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Article

Impact of Coal Mining on the Moisture Movement in a Vadose Zone in Open-pit Mine Areas

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Abstract: Long-term dewatering of groundwater is a necessary operation for mining safety in open-pit coal mines, while extensive dewatering might cause ecological problems due to dramatical changes of moisture movement in the soil, especially in ecological-fragile areas. This paper presents a quantitative methodology to evaluate the impact of the coal mining operation on moisture movement in the vadose zone by taking the Baorixile open-pit coal mine as an example. A long-term in-situ experiments（from 2004 to 2018), laboratory analysis and numerical modelling were conducted to analyse the mechanisms and relationship among the dropping groundwater level, the vadose-zone moistures, and the ecological responses in the grassland area. The experiment data and modelling results suggest that groundwater level dropping during open-pit mining operation has limited influence on the vadose zone, exhibiting a variation of capillary water zone within a depth of 3 m while the vadose zone and soil water zone were at least 16 m deep. The critical evaporation depth of ground water is 8 m. The long-term influence radius of groundwater dewatering is about 2.72 km during the Baorixile mining operation, and the groundwater level change mainly influences the lower part of the intermediate vadose zone and the capillary water zone below 16 m, with little influence on the moisture contents in the soil water zone where the roots of shallow vegetation grow. The results from this study provide useful insight for sustainable development of coal mining in ecological-fragile areas.

Keywords: open-pit coal mine; dewatering; groundwater level; vadose zone; moisture movement; capillary water

1. Introduction

Hulunbuir Grassland, the most concentrated and representative area of temperate grassland in China, includes multiple types of grassland ecosystems. It is not only an important ecological barrier in North and Northeast China [1], but also a main base for the integrated development of coal and electricity in China. Statistics suggest that, the Hulunbuir Grassland degrades at a rate of 2% annually and most of the rivers in the Hulunbuir Grassland area have suffered from flow decline even flow cutoff in recent years [2,3]. Eco-environmental problems have become a major risk, endangering the sustainable development of the mining area and even the ecological security of the entire region [4,5].

Environmental problems related to water in open-pit mines are increasingly arising researcher's interests, in recent years, large efforts have been devoted into studying the consequence of water resources [6-12] and contamination migration [13,14] during open-pit coal mining. Furthermore, ecological issues due to dewater in open-pit coal mining are also becoming attractive to researchers, as suggested by Chu et al [15] the total ecological overburden of open-pit coal mines are 4.31 to 11.36 times that of underground coal mines. Therefore, great progresses of study had been made, in terms of ecological investigation [16-18], assessment [19-22] and management [23-26], corresponding theory model and techniques were also proposed in recent years [27-30], and the influence mechanism had been revealed as the soil moisture change during the water drainage in open-pit coal mining[22,31-33]. These works convince us soil moisture indeed was changed during open-pit coal mining processes. When concerning the impact of soil moisture on the plants near the open-pit coal mines, moisture movement in the vadose zone is a core factor.

Theories and study methods of moisture movement in vadose zones are relatively mature. Such as Darcy's law, Richards flow equation and Philip's non-isothermal flow equation [34], etc. In recent years, progress has been made in the study on the principle of vadose zone moisture movement in different regions and under different environmental conditions [35,36], studies on the changes in moisture in vadose zones caused by coal mining are also showing an increasing tendency [37]. The majority of these studies can be divided into two categories: the movement and adsorption of pollutants in vadose zones, and the moisture movement in vadose zones under soil improvement. It is notable that these studies mainly focus on the influence of water bodies on vadose zone moisture during the process of surface infiltration, at depths of less than 10 m (the depth of shallow vadose zones).

However, for thick and deep vadose zones with below 10 m, research on the influence of deep groundwater level change on the moisture content of the upper vadose zone is quite limited. In the case of open-pit coal mining area, the drainage and dewatering efforts of coal mines further aggravate the drop in groundwater level around the mining area. The water contained in vadose zones serves as an important link between groundwater and surface water and plays a vital role in the water circulation system. Because it disrupts the equilibrium of the initial distribution of soil moisture in a vadose zone, a drop in groundwater level poses a potential threat to the surface ecological environment.

Furthermore, in comparison with coal exploitation in the ecologically vulnerable area of the western grassland, research on the influence of high-intensity mining of open-pit mines in the eastern grassland region on the change in water resource and ecology is limited. The path through coal mining disturbs groundwater resources and the ecological environment can be summarized as "high-intensity mining of the coal, large-scale drainage of the stope, large drop in the groundwater level, change in the vadose zone moisture content, influence on the surface soil and vegetation growth, and then degradation of the ecological environment". The core issue is the influence mechanism and relationship among the coal mining, groundwater level, and change in moisture content in the vadose zone, which is also the basis for analysing the influence of coal mining on the quality of the ecological environment.

Therefore, studying vadose zone moisture movement under the condition of a drop in groundwater level during mining and clarifying the vertical distribution characteristics of vadose zone soil moisture are of great significance for correctly evaluating the influence of coal mining on regional groundwater resources and surface ecology.

2. Study area

2.1. Geographical and hydrological conditions

Baorixile Open-pit Mining Area is located in Hailar District and Chenbaerhu Banner of Hulunbuir city, Inner Mongolia Autonomous Region (see Figure 1). The area has a continental sub-frigid zone climate, with an annual average temperature of -2.6 °C within the range of -48~37.7 °C, an annual average precipitation of 315.0 mm, and an annual average evaporation of 1344.8 mm. The Bao #1 Mine has a production capacity of 20.0 Mt/year and has been in production for 13 years, since 2005. The mining area has a monoclinic structure, with a north-northwest dip direction and a 5-15°dip angle. Within the area, from bottom to top, the Lower Cretaceous Series of the Longjiang Formation, Damoguaihe Formation, and Yimin Formation, as well as the Quaternary System's Holocene series, are the mainly developed strata. The coal-bearing stratum is located in the Damoguaihe Formation of the Lower Cretaceous, where 20 minable coal seams in four minable coal seam groups are developed.

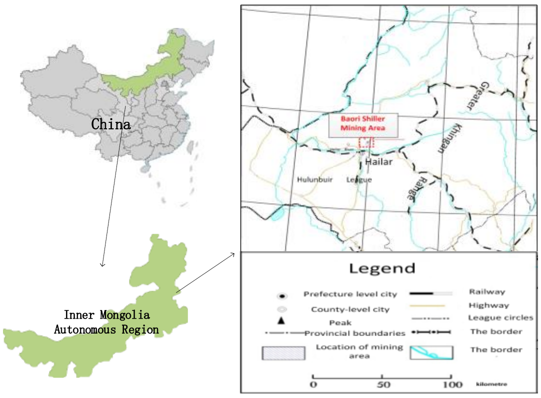

Figure 1. Geographical location map of the study area

Within the mining area, the Quaternary porous water-bearing formation is a relatively stable aquifer affected by mining. The formation is of gravel stratum with a thickness of 17~30 m, which gradually becomes thinner from south to north and from west to east and wedges out to the east of the area. The Quaternary strata in the eastern part of the mining area is not water-bearing. The Cretaceous strata are directly covered by the Quaternary strata, the bottom of which is generally a layer of moraine pebbles, while the top of the coal-bearing strata is composed of mudstone, siltstone and fine sandstone.

2.2. Evolution of groundwater level during the mining period

From 2004 to 2016, the Baorixile Open-pit Mine recorded an annual average production capacity of 20 million tons/year, an annual average stripping capacity of 7.5 million m^3/year, and an annual average water discharge of 3 million m^3/year. In the early stage of dewatering, the water level elevation was 597.35 m, and the water discharged was 14000 m^3/d. In 2004, the groundwater level elevation of the first mining area was 570 m, the dewatering capacity of which was 4900 m^3/d. The dewatering capacity of the stope was 8640 m^3/d in 2010, while the dewatering volume was 2941100 m^3 in 2012. During the same period, affected by the dewatering and drainage of the pit, the groundwater level was negatively correlated with the amount of mining.

3. Study scheme

Physical models and numerical simulation models of the moisture movement in vadose zones are established mainly through field in situ tests, indoor parameter measurement experiments and numerical simulations to quantitatively describe the vertical movement of the moisture in vadose zones during groundwater level fluctuation.

3.1. Field measurements

3.1.1. The lithologic structure of the vadose zone

To elucidate the soil type of the vadose zone in the Baorixile Mining Area, 16 test points are positioned along the north-south and east-west directions, with the cross-section intersection centred in the mining area; then, in situ testing is conducted on the lithological and structural features of the vadose zone in the coalfield. For the locations of the test points, refer to Figure 2.

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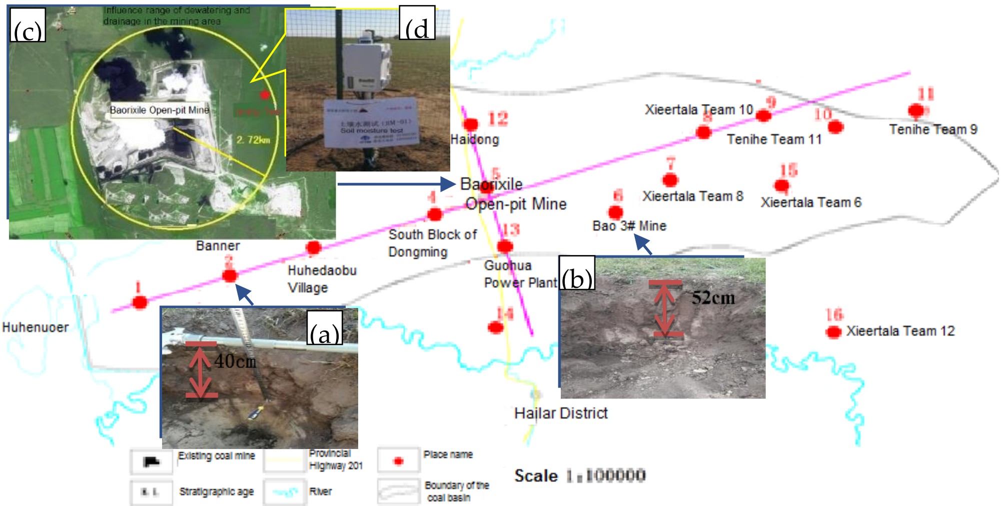


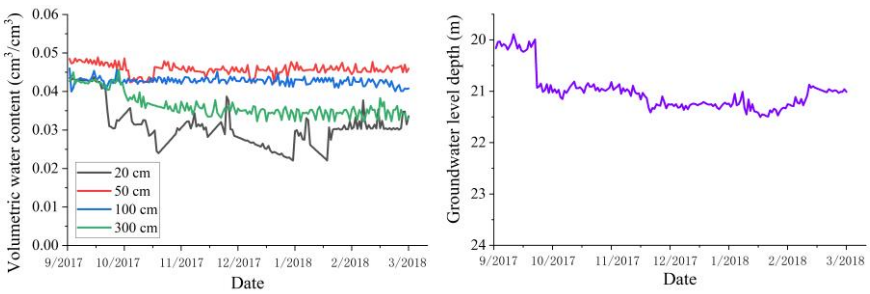
Figure 2. Distribution of the vadose zone lithology test points

The on-site excavation and measurement (see pictures (a) and (b) in Figs. 2) results show that the vadose zone is mainly composed of the upper humus layer and the lower deep sand soil layer, and there is a clear boundary between the two layers. According to the data measured, the thickness of the humus layer is 30~60 cm, with an average thickness of approximately 40 cm.

3.1.2. Water content change along a shallow soil profile

On September 11, 2017, an in-situ test field (N49°24′50.35″, E119°42′34.13″) (see the picture (c) in Figure 2) was constructed in the pasture near the dump site of the mining area. The test field included the selected typical profile, the humus soil thickness of which is 40 cm. Weather, soil moisture and groundwater level data were obtained from September 11, 2017, to March 9, 2018 (180 days in total) (see the picture (d) in Figure 6). Meteorological elements are collected by an automatic weather station installed at the dump site. During the monitoring period, the total precipitation was 1532.1 mm, the daily average net radiation was 4.68 MJ/m², the daily average temperature was -11 °C, the daily average relative air humidity was 68.7%, and the daily average wind velocity was 121.866 km/d.

The soil water content of the vadose zone is measured with EM-50 meters. The 5TM soil water temperature and humidity sensor probes are buried at 0 cm, 20 cm, 50 cm, 100 cm, and 300 cm below the ground. The data are collected every half an hour, and the water content changes obtained are shown in Figure 3.



(a) (b)

Figure 3 Evolution of (a) Soil Moisture Content at Different Depths and (b) groundwater level during the Monitoring Period

The moisture content of shallow soil at a depth of 20 cm varies greatly with time due to the low amount of precipitation and the dominant influence of evaporation during the monitoring period. The soil moisture content at the depth of 50 cm is the greatest and remains stable because of the

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decrease in soil texture and the effect of the local plants. The soil moisture content decreases with increasing depth from 100 cm to 300 cm, and the deeper the soil is, the more stable the water content. Generally, the soil moisture content increases with increasing depth. The groundwater level monitoring data are collected from the mine's groundwater level observation wells at a frequency of once a day. As it is plotted in Figure 3, from the establishment of the in-situ test field to October 3, 2017, the groundwater depth fluctuated around 20 m. Due to large-scale drainage activity at the Baorixile Mine in early October, the groundwater level in the study area lowered. On October 5, the groundwater level was 21 m, a drop of 1 m. The groundwater level continued to lower in December 2017 and fell to 21.5 m on January 20, 2018; it rose again to 21 m in early March 2018.

3.2. Measurement of the soil parameters of a vadose zone

To quantitatively analyse the moisture movement in the vadose zone in the study area, measurement of the basic parameters of the vadose zone soil is required, including the soil bulk density, saturated hydraulic conductivity and soil porosity. The soil samples were analysed for grain composition and then classified according to the international soil texture classification standard [38]. The soil present at depths from 0 cm to 40 cm is a silt loam, and that below 40 cm is loamy sand.

3.2.1. Dry soil densities

The cutting-ring method was adopted to measure the soil bulk density of stratified sections [39]. The drying method is adopted to measure the stratified soil samples [40]. For each soil type, 4 groups are measured and averaged. According to the results obtained, the saturated moisture content of the silt loam is 0.4753 cm^3, and that of the loamy sand is 0.4214 cm^3.

3.2.2. Saturated hydraulic conductivity

The variable head seepage method is adopted [41] to measure the saturated hydraulic conductivity k of the silt loam and loamy sand, and the average permeability coefficient k_{20} of the two types of soil is calculated following

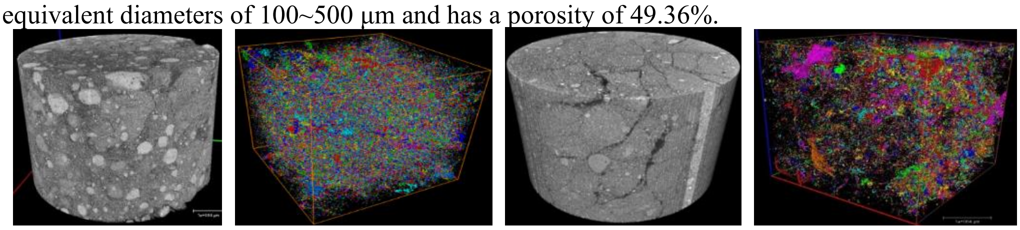
$$k = 2.3\frac{aL}{A(t_2 - t_1)}\log\left(\frac{h_1}{h_2}\right) \tag{1}$$

$$k_{20} = k_T\frac{\eta_T}{\eta_{20}} \tag{2}$$

where a is the sectional area of the variable head tube (cm^2); L is the height of the sample (cm); A is the sectional area of the sample (cm^2); t_1 and t_2 are the starting time and the ending time of the head reading (s); and h_1 and h_2 are the starting water head and the ending water head (cm); η_T is the hydrodynamic viscosity coefficient (kPa·s) at T °C; and η_{20} is the dynamic viscosity coefficient (kPa·s) of water at 20 °C. η_T/η_{20}, the dynamic viscosity coefficient ratio, is derived from related literature[42].

3.2.3. Porosity of soil

To grasp the microstructure of the soil along a typical profile more comprehensively and precisely, digital core analysis technology is used on the soil samples, 3D extraction of the soil pores is carried out with the threshold segmentation method (Figs. 4), and the equivalent pore diameters in the silt loam and loamy sand are determined. The silt loam mainly contains fine pores with an equivalent diameter of 100 μm and has a porosity of 41.87%. The loamy sand contains pores with equivalent diameters of 100~500 μm and has a porosity of 49.36%.



(a) (b) (c) (d)

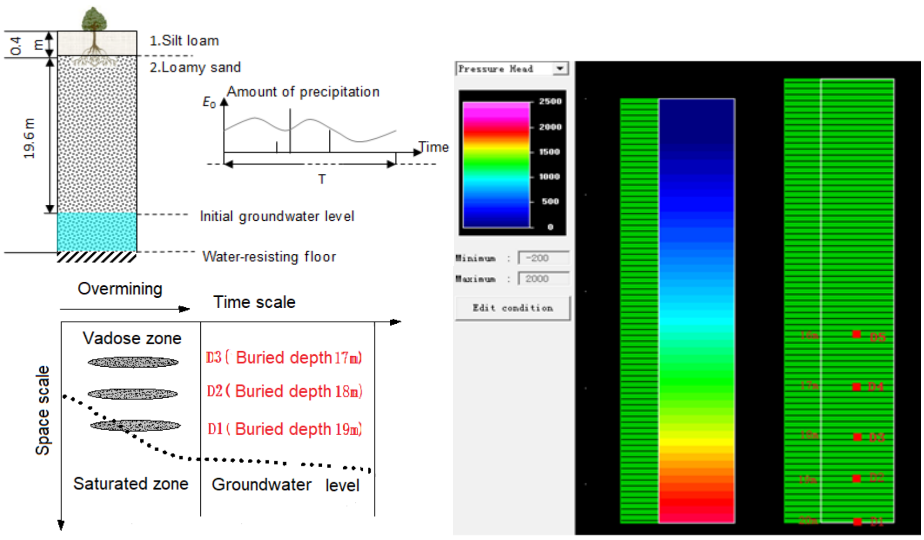
Figure 4. Scanning pictures of (a) Silt Loam (c) Loamy Sand and 3D Extraction of the Pores and Cracks in the (b) Silt Loam and (d) Loamy Sand

3.3. Numerical Simulation of the Moisture Movement in a Vadose Zone

During coal mining, the influence radius of dewatering and drainage in the studied stope is approximately 2.72 km. According to the data monitored on site, the groundwater level near the boundary reaches 20-21.5 m, ranging within 1.5 m; these fluctuations are obvious and due to seasonal changes. With a thickness of approximately 20 m, the vadose zone in the mining area is deep. To quantitatively study the influence of groundwater level changes on the moisture movement in the vadose zone, a vertical one-dimensional numerical simulation model is considered. The model is solved using the Hydrus-1D finite element calculation model, Since the studied area is about 2.72 km, which is large enough to ignore the transverse water recharge, and as demonstrated by Mao et al. [26], moisture movement in vadose zone is mainly triggered by evaporation, thus 1-D modelling is close to 3-D modelling if the main concern is on the vadose zone.

3.3.1. Generalized and numerical model setup

According to the previously discussed measured results, the lithologic structure of the typical vadose zone profile is generalized into two layers with a total thickness of 20 m. The upper layer is a silt loam layer with a thickness of 0.4 m, the lower layer is a loamy sand layer with a thickness of 19.6 m, and each soil medium is homogeneous. The existence of the silt loam layer not only weakens the effect of water evaporation in the vadose zone but also accelerates the water infiltration after rainfall. Therefore, surface runoff will generally not be guided into in the vadose zone in the study area during rainfall. Due to the low rainfall and strong evaporation in this grassland area, the moisture in the vadose zone is mainly exchanged vertically, and its lateral flow can be neglected. The generalized model is shown in Figure 5(a).



(a) (b)

Figure5. Schematic diagram of the (a) generalized model of the study area and (b) its numerical model

The model is built based on the typical profile generalization results and parameters for calculations in two periods. The first period is the mining period (2004-2016), and the corresponding study is primarily focused on the changes in soil moisture content in the middle strip of the upper part of the capillary water belt, that is, the layer between the burial depths of 17 m and 19 m. The saturated moisture content can be taken as the Category I boundary of the lower boundary of the vertical motion of the soil moisture. The upper boundary condition is set as periodic rainfall. Three observation points are set at the burial depths of 17 m, 18 m, and 19 m to monitor the changes in soil moisture content. The second period is the monitoring period (from September 11, 2017, to March 9, 2018), which is divided into three phases of 60 days each. The discretization setting of the soil profile is dissected into a total of 81 nodes at 25 cm equal intervals, and 5 observation points are set at the burial depths of 16 m, 17 m, 18 m, 19 m, and 20 m (as shown in Figure 5(b)) to monitor the changes in soil moisture content.

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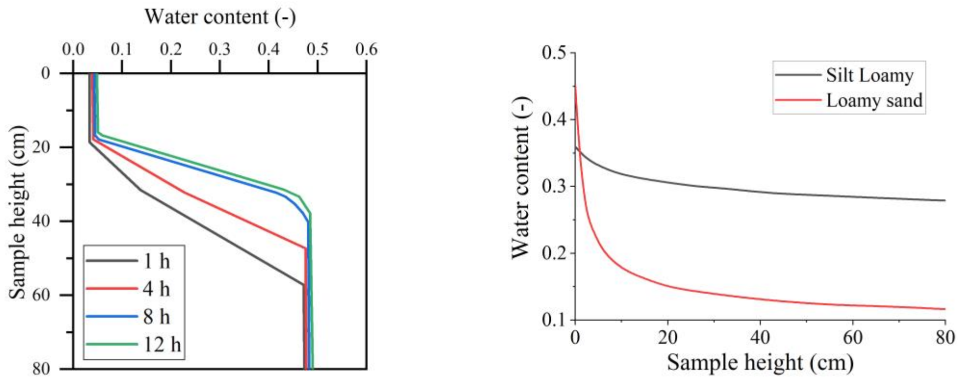
3.3.2. Governing equations

The Van-Genuchten model is used to calculate the parameters of the soil moisture in unsaturated media, and the unsaturated permeability coefficient is predicted in the form of water retention curve. It is assumed that the groundwater level at the bottom of the soil profile remains unchanged during a short period and that the water evaporation intensity of the soil surface is 0. After the moisture distribution in the soil reaches a steady state, the moisture content data monitored at the depths of 20 cm, 50 cm, 100 cm and 300 cm along the profile are fitted. According to the water retention tests as that of reference of [41], hydraulic conductivity tests, saturated soil water content tests and associated with numerical revision of Hydrus 1D, the parameters are summarized as Table 1. The soil water retention curves obtained are shown in Figure 6(a) and the fitted curves by parameters in Table 1 are shown in Figure 6(b).



(a) (b)

Figure 6. Results of (a) water retention test of loamy sand and (b)the Fitted curves of the Soils

3.3.3. Definite conditions

The initial conditions are set according to the field-measured moisture content. The upper boundary of model is set as the atmospheric boundary under natural conditions, which are mainly influenced by rainfall, evaporation and crop transpiration, and irrigation is ignored in this problem. The amount of precipitation is directly measured by the automatic weather station in the area, and the crop transpiration is calculated with the help of the measured meteorological data and the Penman formula. The lower boundary is described with the pressure head indicated by the groundwater level. The fluctuation in the water level at an observation hole is used to represent the change in groundwater level and to select the deep drainage boundary. The bottom flux of the model is selected according to the fluctuation of the groundwater level.

3.3.4. Determination of the numerical parameters

Based on the previously measured parameters of the soil profile, the Marqualdt-Levenberg parameter optimization algorithm in Hydrus is used for the inversion [43] and to obtain the empirical parameter of the vadose zone's soil moisture characteristics. The inversion data are sourced from the moisture content data measured from September 11, 2017, to March 9, 2018 (180 days in total), based on which θ_r (cm^3/cm^3), the residual moisture content of the two layers, and the empirical parameter α (cm^{-1}) are obtained. The final characteristic parameters of soil moisture are shown in Table 1 below.

Table 1. Characteristic Parameters of Soil Moisture

Soil Depth /cm	Residual Moisture Content θ_r /$cm^3 \cdot cm^{-3}$	Saturated Moisture Content θ_s/$cm^3 \cdot cm^{-3}$	Empirical Parameter α/cm^{-1}	Curve Shape Parameter n	Hydraulic Conductivity K_s/$cm \cdot d^{-1}$
0-40	0.043	0.4753	0.03028	1.39	9.623
40-2000	0.061	0.4214	0.005692	2.07	362.2

4. Moisture Movement in a Vadose Zone during the Mining Period

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In soil science, the vadose zone is divided into three belts from the surface to the water table: the soil water belt (capillary suspended water zone), the intermediate vadose belt, and the capillary water belt [44]. To compare the moisture movement and the range of capillary water rise under different groundwater extents, the variation in soil moisture content is chosen to reflect the vadose zone's moisture movement. The numerical simulation scheme is designed as follows:

(1) Based on years of weather data and groundwater level variation characteristics, the moisture movement in the typical profile of the vadose zone is simulated during the coal mining period (2004-2016). The soil moisture movement in the intermediate vadose belt, close to the capillary water belt, during the continuous lowering of the groundwater level is analysed under the mining conditions.

(2) Based on the in-situ test data, the moisture movement in the typical profile of the vadose zone during the monitoring period (from September 11, 2017, to March 9, 2018) is simulated. The influence of groundwater level drop on the soil moisture contents in different vadose zone belts is analysed, the maximum range of capillary rise is determined, and the critical depth to water, which can form a hydraulic relationship with the soil water belt, is simulated and predicted.

4.1. Groundwater level and Vadose Zone Moisture Change during the Mining Period

Combined with the background of coal mining, the long-term moisture movement in the vadose zone under the conditions of periodic rainfall and a deep burial depth is simulated for the typical soil profile to obtain the influence of the long-term drop in the groundwater level on the moisture movement in different areas of the vadose zone.

The changes in soil moisture content at different burial depths during the mining period are shown in Figure 7. The moisture content of the entire vadose zone and its changes are closely related to the scale of coal mining in previous years. From 2004 to 2010, the groundwater level showed a downward trend, and the height of the capillary water belt and the content of soil moisture in the intermediate belt decreased. The groundwater level rebounded slightly only after the coal mining scale was decreased in 2014.

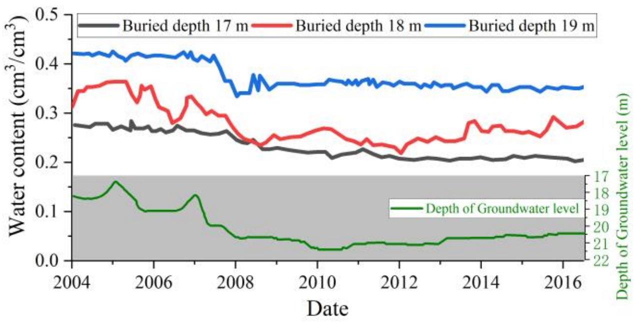

Figure .7 Changes in soil moisture content at different depths during the mining period

Regarding the changes in groundwater level, the average annual yield of the Baorixile Mine from 2004 to 2016 is 20 million tons. The initial water balance of the vadose zone was broken by the lowering of the groundwater level, which occurs at an average rate of 0.2 m/year. The change in soil moisture content with the lowering of the groundwater level were measured at three observation points with different burial depths: (1) At the burial depth of 17 m, the change in soil moisture content was small. When the groundwater level dropped by 3 m in 2010, the soil moisture content dropped from 0.28 cm^3/cm^3 to 0.25 cm^3/cm^3, a drop of 0.03 cm^3/cm^3. When the groundwater level dropped by 2.8 m in 2007, the soil moisture content at 1 m, 2 m, and 3 m above the capillary water belt decreased by 0.09 cm^3/cm^3, 0.06 cm^3/cm^3, and 0.03 cm^3/cm^3, respectively. (2) At the burial depth of 18 m, the soil moisture content decreases with a certain fluctuation, and the maximum height of the capillary water belt was close to 2 m. When the groundwater level lowered by 2.8 m in 2007, the soil moisture content fluctuated between 0.3 cm^3/cm^3 and 0.35 cm^3/cm^3. When the groundwater level lowered by 3 m in 2010, the soil moisture content at this point was 0.28 cm^3/cm^3, i.e., a drop of 0.8 cm^3/cm^3. (3) At the depth of 19 m, when the groundwater level lowered by 2.8 m in 2007, the soil moisture content decreased from 0.43 cm^3/cm^3 to 0.34 cm^3/cm^3, and the maximum height of the capillary water belt dropped below 1 m, the largest drop recorded.

4.2. Groundwater Groundwater Level and Vadose Zone Moisture Change during the Monitoring Period

The soil moisture contents of the profiles at the nodes (as shown in Table 2) are numerically calculated. The four-day meteorological data are used as the upper boundary input data, and the

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monitored value of the topsoil moisture content is used as the initial moisture content. The lower boundary conditions are set according to the depth changes in the groundwater level. The zonality of the vadose zone is determined, and the influence of the lowering of the groundwater level on the soil moisture content is analysed according to the vertical distribution characteristics of the soil moisture.

Table 2 Comparison Table for the Groundwater Depths and Capillary Water Belt Heights at Different Times

Time	2017.9.13	2017.10.5	2018.1.20	2018.3.1
Groundwater depths /m	20	21	21.5	21
Height of capillary water belt /m	1.2	0.8	0.75	0.78

The simulation results are shown in Figs. 8. Based on the changes in soil moisture content with depth, the ranges of the vadose zone's three belts (the soil moisture belt, the intermediate vadose belt, and the capillary water belt) are determined:

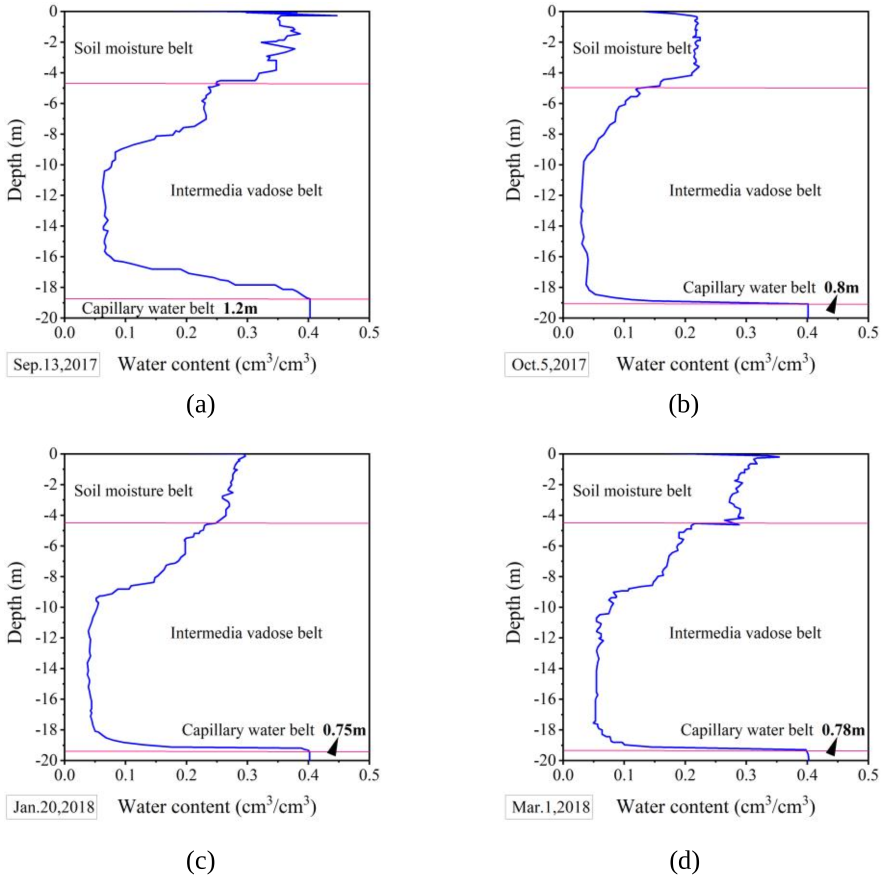

Figure 8. Simulated Value of Soil Profile's Moisture Content on (a)Sep. 13, 2017, (b) Oct. 5, 2017, (c) Jan. 20, 2018 and Mar. 1, 2018

(1) As the soil moisture content begins to decrease significantly at a depth of 4 m below the surface, the area from the surface to a depth of 4 m can be classified as the soil moisture belt. In this belt, the variation in soil moisture content decreases with increasing depth, and the deeper the depth is, the smaller and more stable the moisture. From November to March, as the temperature decreases, the temperature of the shallow vadose zone decreases until the soil moisture is frozen, during which time the soil moisture content is significantly reduced and more stable. In March, the moisture content of the soil moisture belt increases significantly, mainly due to the melting of frozen soil and surface snow.

(2) The area between the burial depths of 4~18.8 m is classified as the intermediate vadose belt. In this belt, the soil moisture content gradually decreases from 4 m to 9 m and remains basically stable from 10 m to 16 m; its hydraulic connection with deep groundwater becomes weak. From the depths of 16 m to 19 m, the soil moisture content increases to a saturation state, making this area the capillary water belt. The soil moisture content is greatly affected by the variation in the capillary water belt's height. At a depth of 16 m, when the height of the capillary water belt is

reduced by 0.4 m, the soil moisture content drops from 0.08 cm3/cm3 to 0.06 cm3/cm3, indicating that the soil moisture close to the capillary water belt shifts downwards as a whole with the lowering of the groundwater level. The soil moisture content of the intermediate vadose belt within the depths of 4.2 m to 16 m is close to the residual water content of the soil and is basically stable. It can be inferred that the change in groundwater level has little effect on the moisture movement of the shallow intermediate vadose belt and the soil moisture belt above the depth of 16 m, this depth can be logically regarded as the critical depth that the dewatering of coal mining can be influenced.

(3) The bottom of the vadose zone is a groundwater-supported capillary water belt with a soil moisture content of approximately 0.4 cm3/cm3.Affected by the drop in groundwater level, the height of the capillary water belt varies from 0.75 m to 1.2 m. On September 13, 2017, the groundwater level reached 20 m, and the height of the capillary water belt was 1.2 m. After the groundwater level was reduced by 1 m due to large-scale dewatering and drainage in the mining area, the height of the capillary water belt dropped by 0.4 m to approximately 0.8 m. On January 20, 2018, the groundwater level continued to drop to 21.5 m, but the height of the capillary water belt stabilized at 0.75 m, a drop of 0.05 m. On March 1, 2018, the groundwater level returned to 21 m, and the height of the capillary water belt increased to 0.78 m, an increase of 0.03 m.

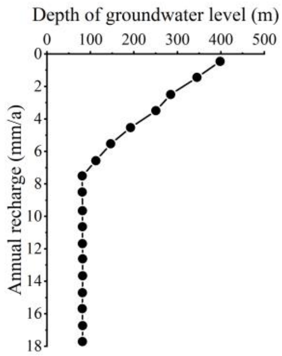

Figure 9. Variation in Groundwater Evaporation Recharge with the Groundwater depth

Based on the calculated results, the correlation curve between the vertical groundwater extent and the recharge amount is plotted in Figure 9. When the depth of the groundwater level is 8 m, the recharge drops from 421 mm/a to 100 mm/a and then remains unchanged, indicating that the recharge does not change as the groundwater level extends deeper than 8 m. Therefore, the critical evaporation depth of the typical profile of the vadose zone is 8 m.

5. Conclusions

Through the investigation of the hydrogeology and lithologic structure of the vadose zone in the Baorixile Mining Area, according to the analysis on the data of in-situ test and numerical modelling results, the following conclusions are drawn:

(1) The vadose zone in Baorixile open-pit coal mine area has obvious zonality. The soil moisture belt within a burial depth of around 4 m; the capillary water belt between depths of about 0.75 m and approximately 1.2 m.

(2) When the groundwater depth is greater than 8 m, it no longer is hydraulically connected with the surface's soil moisture. The drop in groundwater level has little effect on the moisture content of the vadose zone at depths of 16 m and above. The lower part of the intermediate vadose belt is significantly affected by the height variation in the capillary water belt. When the hydraulic connection between the soil and the water surface disappears, the soil moisture content will decrease by an average of about 15%.

(3) During the long-term variation in moisture content in the middle and lower parts of the deep vadose zone caused by the mining-induced drop in groundwater level, the groundwater level dropped by an average of about 0.2 m per year, the height of the capillary water belt decreased by 1 m, and the intermediate vadose belt affected by the capillary water belt was within of 3 m from the surface.

(4) The groundwater level stabilizes under long-term mining conditions and has little influence on the moisture movement in the vadose belt. In addition, the groundwater level change caused by the mining conditions mainly influences the lower part of the intermediate vadose belt and the capillary water belt below the burial depth of 16 m but has little effect on the growth of shallow vegetation. The moisture content of the soil moisture belt is mainly affected by the changes in atmospheric precipitation at the upper boundary.

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