Spatial and Temporal Distribution of Groundwater in Open-Pit Coal Mining: A Case Study from Baorixile Coal Mine, Hailaer Basin, China

Wenfeng Du,1 Lei Chen,1,2 Yunlan He,1 Qiangmin Wang,3 Peiqiang Gao,1,2 and Quansheng Li4,5

1State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology (Beijing), Beijing 100083, China
2College of Geoscience and Surveying Engineering, China University of Mining & Technology (Beijing), Beijing 100083, China
3Xi’an Research Institute of China Coal Technology and Engineering Group Corp, Xi’an 710054, China
4State Key Laboratory of Water Resource Protection and Utilization in Coal Mining, Beijing 102209, China
5National Energy Group Co., Ltd., Beijing 100011, China

Correspondence should be addressed to Wenfeng Du; duwf66@126.com and Lei Chen; chenlei_8971@163.com

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1. Introduction

China is highly rely on the coal, and the proportion of coal in the energy structure will be continuously high [1]. For effective coal production, open-pit coal mining is adopted for their high recovery rate and high safety coefficient [2]. Open-pit coal mining can bring great economic benefits to the mining area; however, it may also induce ecological environment issues, especially in arid and semiarid mining areas [3–9]. Hailaer Basin is an arid and semiarid area, which contains rich coal resources. It is an important base for the integrated development of coal and electricity in China [10]. The carrying capacity of groundwater resources is extremely limited, and the contradiction between groundwater protection and coal development is particularly prominent, especially in opencast coal mines located in grassland areas. Therefore, it is of great significance to study the impact of mining activities on groundwater in arid and semiarid regions.
Open-pit coal mining groundwater drainage can cause groundwater disturbance [9, 11–14], and the existing articles on groundwater in open-pit mines mainly focus on the prediction of groundwater inflow [2, 14–17], groundwater as a disaster-causing factor for the safety evaluation of open-pit mine slopes [18–22], groundwater chemistry [5, 6, 23], and ecological evaluation [3, 4, 23, 24]. There are many articles on the change and prediction of groundwater inflow caused by open-pit mining from the perspective of numerical simulation, such as Soni and Manwatkar [16] used the modflow model to simulate and predict the groundwater inflow and groundwater flow field changes in an open-pit coal mine in India under different mining conditions. Xue et al. [17] used a mining geological model to calculate the groundwater impact under different precipitation levels in the Zhuanlongwan mining area, Inner Mongolia. Zhao et al. [2] used the surfact model to assess the groundwater impact of an opencast coal mine in New South Wales and predicted the inflow of groundwater into the mining area during the entire project mining cycle. Rózkowski et al. [14] used numerical calculation and simulation of groundwater inflow in open-pit mines to formulate a reasonable drainage scheme. Haque et al. [9]
assess the vulnerability of groundwater due to open-pit coal mining using a drastic model. In terms of slope safety, Islam et al. [22] used the fem model to study the stress redistribution caused by mining and the impact of groundwater influx on slope safety. In the chemical change of groundwater in open-pit coal mines, Dong et al. [23] through the groundwater system evolutions in mining area before and after the mining actions of Yimin open-pit coal mine, the interactions between groundwater chemical and its environment was investigated.

In the field of groundwater monitoring in open-pit coal mining areas, through long-term monitoring and analysis of the mining area in Riyadh, Saudi Arabia, Yihdego and Drury [15] found that open-pit mining activities in arid areas resulted in a significant drop in groundwater level. Existing articles on groundwater dynamic observation and data analysis mainly focus on urban groundwater source areas [11, 12, 25–28] and underground coal mining area [29–36], there are few articles about the spatial and temporal distribution characteristics of groundwater, disturbance range, and factors under the condition of high-intensity mining in open-pit coal mines, and the distribution of the diving ecological groundwater level needs to be further studied.

Long-term drainage of groundwater in open-pit coal mining will lead to changes in groundwater flow near the stope [18, 23] and formed groundwater drawdown funnels in the mining pits [13, 15, 29, 37]. Through long-term observation of groundwater, the influence of open-pit coal mining on groundwater can be studied [11], which is helpful for groundwater management and protection [11, 12, 38–45]. Long-term observation of open-pit groundwater in arid areas generally shows a downward trend in groundwater level [15, 46]. At present, the observation of groundwater in an open-pit coal mine is mainly based on manual observation, which is time-consuming, labor-consuming, and error-prone [47]. In the cold and arid area, it is difficult to monitor groundwater due to low temperature in the autumn

Figure 3: The schematic diagram of stratum and aquifer profile in the study area.
and winter. The research on the spatial and temporal distribution characteristics of groundwater under high-intensity mining conditions in cold areas has not been systematically studied. In this paper, through the establishment of a remote three-dimensional observation network of groundwater, the automatic monitoring of groundwater level and temperature and the spatial and temporal distribution of groundwater under high-intensity mining are revealed in Inner Mongolia.
The groundwater disturbance factors are discussed, and the targeted groundwater protection measures are proposed. The result can be of significance for groundwater resources protection and ecological restoration of open-pit coal mines in cold regions.

2. Geological Setting and Coal Mining Activities

The Baorixile open-pit mine (annual output of 35 million tons raw coal) is located in Baorixile town (Figure 1) where it is cold in winter, with the lowest temperature at -47°C and the annual average temperature at -1.9°C. The mining area contains 30 km longitudinally and 10 km latitudinally with a 300 km² mining area. The hydrogeological unit thereby covers about 80 km long from east to west, about 25 km wide from north to south, with an area of about 2000 km².

The topography of the study area is high in the east and low in the west, with an altitude ranging between 600 and 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 flows into the Hailar River in the west.

The mining area belongs to an arid and semi-arid climate with less precipitation and large evaporation. The annual precipitation from 1980 to 2018 is 124.5–619.1 mm (Figure 2), and the average precipitation is 352.3 mm. The precipitation mainly occur in July and August. With global warming and gradual drought, the precipitation in the area is decreasing year by year. From 1980 to 2018, the evaporation range was 996.9–1582.7 mm, and the average evaporation was 1205.9 mm, showing an increasing trend year by year. Evaporation is greater than precipitation, which will reduce surface water to some extent.

The main strata of the mining area are Cretaceous (K) and Quaternary (Q), and the coal-bearing strata are the Cretaceous Damoguaihe formation (K, d). There are three main mineable coal layers, which are named no. I, no. II, and no. III coal seams from top to bottom. At present, the main coal seam of the Baorixile open-pit coal mine is no. I. The aquifers are mainly Quaternary phreatic aquifer and Cretaceous coal bearing rock confined aquifer (Figure 3). The lithology of the Quaternary phreatic aquifer is mainly gravels, and the lithology of the Cretaceous confined aquifer is mainly composed of coal seam with developed fractures, roof, and floor conglomerate and sandstone, which are named coal-bearing aquifer no. I, coal-bearing aquifer no. II, and coal-bearing aquifer no. III from top to bottom. The lithology of the impermeable layer is mainly mudstone and siltstone.

Since the commissioning of the Baorixile mining area in 2001, at first, due to the high groundwater abundance of coal bearing formation, the initial value of artificial drainage of groundwater is relatively large, and the coal production is low. With the continuous groundwater drainage operation, the drainage amount increases first and then decreases. After the completion of the drainage of the static groundwater reserves, the drainage is mainly dynamic reserves, and the drainage amount reaches relatively stable. The coal production gradually increases and then tends to be relatively stable. Raw coal production was inversely proportional to drainage volume (Figure 4).

3. Methodology

3.1. Groundwater Data Acquisition Method. Groundwater data collection is divided into automatic acquisition and manual acquisition. The groundwater level acquisition method in the study area has been used for irregular artificial observation of groundwater before the construction of an automatic observation network. The error is large, and the observation well is few. The cold weather in winter brings difficulties to the artificial long-term observation of groundwater. In order to realize the automatic collection of groundwater data, the three-dimensional automatic observation network of groundwater is designed firstly. This observation network takes the open-pit stope as the center, showing a radioactive distribution, based on hydrogeological conditions, and observes different aquifers. The confined groundwater in the Quaternary phreatic layer and the aquifer layer of coal no. I is observed hierarchically, and the long-term monitoring of groundwater in different directions and aquifers is realized.

Groundwater observation network in the Baorixile open-pit mine is shown in Figure 5. The observation network is centered on an open-pit mine, and 20 hydrological boreholes are arranged on the plane (Table 1), including 11 Quaternary aquifer observation wells and 9 coal no. I bearing aquifer observation wells. After the completion of each hydrological observation hole, the construction of a

| Aquifer | Well | Equipment depth (m) | Distance from open-pit mine (m) |
|--------|------|---------------------|---------------------------------|
| Q1     | 14.96| 10000               |
| Q2     | 28.67| 11000               |
| Q3     | 32.26| 7000                |
| Q4     | 48.39| 4000                |
| Q5     | 50.80| 10000               |
| Q6     | 108.00| 3000               |
| Q7     | 30.42| 4000                |
| Q8     | 34.73| 14000               |
| Q9     | 48.49| 7000                |
| Q10    | 59.96| 4000                |
| Q11    | 120.00| 3000               |
| Q12    | 50.80| 10000               |
| Q13    | 140.00| 3000               |
| M1     | 40.02| 5000                |
| M2     | 59.68| 8000                |
| M3     | 120.00| 11000              |
| M4     | 28.74| 12000              |
| M5     | 108.00| 3000               |
| M6     | 108.00| 3000               |
| M7     | 108.00| 3000               |
| M8     | 108.00| 3000               |
| M9     | 108.00| 3000               |
groundwater automatic monitoring well is carried out. The automatic monitoring equipment for groundwater cold resistance (Figure 6) is installed in each observation well. The acquisition and transmission time of groundwater parameters (groundwater level and groundwater temperature double parameters) is set. The groundwater data is collected every 12 hours and transmitted to the Aliyun server through the internet of things wireless network. The groundwater level data is viewed and downloaded online through the remote monitoring system. This project has been completed in November 2019. The automatic acquisition, wireless transmission, and online remote monitoring of

Figure 6: Groundwater automatic observation network construction process pictures. (a) Workers are observing the groundwater level of herdsmen’s wells. (b) Workers are drilling hydrogeological boreholes. (c) Workers are installing automatic groundwater level observation equipment. (d) Workers are calibrating parameters of automatic groundwater level observation equipment. (e) This is the client interface of the automatic groundwater observation system.
groundwater data (groundwater level and groundwater temperature) under high-intensity mining conditions of open-pit coal mines in cold regions are accomplished.

3.2. Weight Analysis Method of Groundwater Disturbance Factors. Determining the weight of groundwater disturbance factors can help to develop targeted groundwater protection measures [48], this paper uses the analytic hierarchy process (AHP) [49, 50] qualitatively and quantitatively evaluated the index weight [51]. The target was divided into several levels, the factors in each level were compared in pairs to obtain the relative comparison value of any two factors, and then the judgment matrix at each level was constructed. The maximum eigenvalues and corresponding eigenvectors of the judgment matrix at each level are calculated, and the rationality of the element value of the judgment matrix is verified by the consistency test results of the judgment matrix. Finally, the weight value of each factor in the judgment matrix relative to all factors in the corresponding level is obtained after normalization.

3.2.1. Construction of Judgment Matrix. When using AHP analysis, it is necessary to establish a judgment matrix for the same level of indicators by pairwise comparison. The level W contains events \( W_1, W_2, \ldots, W_n \). The expression of judgment matrix is

\[
W = [W_1, W_2, \ldots, W_n],
\]

(1)

\[
W_i = [W_{i1}, W_{i2}, \ldots, W_{ij}, \ldots, W_{im}].
\]

(2)

Among them, \( W_{ij} \) is the relative importance of \( W_i \) to \( W_j \), which is usually expressed by the natural number 1–9 and its reciprocal. The larger the value, the higher the importance of \( W_i \) to \( W_j \). The scale and meaning of the judgment matrix are shown in Table 2.

3.2.2. Calculate the Sum of Feature Vectors and the Corresponding Feature Roots. According to the constructed judgment matrix, the feature vector and feature root are obtained, and the judgment matrix is normalized:

\[
W_{ij} = \frac{W_{ij}}{\sum_{k=1}^{m} W_{ij}} (i, j = 1, 2, 3, \ldots, m).
\]

(3)

The normalized judgment matrix is added by rows to obtain \( \overline{U}_{ij} \):

\[
\overline{U}_{ij} = \sum_{j=1}^{m} \overline{W}_{ij}(i, j = 1, 2, 3, \ldots, m).
\]

(4)

Calculating the maximum eigenvalue of judgment matrix \( \lambda_{\text{max}} \):

\[
\lambda_{\text{max}} = \frac{1}{m} \sum_{j=1}^{m} \sum_{i=1}^{m} W_{ij} \overline{U}_{j}.
\]

(5)

3.2.3. Consistency Testing. Consistency test for constructed judgment matrix. Consistency indicators:

\[
CI = \frac{\lambda - n}{n - 1}.
\]

(6)

The random indicators RI are shown in Table 3. Define consistency ratios:

\[
CR = \frac{CI}{RI}.
\]

(7)

Usually, \( CR < 0.1 \) passes the consistency test.

4. Results

4.1. Distribution of Groundwater Flow Field under Mining Conditions. In order to study the spatial distribution characteristics of groundwater, we draw the groundwater flow field diagram according to the monitoring data of groundwater level in 2020. It can be seen from the groundwater contour map (Figure 7) of the Quaternary phreatic aquifer that the flow direction of groundwater in the Quaternary aquifer is generally northeast to southwest. In the mining area, the contour density increases, the hydraulic gradient increases, and the groundwater level decreases significantly, forming a groundwater drawdown funnel, and the central groundwater level is 570 m. It can be seen from the groundwater

| Scale | Implication |
|-------|-------------|
| 1     | Comparing the two factors, they have the same importance. |
| 3     | Comparing two factors, the former is slightly more important than the latter. |
| 5     | Comparing the two factors, the former is more important than the latter. |
| 7     | Comparing two factors, the former is more important than the latter. |
| 9     | Representing the intermediate value of the above judgment |
| 2, 4, 6, 8 | The scale of factor i versus j is the reciprocal of the scale of factor j versus i. |

| n   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-----|---|---|---|---|---|---|---|---|
| RI  | 0 | 0 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 |

Table 3: Random indicators RI.

Table 2: Judgement matrix scale and its meaning.
**Figure 7:** Groundwater contour map of Quaternary aquifer under open-pit coal mining conditions in 2020.

**Figure 8:** Groundwater contour map of coal I aquifer after open pit mining in 2020.
contour map of aquifer I (Figure 8) that the flow direction of groundwater is generally similar to that of the Quaternary phreatic aquifer, and runoff flows from northeast to southwest. In the mining area, the closer to the pit, the greater the contour density, forming a groundwater drawdown funnel, the central groundwater level is 535 m.

4.2. Variation of Groundwater Flow Field before and after Mining. In order to study the characteristics of groundwater disturbance after coal mining, the groundwater level data of the coal-bearing seam before coal mining in 1985 were collected. At that time, the coal mine had not been developed, and the flow field was mainly controlled by topography. The groundwater level data can be used as the initial value of the groundwater level. From the contour map of the groundwater flow field before coal mining (Figure 9), the groundwater flow east to west as a whole, and the groundwater elevation in the mining area is 595–620 m.

After interpolation of groundwater level data in Figures 8 and 9, the contour map of drawdown (Figure 10) can be obtained. From the diagram, it can be seen that the maximum drawdown of groundwater level in the mining area is about 60 m. Through measurement, the influence radius and range of groundwater disturbance in open-pit coal mining can be obtained (Table 4). The maximum influence radius is about 8 km, and the maximum influence area is about 200 km². The mining affected type mainly occurs in the mining area, and the maximum influence area accounts for about 66.7% of the mining area and 10% of the research area.

4.3. Temporal Variation of Groundwater Level. According to the groundwater level data of groundwater automatic monitoring network in 2020, the variation curve is plotted. Combined with the fluctuation of the groundwater level curve and the variation of precipitation and drainage, the variation curve of the groundwater level can be divided into precipitation affected type, unaffected type, and mining affected type.

4.3.1. Precipitation Affected Type. This type is revealed by the observation wells of Q11, Q13, and M2. The fluctuation of the groundwater level curve of observation wells changes with the change of precipitation (Figure 11). The groundwater level increases after the increase of precipitation and decreases after the decrease of precipitation. The peak value of groundwater level lags slightly behind the peak value of precipitation and is less affected by drainage. It is mainly distributed in the area far from the open pit coal mining pit, deep aquifer burial, and good precipitation infiltration conditions.

4.3.2. Unaffected Type. This type is revealed by the observation wells of Q2, Q8, Q9, Q12, and M7. The fluctuation of groundwater level curve of observation wells is gentle
4.3.3 Mining Affected Type. This type is revealed by the observation wells of Q3, Q5, Q6, Q7, Q10, M1, M3, M4, M5, M6, M8, and M9. The fluctuation of groundwater level curve of observation wells is greatly affected by drainage (Figure 13). When the precipitation increases, the groundwater level does not increase but decreases. When the drainage amount is greater than the supply amount, the groundwater level shows a gradual downward trend, and the groundwater level dynamic shows a typical consumption type, which is mainly distributed in the area near the open-pit coal mining area.

4.4 Spatial Variation of Groundwater before and after Coal Mining. 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 measure strata, which changed the running state of the groundwater. And under the action of gravity, the mining pits became the new groundwater catchment center, and the open-pit coal mine drainage became the main factor controlling the groundwater flow field. The 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 groundwater disturbance factor is mainly the influence of artificial drainage, followed by precipitation evaporation. When the drainage groundwater and precipitation evaporation are consistent, the groundwater disturbance at different locations is also affected by the distance between observation wells and mining pits, recharge

(Figure 12), which is basically not affected by drainage and precipitation changes. It is mainly distributed in areas far from open pit coal mining, good groundwater runoff conditions, and deep aquifer burial.

Table 4: Radius and range of groundwater disturbance after open pit mining.

| 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                 |
runo ff conditions, aquifer buried depth, and landform factors. With the expansion in the scale of open-pit coal mining and the nonstop advancement of the 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. Discussion

5.1. Groundwater Disturbance Influencing Factors after Coal Mining. In the process of open-pit mining, the load above the coal seam in the mining area will be completely stripped, the aquifer above the coal series will be drained, and an open funnel area will be formed. The groundwater discharge of the aquifer in the mining area changes from the original natural runoff discharge along the dip direction of the strata to the drainage mode dominated by drainage and artificial discharge. Due to the destruction of the natural recharge, runoff, and discharge conditions of the groundwater in the region, the groundwater recharge in the downstream area is reduced, and the groundwater resources are reduced. The destruction of groundwater resources during open-pit mining is mainly caused by the drainage of groundwater caused by coal mining, which leads to the loss of regional groundwater resources. Drainage volume and precipitation are the direct factors that cause groundwater level fluctuation.

5.1.1. Drainage Volume. In order to study the relationship between drainage volume and groundwater level, taking M5 observation station as an example, the plot of average groundwater level from January to December 2020 and the corresponding monthly drainage volume are drawn. The correlation diagram between the two was established (Figure 14). It can be seen from the diagram that with the increase of drainage, the groundwater level decreases, the decline is large, and the trend is obvious. There is a negative correlation between the two, and $R^2$ value is 0.9316. It indicates that a large amount of groundwater drainage is an important reason for groundwater level decline.

5.1.2. Precipitation. Precipitation is an important source of groundwater recharge, and its seasonal and interannual variations have important driving significance for the dynamic
Figure 13: Time series dynamic curve characteristics of mining-affected groundwater level (M5).

\[ y = -0.0176x^3 + 30.697x^2 - 17828x + 3 \times 10^6 \]

\[ R^2 = 0.9316 \]

Figure 14: Correlation curve between groundwater level of M5 observation well and drainage volume of coal mine (January–December 2020).

\[ y = 1558.4x^2 - 2 \times 10^6x + 6 \times 10^8 \]

\[ R^2 = 0.5666 \]

Figure 15: Correlation curve between groundwater level and precipitation in M2 observation well (January–December 2020).
change of groundwater in the region. Groundwater recharge is directly related to the amount of local precipitation. Precipitation in open-pit mining area is directly converted into water accumulation in mining area. In order to further analyze the variation of groundwater level with precipitation, the groundwater level from January to December in 2020 was used as the abscissa, and the corresponding monthly precipitation was used as the ordinate. The correlation diagram between the two was established (Figure 15). From the diagram, it can be seen that with the increase of precipitation, the groundwater level increased, and the groundwater level decreased after the decrease of precipitation, they were shown to be positively correlated, and the $R^2$ value reached 0.5666.

5.1.3. Other Influencing Factors. In a certain period of drainage and precipitation, the groundwater level at different locations is disturbed differently. In order to study the relationship between groundwater drawdown and pit distance, the groundwater level drawdown of M1, M2, M3, M4, M5, M6, and M7 observation wells is used as the abscissa, and the distance from the pit is used as the ordinate. The correlation diagram between the two is established (Figure 16). It can be seen from the figure that the closer to the open-pit coal mine, the greater the decline of groundwater level in the observation well. The decline of groundwater level is negatively correlated with the distance to the open-pit mine, and the $R^2$ value reaches 0.942. It indicates that drainage is an important factor affecting groundwater resources. The closer to the mining pit, the greater the amount of artificial drainage is, and the greater the disturbance is. The drainage effect of mining pit has different degrees of influence on groundwater resources in different distribution areas, and the magnitude of this influence is inversely proportional to

\[ y = -0.0122x^4 + 1.3508x^3 - 44.266x^2 + 174.7x + 13364 \]

\[ R^2 = 0.942 \]
the distance from the coal mining area, that is, the closer to the open-pit coal mine, the greater the influence of coal mining on groundwater resources.

In addition to drainage volume, precipitation, and observation well location, groundwater disturbance is also affected by other secondary factors such as topography, aquifer depth, and recharge runoff conditions: The lower the terrain is, the more groundwater will be collected, and the more groundwater will be lost after dredging. The shallower the aquifer is, the more easily it will be disturbed. The location with more groundwater recharge and less discharge will be more likely to be disturbed after dredging and drainage. The discharge volume increases, and the groundwater disturbance degree increases.

5.2. Quantitative Analysis of Groundwater Disturbance Factors

5.2.1. Different Influencing Factors Classification. Combined with mining conditions, six factors, namely, artificial drainage (A), precipitation (B), landform (C), distance from mining pit (D), aquifer burial depth (E), and recharge-runoff condition (F), were determined to classify the target layer hierarchically (Figure 17).

5.2.2. Different Influencing Factors Weight. Random consistency ratio CR = 0 < 0.1 (Tables 5, 6, and 7). It shows that the judgment matrix is consistent and does not need to adjust the element value of the judgment matrix.

The analytic hierarchy process (AHP) was used to analyze the influencing factors of each disturbance, and the weight value of each influencing factor in different mining periods (Table 8) was determined. The calculation results show that the artificial drainage weight is 0.5625, which is the main factor, followed by the distance from the mining pit, the weight is 0.1875, the influence weight of precipitation, recharge runoff conditions, aquifer depth, and topography are 0.125, 0.075, 0.025, and 0.025.

5.3. Suggestions on Groundwater Protection in High-Strength Mining Area. According to the characteristics of groundwater disturbance factors and the results of influence weight analysis, artificial drainage is the main factor. Precipitation-evaporation, topography, distance from mining pit, and recharge runoff conditions are secondary factors and objective natural factors. With the climate drought, the decrease of precipitation, and the increase of evaporation, the groundwater level decreased to some extent. By reducing the drainage capacity of groundwater and improving the utilization rate of drainage are the main measure to reduce the disturbance of groundwater in mining area. The excessive drainage of groundwater in mining area can be reduced by stopping drainage vertical wells. After the groundwater gushing from the mining pit is treated as the production and living water for recycling, the abundant water is stored in the underground reservoir constructed under the dump and the ground reservoir after the ecological restoration of the waste land on the dump for standby. These water saving measures have important practical significance for the protection of groundwater in the high-intensity mining of open-pit coal mines and are beneficial to the coordinated development of green mining of open-pit coal mines and the sustainable utilization of groundwater.

6. Conclusions

To address the groundwater dynamic change data under the mining conditions of open-pit coal mines, a three-dimensional automatic observation network of groundwater was constructed to obtain long-term dynamics, with the variation of groundwater flow field under the mining conditions can be compared and analysed, the conclusions obtained are as follows:

(1) The maximum drawdown in the study area was about 60 m and the maximum influence radius of about 8 km. The maximum influence range accounted for about 66.7% of the mining area and about 10% of the hydrological unit area

(2) Apart from mining influenced groundwater variation curves, the precipitation influenced and unaffected groundwater were also recognized. Both of which are distributed in the mining area and beyond, accounting for 33.3% of the mining area. The
precipitation affected type was mainly distributed upstream of the mining area, and the precipitation infiltration conditions were good. The unaffected type was mainly distributed in the north and south of the mining area, far from the mining pit, and the aquifer is deeply buried.

(3) The groundwater was influenced by topography and precipitation before coal mining, of which topography was the most important. After mining, artificial drainage and precipitation were the key factors. Thus, groundwater recycling and protection should be conducted during mining activities.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

Part of the manuscript has been published in the preprint, the link to the preprint is doi:10.20944/preprints202202.0016.v1, although the preprint has been successfully withdrawn.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Funding acquisition and methodology were done by Wenfeng Du; conceptualization, data curation, and writing—original draft were done by Lei Chen; investigation was done by Yunlan He; investigation and methodology were done by Qiangmin Wang; investigation was done by Peiqiang Gao; project administration was done by Quansheng Li.

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References

[1] H. P. Xie, L. X. Wu, and D. Z. Zheng, “Prediction on the energy consumption and coal demand of China in 2025,” Journal of China Coal Society, vol. 44, no. 7, pp. 1949–1960, 2019.

[2] L. Zhao, T. Ren, and N. Wang, “Groundwater impact of open cut coal mine and an assessment methodology: a case study in NSW,” International Journal of Mining Science and Technology, vol. 27, no. 5, pp. 861–866, 2017.

[3] H. B. Feng, J. W. Zhou, A. G. Zhou et al., “Grassland ecological restoration based on the relationship between vegetation and its below-ground habitat analysis in steppe coal mine area,” Science of the Total Environment, vol. 778, no. 2021, article 146221, 2021.

[4] H. Q. Lian, H. Y. Yi, Y. Yang, B. Wu, and R. Wang, “Impact of coal mining on the moisture movement in a vadose zone in open-pit mine areas,” Sustainability, vol. 13, no. 8, p. 4125, 2021.

[5] J. Liu, D. W. Jin, T. T. Wang, M. Gao, J. Yang, and Q. Wang, “Hydrogeochemical processes and quality assessment of shallow groundwater in Chenzhi coalfield, Inner Mongolia, China,” Environmental Earth Sciences, vol. 78, no. 12, p. 347, 2019.

[6] H. L. Liu, Q. Wu, M. J. Wang, and M. Zhang, “Multivariate analysis of water quality of the Chenzhi Basin, Inner Mongolia, China,” Mine Water and the Environment, vol. 37, no. 2, pp. 249–262, 2018.

[7] M. H. Xia, S. G. Dong, Y. Chen, and H. Liu, “Study on evolution of groundwater-lake system in typical prairie open-pit coal mine area,” Environmental Geochemistry and Health, vol. 43, no. 10, pp. 4075–4087, 2021.

[8] J. Park, E. Kwon, E. Chung, H. Kim, B. Battogtokh, and N. C. Woo, “Environmental sustainability of open-pit coal mining practices at Bagtanuur, Mongolia,” Sustainability, vol. 12, no. 1, p. 248, 2020.

[9] E. Haque, S. Reza, and R. Ahmed, “Assessing the vulnerability of groundwater due to open pit coal mining using DRASTIC model: a case study of Phulbari coal mine, Bangladesh,” Geosciences Journal, vol. 22, no. 2, pp. 359–371, 2018.

[10] Q. Li, “Progress of ecological restoration and comprehensive remediation technology in large-scale coal-fired power base in the eastern grassland area of China,” Journal of China Coal Society, vol. 44, no. 12, pp. 3625–3635, 2019.

[11] M. Islam, M. Van Camp, D. Hossain et al., “Impacts of large-scale groundwater exploitation based on long-term evolution of hydraulic heads in Dhaka City, Bangladesh,” Water, vol. 13, no. 10, p. 1357, 2021.

[12] Y. Zhou, D. Dong, J. Liu, and W. Li, “Upgrading a regional groundwater level monitoring network for Beijing Plain, China,” Geoscience Frontiers, vol. 4, no. 1, pp. 127–138, 2013.

[13] Q. W. Chunhu Zhao, H. Wang, J. Yang, J. Liu, and Y. Zhan, “Analysis of influence of open-pit coal mining on groundwater system and curtain wall protection in grassland area of Northeastern China,” Journal of China Coal Society, vol. 44, no. 12, pp. 3685–3692, 2019.

[14] K. Rózkowski, R. Zdechlik, and W. Chudzik, “Open-pit mine dewatering based on water recirculation—case study with numerical modelling,” Energies, vol. 14, no. 15, p. 4576, 2021.

[15] Y. Yihdego and L. Drury, “Mine dewatering and impact assessment in an arid area: case of gulf region,” Environmental Monitoring and Assessment, vol. 188, no. 11, p. 634, 2016.

[16] A. K. Soni and B. Manwatkar, “Seepage modeling for a large open pit coal mine in India,” Geotechnical and Geological Engineering, vol. 33, no. 4, pp. 997–1007, 2015.

[17] S. Xue, Y. Liu, S. Liu, W. Li, Y. Wu, and Y. Pei, “Numerical simulation for groundwater distribution after mining in Zhanlongwan mining area based on visual MODEFLOW,” Environmental Earth Sciences, vol. 77, no. 11, p. 400, 2018.

[18] S. Jiang, X. Kong, H. Ye, and N. Zhou, “Groundwater dewatering optimization in the Shengli no. 1 open-pit coalmine, Inner Mongolia, China,” Environmental Earth Sciences, vol. 69, no. 1, pp. 187–196, 2013.
[19] A. I. Theocharis, I. E. Zevgolis, A. V. Deliveris, R. Karametou, and N. C. Koukouzas, “From climate conditions to the numerical slope stability analysis of surface coal mines,” *Applied Sciences*, vol. 12, no. 3, p. 1538, 2022.

[20] Y. Hong, Z. Shao, G. Shi, Y. Dou, W. Wang, and W. Zhang, “Freeze-thaw effects on stability of open pit slope in high-altitude and cold regions,” *GeoFluids*, vol. 2021, Article ID 8409621, 10 pages, 2021.

[21] T. Guo, W. Zhou, Z. Li et al., “Optimization of land saving and loss reducing and slope stability variation patterns in open-pit mine,” *GeoFluids*, vol. 2021, Article ID 6620235, 10 pages, 2021.

[22] M. R. Islam, R. Shinjo, M. O. Faruque, H. Shimada, and M. F. Howladar, “Finite element method (FEM) groundwater inflow modeling associated with an unconfined aquifer into the open-pit coalmine of the Phulbari area, NW Bangladesh,” *Arabian Journal of Geosciences*, vol. 9, no. 5, 2016.

[23] S. Dong, H. Feng, M. Xia, Y. Li, C. Wang, and L. Wang, “Spatial–temporal evolutions of groundwater environment in prairie opencast coal mine area: a case study of Yinmin coal mine, China,” *Environmental Geochemistry and Health*, vol. 42, no. 10, pp. 3101–3118, 2020.

[24] Z. Q. Hu, Q. Zhu, Y. Wang, Y. Zhao, and X. Ren, “Modeling associated with an uncon, vol. 9, no. 5, 2016.

[25] Y. M. Liu, H. Wang, Y. G. Wu, Y. Zhao, and X. Ren, “Aquifer response to stream-stage fluctuations: field tests and analytical solution for a case study of the Yangtze River in Wuhan, China,” *Water*, vol. 13, no. 17, p. 2388, 2021.

[26] L. Lin and H. Lin, “Determination of groundwater sustainable yield using a numerical modelling approach for the Table Mountain group sandstone aquifer, Rawsonville, South Africa,” *Hydrogeology Journal*, vol. 27, no. 3, pp. 841–855, 2019.

[27] H. E. Júnior, G. B. Riera, E. Saucedo, and A. Pacheco-Guerrero, “Influence of available data on the geostatistical-based design of optimal spatiotemporal groundwater-level-monitoring networks,” *Hydrogeology Journal*, vol. 27, no. 4, pp. 1207–1227, 2019.

[28] J. Alkhaitib, I. Engelhardt, L. Ribbe, and M. Sauter, “An integrated approach for choosing suitable pumping strategies for a semi-arid region in Jordan using a groundwater model coupled with analytical hierarchy techniques,” *Hydrogeology Journal*, vol. 27, no. 4, pp. 1143–1157, 2019.

[29] Z. Chunhu, J. Dewu, W. Qiangmin et al., “Water inflow characteristics of coal seam mining aquifer in Yushen mining area, China,” *Arabian Journal of Geosciences*, vol. 14, no. 4, p. 278, 2021.

[30] S. Liu, S. Dai, W. Zhang et al., “Impacts of underground coal mining on phreatic water level variation in arid and semiarid mining areas: a case study from the Yushenfu mining area, China,” *Environmental Earth Sciences*, vol. 81, no. 9, p. 269, 2022.

[31] Z. Wang, W. Li, Q. Wang, Y. Hu, and J. du, “Monitoring the dynamic response of the overlying rock–soil composite structure to underground mining using BOTDR and FBG sensing technologies,” *Rock Mechanics and Rock Engineering*, vol. 54, no. 9, pp. 5095–5116, 2021.

[32] W. J. Sun, Q. Wu, H. L. Liu, and J. Jiao, “Prediction and assessment of the disturbances of the coal mining in Kaiyuan to karst groundwater system,” *Physics and Chemistry of the Earth*, vol. 89-90, no. 2015, pp. 136–144, 2015.

[33] Q. Wang, S. Dong, H. Wang et al., “Effects of groundwater table decline on vegetation transpiration in an arid mining area: a case study of the Yushen mining area, Shaanxi Province, China,” *Mine Water and the Environment*, vol. 39, no. 4, pp. 839–850, 2020.

[34] Q. Wu, Y. Liu, X. Wu, S. Liu, W. Sun, and Y. Zeng, “Assessment of groundwater inrush from underlying aquifers in Tunbai coal mine, Shanxi province, China,” *Environmental Earth Sciences*, vol. 75, no. 9, p. 737, 2016.

[35] M. Chi, Z. Cao, Q. Li et al., “Water supply and regulation of underground reservoir in coal mine considering coal-water occurrence relationship,” *GeoFluids*, vol. 2022, Article ID 2892694, 22 pages, 2022.

[36] Z. Wu, T. Xia, J. Nie, and F. Cui, “The shallow strata structure and soil water content in a coal mining subsidence area detected by GPR and borehole data,” *Environmental Earth Sciences*, vol. 79, no. 22, 2020.

[37] B. Pepliński and W. Czubak, “The influence of opencast lignite mining dehydration on plant production—a methodological study,” *Energies*, vol. 14, no. 7, p. 1917, 2021.

[38] M. T. Bhatti, A. A. Anwar, and M. Aslam, “Groundwater monitoring and management: status and options in Pakistan,” *Computers and Electronics in Agriculture*, vol. 135, no. 2017, pp. 143–153, 2017.

[39] H. H. Zhu, Y. A. Dong, L. T. Xing, X. Lan, L. Yang, and Z. Liu, “Protection of the Liuzheng water source: a karst water system in Dawu, Zibo, China,” *Water*, vol. 11, no. 4, p. 698, 2019.

[40] Y. Li, F. Zhang, Z. Han, P. Wang, H. Chen, and Z. Zhang, “Evolution characteristics and influence factors of deep groundwater depression cone in North China Plain, China—a case study in Changzhu region,” *Journal of Earth Science*, vol. 25, no. 6, pp. 1051–1058, 2014.

[41] Z. P. Xu, X. Zhou, R. G. Chen, Y. Shen, Z. Shang, and K. Hai, “Numerical simulation of deep thermal groundwater exploitation in the Beijing plain area,” *Water*, vol. 11, no. 7, p. 1494, 2019.

[42] K. Martens, M. Van Camp, and K. Walraevens, “Quantification of water table dynamics as a reference for impact assessment of ecohydrological enhancement measures in a dune area in Belgium,” *Environmental Earth Sciences*, vol. 73, no. 5, pp. 2223–2240, 2014.

[43] H. H. Li, Y. D. Lu, C. Zheng, X. Zhang, B. Zhou, and J. Wu, “Seasonal and inter-annual variability of groundwater and their responses to climate change and human activities in arid and desert areas: a case study in Yoa oasis, Northwest China,” *Water*, vol. 12, no. 1, p. 303, 2020.

[44] M. Kavusi, A. K. Siuki, and M. Dastoureni, “Optimal design of groundwater monitoring network using the combined election-kriging method,” *Water Resources Management*, vol. 34, no. 8, pp. 2503–2516, 2020.

[45] L.-M. Fan, T. Li, M. Xiang et al., “Effect of coal mining on springs in the Yushenfu mining area of China,” *GeoFluids*, vol. 2018, no. 2018, Article ID 3564360, p. 16, 2018.

[46] M. Hosseini and R. Kerachian, “Improving the reliability of groundwater monitoring networks using combined numerical, geostatistical and neural network-based simulation models,” *Hydrological Sciences Journal*, vol. 64, no. 15, pp. 1803–1823, 2019.

[47] S. Q. Wang, X. F. Song, Q. X. Wang, G. Xiao, C. Liu, and J. Liu, “Shallow groundwater dynamics in North China plain,” *Journal of Geographical Sciences*, vol. 19, no. 2, pp. 175–188, 2009.
[48] Y. Xu, L. Ma, and Y. Yu, “Water preservation and conservation above coal mines using an innovative approach: a case study,” *Energies*, vol. 13, no. 11, p. 2818, 2020.

[49] T. L. Saaty, *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, Mcgraw-Hill, 1980.

[50] M. Uyan, “GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region, Konya/Turkey,” *Renewable & Sustainable Energy Reviews*, vol. 28, pp. 11–17, 2013.

[51] Q. Li and W. Sui, “Risk evaluation of mine-water inrush based on principal component logistic regression analysis and an improved analytic hierarchy process,” *Hydrogeology Journal*, vol. 29, no. 3, pp. 1299–1311, 2021.