal mine is hilly area, which serves as boundary for water supply. F_{16} normal fault locates in the north of mine lot, which cut into Xilin river valley in east-west direction and connects with mine lot. In the east of mine lot, there is a group of extension fractures, linking the Xilin river valley water. Therefore, the east and north of mine lot are water supply boundaries.

In the east of mine lot, the Xilin river water and valley water locate above coal seam group. At 4-2, 5-2 pore area, valley water covers above coal suboutcrop, accepting vertical cross-flow supplement of valley water. Therefore, the valley water and river water at the east of mine lot are main recharge source for mine drainage and water burst.

Taking comprehensive consideration on geological conditions and water recharge avenue, the east, north and west of mine lot are supply boundaries.

2.2.2. Confining boundary

The mine area is in syncline structure, surrounded by several normal faults. According to the study [21], several normal faults (including F_1, F_{25}) exist in the south of mine area, as shown in Table 1.

The stratum surrounding the points of abovementioned normal faults mainly consists of plastic mudstone and clay cementing sandstone, with few fractures. Fault fracture zone is undeveloped, with no water storage space or water transmitting ability. As faults are not stripped at mine lot, the open-pit mine locates at the hanging side of fault.

The south boundary of first mining area is trenching position, and the underground water level has reduced to water-resisting floor during mining period. Therefore, the south of mine lot is regarded as confining boundary.

3. Methods

3.1. Demonstration range parameter

3.1.1. Demonstration range area

In this paper, the demonstration range mainly refers to the drainage area of Shengli 1 open-pit coal mine, including quaternary pore-phreatic recharge area and No. 5 coal water outcrops recharge area. According to mine area dividing scheme, the first mining area is measured to be 7.75 km^2, the quaternary pore-phreatic recharge area is identical to that of first mining area (also 7.75 km^2), both of which are plain area. According to practical boundary condition, No. 5 coal seam fracture confined outcrop area is set to be 14.5 km^2.

Table 1
Main characteristics of faults within area

Fault	Nature	Fall (m)	Length (m)	Degree of reliability
F_1	Normal fault	0–105	20,000	Reliable
F_{25}	Normal fault	0–55	4,700	Reliable
F_{27}	Normal fault	20–50	550	Relatively reliable
F_{29}	Normal fault	0–50	5,700	Reliable
F_{30}	Normal fault	0–15	530	Relatively reliable

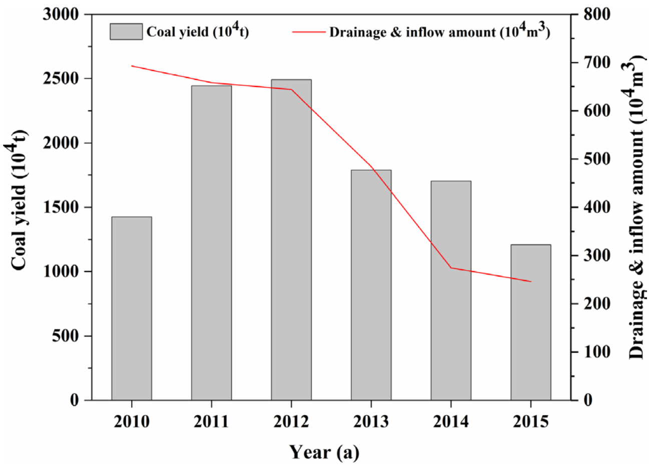

Fig. 3. Coal yield and drainage and inflow amount from 2010 to 2015.

3.1.2. Hydraulic conductivity (K)

The quaternary pore-phreatic aquifer has three pumping holes. According to hydrogeological map of coal mine, the arithmetic mean value of osmotic coefficients of 87-1 hole and 87-3 hole is calculated to be 14.36 m/d.

For No. 5 coal-series top-conglomerate pore-fissure aquifer, the osmotic coefficient of 12-1 hole is adopted, which is 0.877 m/d.

For No. 5 coal seam fracture confined aquifer, the arithmetic mean value of osmotic coefficients of BK075 hole and BK096 hole is adopted, which is 1.3054 m/d.

For No. 6 coal seam fracture confined aquifer, the arithmetic mean value of osmotic coefficients of 5-2 hole and 736 hole is adopted, which is 0.00529 m/d.

3.1.3. Reference radius (r_0)

The slot mining area can be regarded as a rectangle, of which the east and west side lengths are regarded as slot width (1,076 m), while the south and north side lengths are regarded as slot length (1,800 m). The calculation formula is shown as below:

$$r_0 = \frac{P}{2\pi} \tag{1}$$

$$P = 2(a+b) \tag{2}$$

In formula (1), P represents the perimeter of demonstration area; In formula (2), a represents the length of south and west side slot, which is 1,800 m; b represents the length of east and west side slot, which is 1,076 m.

The reference radius can be calculated as r_0 = 915.92 m.

3.1.4. Influencing radius (R)

In borehole pumping test, the influencing radius only represents the value under drawdown condition. In actual engineering, the drawdown S should be equal to the height (H) of water head.

$$R=2S\sqrt{HK} \tag{3}$$

$$R=10S\sqrt{K} \tag{4}$$

$$R_0 = R + r_0 \tag{5}$$

Formula (3) shows the calculation method of influencing radius of phreatic aquifer; formula (4) shows the calculation method of influencing radius of confined aquifer; formula (5) shows the calculation method of reference radius.

3.2. Horizontal catchment channel method

As the first mining area advances to west boundary, when the water level reduces to below confining bed roof, the water-filled aquifer shifts from pressure-bearing state to non-pressure state. Therefore, pressure-bearing to non-pressure formula for one-side inflow is adopted.

$$Q = BK\frac{(2S - M)M}{2R} \tag{6}$$

where Q represents mine pit water inflow (m^3/d), B represents inflow width (m), K denotes the osmotic coefficient of aquifer where coal seam locates, R is influencing radius. Phreatic aquifer is calculated by formula (3), confined aquifer is calculated according to formula (4), M represents aquifer thickness (m).

3.3. Big well method

According to the study by No. 153 geological team of Inner Mongolia Coalfield Geology Bureau [22], the first mining area is analyzed based on aquifers at mining lot. The calculation formula of big well method is shown as below:

$$Q = 1.366K\frac{(2H - M)M}{LgR_0 - Lgr_0} \tag{7}$$

where the arithmetic mean value of aquifer drilling thicknesses is taken as the aquifer thickness H.

3.4. Replenishment quantity method

According to the hydraulic relation of aquifers of open-pit mine as well as analysis of water filling factors, it can be known that the recharge sources within researched area mainly include: channel leakage recharge, rainfall recharge and side runoff recharge.

Channel leakage recharge for quaternary phreatic aquifer mainly concentrate from June to August during flood season, that is, the total recharge period is 92 d per year. The side runoff recharge from western hilly area and eastern valley plain is mainly responsible for No. 5 coal seam fracture confined aquifer.

$$Q_1 = 10^{-4}BK\frac{(H^2 - h^2)}{2L}t_1 \tag{8}$$

$$P_r = 10^{-1}PaF \tag{9}$$

$$Q = 10^{-4}KIHLt_2 \tag{10}$$

Formula (8) represents the calculation for channel leakage recharge. Q_1 represents channel recharge rate (10^4 m^3); B is the width of river recharge to mine pit, that is, the sum of quaternary phreatic aquifer boundary length and influencing radius; L is the distance between river and pit recharge boundary, which is 900 m; t_1 is recharge time, which is 92 d. Formula (9) represents rainfall recharge rate. Pr is the precipitation infiltration amount (10^4 m^3); P is the precipitation under assurance rate of 97%, which is 111.0 mm; F is the Calc Zone area, the quaternary phreatic recharge area (all plain area) is 7.75 km^2, the No. 5 coal fracture confined aquifer outcrop area is 14.5 km^2. α is the rainfall infiltration recharge coefficient, the rainfall infiltration recharge rates for quaternary phreatic aquifer and No. 5 coal seam fracture confined aquifer are 0.13 and 0.05, respectively. Formula (10) is the calculation formula for side runoff recharge. Q represents side runoff recharge rate (10^4 m^3); K represents the average osmotic coefficient of side recharge cross section, which is 1.305 m/d; I represents the average groundwater head gradient perpendicular to the section, which can be calculated according to water level contour map of first mining area,

Table 2
Hydrogeological parameters of first mining area

Recharge Boundary	Aquifer	Symbol	Boundary length B (m)	Hydraulic conductivity K (m/d)	Drawdown S (m)	Aquifer thickness M (m)	Influencing radius R (m)
East side	Quaternary pore-phreatic aquifer	Q	1,076	14.36	14.85	14.85	433.70
	No. 5 coal-series top-conglomerate pore-fissure aquifer	5*	1,076	0.877	47.74	17.15	447.08
	No.5 coal seam confined aquifer	5	1,076	1.3054	56.35	22.71	643.82
	No. 6 coal seam confined aquifer	6	1,076	0.00529	137.70	30.25	100.15
North side	No. 5 coal-series top-conglomerate pore-fissure aquifer	5*	1,800	0.877	47.74	16.42	447.08
	No. 5 coal seam confined aquifer	5	1,800	1.3054	56.35	19.48	643.82
	No. 6 coal seam confined aquifer	6	1,800	0.00529	137.70	28.64	100.15
West side	No. 5 coal-series top-conglomerate pore-fissure aquifer	5*	1,076	0.877	47.74	16.42	447.08
	No. 5 coal seam confined aquifer	5	1,076	1.3054	56.35	21.22	643.82
	No. 6 coal seam confined aquifer	6	1,076	0.00529	137.70	28.64	100.15

wherein the east average groundwater head gradient is 2.92%, and the west is 4.63%. H represents aquifer thickness, wherein the east one is 22.71 m, while the west one is 21.22 m; L represents side runoff recharge section length, wherein the east one is 2,363.64 m, while the west is 1,719.82 m; t_2 represents time, which is 365 d.

4. Results and discussions

4.1. Hydrogeological condition changes

The calculation results by horizontal catchment channel method are shown in Table 3. The method does not need to be converted. The calculation result is 6.357 million m^3/a.

According to the study [23], when big well method is adopted as the calculation method for coal mine water inflow, 30%–50% reduction should be considered and the security coefficient for this demonstration is set to 0.5. Therefore, the calculation results by big well method is 9.096 million m^3/a (24,920.65 m^3) (Table 4).

The recharge rate is calculated according to formula (10), as shown in Table 5. Considering the high-flow and low-flow cycles of recharge, the reduction coefficient is set to 0.9, then the stable recharge rate is 3.1775 million m^3/a.

4.2. Prediction of future water inflow

As Shengli 1 open-pit coal mine reached the design capacity around 2011, the water inflow will not show increasing trend (Fig. 3). As show in Table 6, the water inflow values predicted by horizontal catchment channel method and big well method are close to actual value around 2011, while the water inflow value predicted by replenishment quantity method is close to the value in 2015.

The calculation results of big well method are obtained based on borehole pumping test only, and water inflow is calculated under the premise that one-time drawdown reaches the mining level, therefore the calculated value of water inflow is relatively larger. However, the coal mine drainage is a long-term gradient process, the water inflow can be better predicted through analyzing static storage and recharge rate.

By comprehensively considering the hydrogeological condition of researched area, it can be concluded that underground water static storage accounts for large proportion of water inflow before 2014; while after 2014, underground water static storage disappears, instead the water inflow is approximately equal to recharge rate, reaching a recharge-runoff-drainage cycle. On this basis, it can be predicted that the water inflow and recharge rate will be roughly the same for Shengli 1 open-pit coal mine, which is 3 million m^3/d.

4.3. Calculation of influencing radius

For the bottom boundary of open-pit coal mine, the east-west length is 5.62 km, the south-north width is 4.49 km, and the total area is 24.70 km^2. After exploiting coal seam, the underground water of quaternary pore-phreatic aquifer group within field area will be completely drained, and thus the water level of peer aquifer within surrounding unexploited area will decrease.

The construction and production of open-pit coal mine will impact the environment within an influencing radius (R) range. Outside of such range, hydrogeological condition changes make no influence. The influencing radiuses of aquifers can be calculated according to formula (5), as shown in Table 7.

It is calculated that the area affected by open-pit mining to Q is 34.668 km^2, the area ratio to the mining area is about 1.37, which means that the mining area in this area is limited.

According to the calculated values of influencing radiuses and actual open-pit mining condition, it can be known that influencing radius of open-pit coal mine to aquifer is mainly determined by osmotic coefficient, aquifer depth and thickness.

Table 3
Calculation results of drainage and inflow by horizontal catchment channel method

Recharge boundary	Aquifer	Q (m^3/d)	Q ($10^4 m^3$/a)
East side	Q	3,928.19	143.38
	5*	1,417.72	51.75
	5	2,229.32	81.37
	6	210.73	7.69
North side	5*	2,291.87	83.65
	5	3,313.74	120.95
	6	335.96	12.26
West side	5*	1,370.03	50.01
	5	2,117.54	77.29
	6	200.83	7.33
Total		17,415.93	635.68

Table 4
Calculation results of drainage and water inflow by big well method

Aquifer	H (m)	R (m)	Q (m^3/d)	Q ($10^4 m^3$/a)
Q	14.85	433.71	25,694.18	937.84
5*	47.74	477.08	9,008.30	328.80
5	56.35	643.82	14,005.98	511.22
6	137.70	100.15	1,133.19	41.36
Total			49,841.29	1,819.21

Table 5
Calculation results by recharge methods ($10^4 m^3$)

Channel leakage recharge rate	Rainfall recharge rate	Side runoff recharge rate	Total recharge rate	Recharge rate (after reduction)
318.31	19.23	15.52	353.06	317.75

Table 6
Comparison of water inflows by three methods ($10^4 m^3 a^{-1}$)

Horizontal catchment channel	Big well method	Replenishment quantity method	Water inflow in 2010	Water inflow in 2015
635.68	909.60	317.75	692.91	245.72

Table 7
Influencing radius of upper aquifer

Aquifer	Osmotic coefficient (m/d)	Aquifer thickness (m)	Influencing radius (m)
Q	14.36	14.85	433.70
5*	0.877	16.42	447.08
5	1.3054	19.48	643.82
6	0.00529	28.64	100.15

5. Conclusions

- The hydrogeological condition changes caused by open-pit mining are mainly manifested in two aspects, including underground water storage and aquifer reconstruction. Underground water storage change is mainly manifested in water inflow, wherein the static storage capacity should be attached with great attentions of engineering practitioners.
- he water inflow of open-pit coal mine in steppe area can be calculated by classic theories and formulas. Before reaching designed capacity, horizontal catchment channel method and big well method are recommended calculation methods, while recharge method is more suitable for calculating water inflow after reaching designed capacity.
- The influencing radius of open-pit mining in steppe area to aquifer is mainly determined by aquifer hydraulic conductivity, aquifer depth and thickness.

Acknowledgements

The authors acknowledge the State Key Research Development Program of China (Grant: 2016YFC0501102).

References

[1] H.Z. Zhao, X. Zhen, M.J. Li, Current development situation of open-pit coal mine in China, China Min. Mag., 25 (2016) 12–15 (in Chinese).
[2] C.S. Ji, Overview of the development of open pit coal mining technology in China, J. Min. Saf. Eng., 25 (2008) 297–300 (in Chinese).
[3] A. Ordóñez, S. Jardón, R. Álvarez, C. Andrés, F. Pendás, Hydrogeological definition and applicability of abandoned coal mines as water reservoirs, J. Environ. Monit., 14 (2012) 2127.
[4] D.Z. Gu, J.M. Zhang, Modern coal mining affected to underground water deposit environment in West China mining area, Coal Sci. Technol., 40 (2012) 114–117 (in Chinese).
[5] D.Z. Gu, Y. Zhang, Z.G. Cao, Technical progress of water resource protection and utilization by coal mining in China, Coal Sci. Technol., 44 (2016) 1–7 (in Chinese).
[6] P.L. Younger, N.S. Robins, Mine Water Hydrogeology and Geochemistry, Geological Society of London Publishing House, 2002.
[7] S. Jiang, X. Kong, H. Ye, N. Zhou, Groundwater dewatering optimization in the Shengli no. 1 open-pit coalmine, Inner Mongolia, China, Environ. Earth Sci., 69 (2013) 187–196.
[8] P.D. Vermeulen, M. Burger, A.V. Wyk, Potential hydrological interaction of a gold mine and a coal mine in South Africa, Mine Water Environ., 33 (2014) 3–14.
[9] P. Cook, S. Dogramaci, J. Mccallum, J. Hedley, Groundwater age, mixing and flow rates in the vicinity of large open pit mines, Pilbara region, northwestern Australia, Hydrogeol. J., 25 (2017) 39–53.
[10] P. Baur, Water and the mining industry, Water Wastewater Int., 13(1998) 138–140.
[11] L.K. Sahoo, S. Bandyopadhyay, R. Banerjee, Water and energy assessment for dewatering in opencast mines, J. Clean. Prod., 84 (2014) 736–745.
[12] C.J. Booth, Strata-movement concepts and the hydrogeological impact of underground coal mining, Groundwater, 24 (1986) 507–515.
[13] J.M. Kim, R.R. Parizek, D. Elsworth, Evaluation of fully-coupled strata deformation and groundwater flow in response to longwall mining, Int. J. Rock Mech. Min. Sci., 34 (1997) 1187–1199.
[14] M.R. Islam, D. Hayashi, A.B. Kamruzzaman, Finite element modeling of stress distributions and problems for multi-slice longwall mining in Bangladesh, with special reference to the Barapukuria coal mine, Int. J. Coal Geol., 78 (2009) 91–109.
[15] R.N. Singh, A.S. Atkins, Application of idealized analytical techniques for prediction of mine water flow, Min. Sci. Technol., 2(1985) 131–138.
[16] F.D. Ardejani, R.N. Singh, T.E. Kish, S.M. Reed, Prediction of the groundwater rebound process in a backfilled open cut mine using an artificial neural network, Mine Water Environ., 32 (2013) 1–7.
[17] P. Liu, Y. Tao, M. Shang, Y. Mei, The calculation of mine water yield using the non-continuous flow theory, Environ. Earth Sci., 71 (2014) 975–981.
[18] J.L. Xu, W.B. Zhu, X.Z. Wang, New method to predict the height of fractured water-conducting zone by location of key strata, J. China Coal Soc., 37 (2012) 762–769 (in Chinese).
[19] Q. Wu, W. Pang, Y.C. Wei, J. Yu, Vulnerability forecasting model based on coupling technique of GIS and ANN in floor groundwater bursting, J. China Coal Soc., 31 (2006) 314–319 (in Chinese).
[20] L. Chen, X. Feng, W. Xie, D. Xu, Prediction of water-inrush risk areas in process of mining under the unconsolidated and confined aquifer: a case study from the Qidong coal mine in China, Environ. Earth Sci., 75 (2016) 706.
[21] Shenhua Geological Survey Co., Ltd.,Supplement Exploration Report on First Mining Area of Shengli 1 Open-Pit Coal Mine in Inner Mongolia Autonomous Region, 2015.
[22] 153 Geological Team of Inner Mongolia Coalfield Geology Bureau,Geologic Report on Open-Pit Exploitation of Shengli 1 Coal Mine in Xilinhot of Inner Mongolia, 1994.
[23] GB50215-2005, Coal Mine Design Specification, 2005.