The influence characteristics of open-pit coal mining on groundwater level in Baorixile

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Abstract: In the context of extensive high-intensity mining in open-pit coal mines, the temporal and spatial changes of the groundwater level and the range of disturbance caused by the mining activities remain unclear, and the traditional hydrological observation methods are insufficient in obtaining accurate and real-time groundwater monitoring data under the open-pit mining conditions. To address these challenges, the construction of an automatic groundwater observation network to obtain long-term groundwater level dynamic monitoring data via wireless remote transmission, integrated with hydrological background value survey, open-pit coal mine production and drainage data, meteorological data, and hydrogeological data, will reveal the temporal and spatial change characteristics of groundwater under open-pit coal mining conditions and disturbances radius and area of influence on groundwater. The results show: 1) The drainage operation during the open-pit mining caused the drop of groundwater level and forming of a cone of depression, with maximum drawdown of the central groundwater level at 60 m. The disturbance mainly occurred in the mining area where the maximum groundwater disturbance radius was 8 km, and the disturbance area accounted for 66.7% of the mining area and 10% of the hydrogeological units; 2) The range of groundwater level drop within the disturbance radius is closely related to the distance from the open-pit coal mine and the drainage volume. The closer the distance to the open-pit coal mine and the greater the drainage volume led to the greater the groundwater level drop; 3) The change characteristics of dynamic curve of groundwater can be divided into 3 types (weather-affected, unaffected and mining-affected). Therefore it is of great significance for groundwater resources protection and ecological restoration in open-pit coal mines to conduct automatic monitoring of groundwater, and study the influence of open-pit coal mining on groundwater by establishing a three-dimensional observation network of groundwater in open-pit mines.

Keywords: Groundwater flow field; Groundwater Automatic Monitoring Network; open-pit coal mine; Baorixile

1. Introduction

With the growing population and economic development, the over-exploitation of groundwater has become an increasingly serious phenomenon and evolve into a crisis of groundwater resources, the shortage of which is now an important global issue. Energy is the foundation of economic development. The proportion of coal is very high in China’s energy mix because of China’s abundant coal deposits and shortage in petroleum and gas reserves. Open-pit mining has the advantages of high output, high safety coefficient and mechanized production. However, with the huge economic benefits that the coal mining
industry brings to the mining areas comes also the impact on the ecological environment of the mining area. Open-pit coal mining will particularly have an impact on groundwater. Groundwater drainage in open-pit coal mining will cause groundwater disturbance\cite{1, 2}, resulting in the change of groundwater flow near the stope\cite{3}, and the formation of groundwater cones of depression in the mining pit\cite{4}. A downward trend in groundwater level has been found through long-term observation of groundwater in open-pit mines in arid areas\cite{5, 6}. At present, the observation of groundwater in open-pit coal mines is mainly based on manual observation by long hydrological observation holes. The impact of coal mining in open-pit mines on groundwater can be analyzed and studied through observations\cite{7}. However, the research on the impact of open-pit coal mining on groundwater in severe cold regions is not systematic enough. Therefore, conducting automatic monitoring of groundwater to study the characteristics of the impact of open-pit coal mining on groundwater through establishing a three-dimensional observation network for groundwater in open-pit mines is of great significance in ecological restoration.

2. Overview of the Mining Area

Baorixile Open-pit Mine is located in Baorixile Town (Figure 1), Prairie Chenbarhu Banner, Hulun Buir City in northeastern Inner Mongolia, with an annual output of raw coal of 35 million tons. A group of coal mines are distributed around the Baorixile open-pit mine, forming a mining area with Baorixile open-pit mine in the center. The mining area is 30 km long from east to west, 10 km wide from north to south, and covers an area of 300 km². The hydrogeological unit where the mining area is located is 80 km long from east to west, 25 km wide from north to south, and covers an area of 2000 km².

The topography of the study area is high in the east and low in the west, with an altitude ranging between 600-750 m. The Hailar River in the south is the main river in this area, and the Dongdagou River in the east flows into the Hailar River from north to south. The Mergel River runs from north to west and flow into the Hailar River in the west.

The mining area belongs to arid and semi-arid areas, with very cold winters. The lowest temperature can reach down to -47°C, and the annual average temperature is -1.9°C. The precipitation range is 124.5-619.1 mm(Figure 1), and the average precipitation is 352.3 mm, which has a tendency to decrease year by year. The evaporation range is 996.9-1582.7 mm, and the average evaporation is 1205.9 mm, and there is a trend of increasing year by year.

The main strata in the mining area are Cretaceous (K) and Quaternary (Q), and the coal-bearing stratum is Cretaceous Damoguaihe Formation (K₁d), in which there are three main mineable coal layers, which are named No. I, No. II and No. III coal seams from top to bottom. The aquifers are mainly Quaternary submerged aquifers and Cretaceous confined aquifers (Figure 3). The lithology of Quaternary submerged aquifers is mainly gravel; and for Cretaceous confined aquifers the lithology are mainly conglomerate and sandstone, composed primarily of coal seams with developed fissures and clastic rocks of roof and floor; the lithology of the aquifers is mainly mudstone and siltstone.

Since the operation of Baorixile Mine started in 2001 (Figure 4), there has been an inverse correlation between raw coal production and drainage volume.
Figure 1. Geographical location map of the study area.

Figure 2. Change curve of annual precipitation and evaporation in study area.
3. Groundwater data acquisition method

For the collection of groundwater data, the groundwater observation network was firstly designed and constructed with the open-pit stope as the center. Hydrological observation holes were arranged in radiating shape on the horizontal surface to carry out
layer-specific observation on the Quaternary submerged layer and coal seam confined aquifers, to achieve long-term monitoring of groundwater in different positions and different aquifers. The figure shows the actual layout of the groundwater observation network of the Baorixile open-pit mine (Figure 5). The observation network is centered around the open-pit mine. There are 20 hydrological boreholes on the horizontal surface, including 11 observation wells for Quaternary aquifers and 9 coal seam aquifer observation wells.

After each hydrological observation hole was completed, the construction of automatic groundwater monitoring wells was carried out and the automatic groundwater monitoring equipments were installed in each observation well. Then the configuration of groundwater data collection and transmission time were set with an interval of 12 hours. The data transmission were done via wireless network to realize the automatic collection of groundwater data.

Figure 5. The layout of the borehole design of the groundwater automatic observation network in the open-pit mining area

4. Results and Discussion

4.1. Spatial distribution characteristics of water level under coal mining disturbance

4.1.1. Spatial distribution characteristics of water level in submerged aquifers under the disturbance of coal mining

From the contour map of groundwater in the submerged aquifers (Figure 6) it can be seen that the flow direction of groundwater in the Quaternary aquifer is mainly from northeast to southwest. In the mining area, the isoline density increases, the hydraulic gradient increases, and the groundwater level drops significantly, forming a cone of depression with a central groundwater level of 570 m.
4.1.2. Spatial distribution characteristics of water level in confined aquifers under coal mining disturbances

From the contour map of groundwater in No.1 aquifer (Figure 7), it can be seen that the flow direction of groundwater is generally from northeast to southwest. In the mining area, the isoline density increases as it moves closer to the mining pit, and a cone of depression is formed with a central groundwater level of 535 m.

Figure 6. Quaternary aquifer groundwater contour map under open pit mining conditions (2020)

Figure 7. Contour map of groundwater in coal seam confined aquifer after open pit mining (2020)
4.2. Radius and scope of groundwater temporal and spatial disturbance before and after open-pit coal mining

4.2.1. Spatial distribution characteristics of water level in coal seam confined aquifers before open-pit coal mining

In order to study the characteristics of groundwater disturbance after open-pit mining, the groundwater level data of the coal seam confined aquifer before the open-pit mining were collected(1985). Since the coal mine was not yet developed at that time, the data can be used as the initial value of the groundwater level. From the contour map of the groundwater flow field before mining (Figure 8), it can be seen that the groundwater flows mainly from east to west. The groundwater level in the mining area ranges between 595 - 620 m. The water flow field is mainly controlled by the topography and geomorphology.

![Figure 8. Contour map of groundwater in coal seam confined aquifers before open-pit mining (1985)](image)

4.2.2. Disturbance radius and range of groundwater spatial distribution before and after open-pit coal mining

The disturbance radius and range of groundwater disturbed by open-pit coal mining were obtained according to the groundwater flow field before and after mining(Table 1). The maximum drawdown depth of water level in the mine area is 60m. The largest affected area is 200 km², mainly located in the mining area, which accounts for 66.7% of the mining area and 10% of the study area.

| Groundwater drawdown(m) | Influence radius(km) | Influence area (km²) |
|-------------------------|----------------------|----------------------|
| 5                       | 4.0-8.0              | 50-200               |
| 10                      | 3.5-7.5              | 38-176               |
| 20                      | 3.5-7.0              | 38-153               |
| 30                      | 3.0-6.0              | 28-113               |
| 40                      | 2.5-3.5              | 20-39                |
| 50                      | 2.0-2.5              | 12-20                |
| 60                      | 1.5-2.0              | 7-12                 |
4.2.3. Analysis of influencing factors of groundwater disturbance in open-pit coal mining

1) The relationship between groundwater level and coal mine drainage under disturbance of open-pit coal mining

Taking the M5 observatory as an example, the correlation curve between the monthly average groundwater level and drainage volume from January to December 2020 was analyzed (Figure 9). The results show that there is a certain negative correlation between the groundwater level and the drainage volume, and the $R^2$ value reaches 0.9316. With the increase of the drainage volume, the groundwater level shows a downward trend.

Figure 9. Correlation curves of groundwater level and drainage volume at M5 observation station from January to December 2020.

2) The relationship between the water level drawdown and the distance to the coal mine under the disturbance of open-pit coal mining

Taking M1, M2, M3, M4, M5, M6, and M7 observation wells as examples, the correlation curve between the drop of water level and the distance to the open-pit mine was analyzed (Figure 10). The results show that the drop of groundwater level is negatively correlated with the distance to the open-pit mine, and the $R^2$ value reaches 0.942. It can be seen that the closer the distance to the open-pit mine is, the greater is the drop of groundwater level in the observation well, indicating that drainage is an important factor affecting groundwater water resources and that the groundwater resources in different locations in the mining area are affected by different degrees, which is inversely proportional to the distance to the coal mine, i.e., the closer the area is to the open-pit coal mine, the greater the impact of coal mining on groundwater resources.

Figure 10. Correlation curve between groundwater drawdown and open-pit coal mine distance in 2020.
4.3. Time series dynamic change characteristics of groundwater level under open-pit coal mining conditions

According to the change characteristics of the groundwater dynamic level curve with precipitation and drainage, the groundwater level change curve can be divided into weather influence type, unaffected type, and mining influence type (Table 2).

Table 2. Genetic types and main characteristics of groundwater level dynamics

| Types of groundwater dynamics | observation well | Main features | typical example |
|------------------------------|------------------|--------------|----------------|
| 1) Precipitation influence type | Q11, Q13, M2 | This type is mainly distributed far away from the open-pit coal mine. The aquifer is deeply buried and the precipitation infiltration conditions are good. It is basically not affected by the drainage. Groundwater level changes with precipitation and the peak groundwater level slightly lags behind the peak precipitation. |  |
| 2) Unaffected type | Q2, Q8, Q9, Q12, M7 | This type is mainly distributed far away from the open-pit coal mines. The groundwater runoff conditions are good and the aquifer is buried deep. It is basically not affected by drainage and precipitation, the groundwater level changes gently, with small annual variation values. |  |
| 3) Mining influence type | Q3, Q5, Q6, Q7, Q10, M1, M3, M4, M5, M6, M8, M9 | This type is mainly distributed in the vicinity of open-pit coal mining areas. The water level of the observation well is greatly affected by the drainage, and when the precipitation increases, the groundwater level drops instead. When the drainage volume is greater than the recharge volume, the groundwater level shows a gradual downward trend and the water level dynamics are typical of consumption type. |  |

4.4. Temporal and spatial disturbance characteristics of groundwater before and after high-intensity mining in open-pit coal mines

Before open-pit coal mining, the groundwater flow field was mainly controlled by topography. The distribution of groundwater was basically consistent with the topography, and the groundwater flow field generally flowed from northeast to southwest. After
the open-pit coal mining, the overburden and rock layers on the coal seam were completely stripped, resulting in the destruction of the aquifer above the coal-bearing stratum, which changed the running state of the groundwater. And under the action of gravity, the mining pits became the new water catchment centers, and the open-pit coal mine drainage became the main factor controlling the groundwater flow field. Drainage of open-pit coal mines is a dynamic and continuous process. With the continuous drainage of aquifers, the groundwater level continues to drop, forming a groundwater depression cone with the mining pit as the center. In the groundwater cone area, the flows of groundwater are changed from the horizontal direction to the vertical, increasing both the hydraulic gradient and the groundwater velocity. The decline of groundwater level is mainly affected by artificial drainage, and secondly by precipitation replenishment. With the expansion in the scale of open-pit coal mining and the non-stop advancement of stope, the outflow of groundwater increases continuously, the groundwater level drops, and the cone of depression becomes larger. When the static reserves of groundwater in the open-pit coal mining area are drained to reach the dynamic reserves, the groundwater depression cone also reaches a dynamic equilibrium, and the groundwater flow field is mainly determined by the topography and the open-pit coal mine drainage combined, instead of being determined solely by the topography.

5. Conclusions

(1) In order to collect groundwater data, a three-dimensional observation network for groundwater was constructed with the stope of the open-pit mine as the center. 20 hydrological observation holes were arranged on in radiating shape on the horizontal surface, including 11 observation wells for Quaternary aquifers and 9 observation wells for coal aquifers. Layered observation of Quaternary aquifers and confined water in coal seams enables long-term monitoring of groundwater in different directions and aquifers.

After each hydrological observation hole was completed, the construction of automatic groundwater monitoring wells was carried out and the automatic groundwater monitoring equipments were installed in each observation well. Then the configuration of groundwater data collection and transmission time were set and The data transmission were done via wireless network to realize the automatic collection of groundwater data.

(2) The spatial distribution characteristics of groundwater level under open-pit coal mining conditions were analyzed, the groundwater flow field diagram before and after mining was drawn, and the variation characteristics of the water flow field under mining conditions were compared and analyzed. After mining, a groundwater falling funnel centered on the mining pit was formed., the maximum drawdown is 60 m, and the maximum influence radius is 8 km. The maximum influence range accounts for 66.7% of the mining area and 10% of the hydrological unit area. The disturbance only occurs in the mining area, and only the groundwater drop funnel is formed in the mining area, which does not change the overall flow field direction of the hydrogeological unit.

(3) The influencing factors of the dynamic change of the groundwater level are analyzed. The change of the groundwater level is mainly affected by the drainage volume and the distance from the mining pit, which is negatively correlated with the drainage volume and the location of the mine. The lower the water level, the greater the drop. The time-series dynamic change characteristics of groundwater level under the condition of open-pit coal mining are analyzed. According to the change characteristics of groundwater dynamic curve, it can be divided into three types (weather influence type, unaffected type and mining influence type). The weather impact type is mainly distributed far away from the open-pit coal mine, the aquifer is buried deep, the precipitation infiltration conditions are good, and it is basically not affected by the drainage and drainage. The observation holes of the affected type are mainly distributed far away from the mining pits of the open-pit coal mine, the groundwater runoff conditions are good, the aquifer is buried deep, and is basically not affected by drainage and precipitation, the groundwater level changes gently, and the annual change value is small; the mining-affected type is mainly distributed
in the vicinity of groundwater open-pit coal mining areas. The water level of the observation well is greatly affected by the drainage, and when the precipitation increases, the groundwater level drops instead. When the drainage volume is greater than the recharge volume, the groundwater level shows a gradual downward trend and the water level dynamics are typical of consumption type.

Therefore it is of great significance for water resources protection and ecological restoration in open-pit coal mines to conduct automatic monitoring of groundwater, and study the influence of open-pit coal mining on groundwater by establishing a three-dimensional observation network of groundwater in open-pit mines.

**Author Contributions:** Conceptualization, data curation, Writing – original draft., Lei CHEN.; funding acquisition, methodology, Wenfeng DU.; investigation, Yunlan HE.; investigation, methodology, Qiangmin WANG.; investigation, Wei ZHAO.; project administration, Zhiguo CAO.

**Funding:** This research was funded by China's National Key Research and Development Program (No. 2016YFC0501102)

**Data Availability Statement:** Not applicable.

**Acknowledgments:** All individuals included in this section have consented to the acknowledgement.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Islam, M.; Van Camp, M.; Hossain, D.; Sarker, M.M.R.; Khatun, S.; Walraevens, K. Impacts of Large-Scale Groundwater Exploitation Based on Long-Term Evolution of Hydraulic Heads in Dhaka City, Bangladesh. Water 2021, 13, 1357, doi:10.3390/w13101357.

2. Zhou, Y.; Dong, D.; Liu, J.; Li, W. Upgrading a regional groundwater level monitoring network for Beijing Plain, China. Geoscience Frontiers 2013, 4, 127-138, doi:10.1016/j.gsf.2012.03.008.

3. Haque, E.; Reza, S.; Ahmed, R. Assessing the vulnerability of groundwater due to open pit coal mining using DRASTIC model: a case study of Phulbari Coal Mine, Bangladesh. Geosciences Journal 2018, 22, 359-371, doi:10.1007/s12303-017-0054-0.

4. Dong, S.; Feng, H.; Xia, M.; Li, Y.; Wang, C.; Wang, L. Spatial–temporal evolutions of groundwater environment in prairie opencast coal mine area: a case study of Yimin Coal Mine, China. Environmental Geochemistry and Health 2020, 42, 3101-3118, doi:10.1007/s10653-020-00544-z.

5. Chunhu, Z.; Dewu, J.; Qiangmin, W.; Hao, W.; Zhixue, L.; Xiaolong, S.; Mingpei, L.; Shaoqiang, W. Water inflow characteristics of coal seam mining aquifer in Yushen mining area, China. Arabian Journal of Geosciences 2021, 14, doi:10.1007/s12517-021-06535-3.

6. Yihdego, Y.; Drury, L. Mine dewatering and impact assessment in an arid area: Case of Gulf region. Environ Monit Assess 2016, 188, 634, doi:10.1007/s10661-016-5542-6.

7. Hosseini, M.; Kerachian, R. Improving the reliability of groundwater monitoring networks using combined numerical, geostatistical and neural network-based simulation models. Hydrological Sciences Journal 2019, 64, 1803-1823, doi:10.1080/02626667.2019.1676429.

8. Wang, S.Q.; Song, X.F.; Wang, Q.X.; Xiao, G.Q.; Liu, C.M.; Liu, J.R. Shallow groundwater dynamics in North China Plain. Journal of Geographical Sciences 2009, 19, 175-188, doi:10.1007/s11442-009-0175-0.