Based on the Numerical Simulation Analysis of the Impact of Coal Mining in the Land Conservation Area

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Abstract

As China pays more attention to the protection of water resources, there are overlapping areas between the planned reservoir conservation area and planned coal mine field. In the coal mining process, a water-conducting fracture zone is formed after the roof of the goaf is damaged, and cracks also generated on the surface of the mining area. In order to study the effect of coal mining on the recharge of surface water into the reservoir in the land conservation area, FLAC3D and Visual MODFLOW are used to simulate the development law of water-conducting fracture zone and surface subsidence cracks in the roof of the coal seam after coal mining in the land conservation area of the reservoir. Prediction and analysis on the change of the reservoir recharge capacity after coal mining in the land reserve are conducted. The results show that the maximum growth height of the water-conducting fracture zone in the overlying strata of the goaf after coal mining

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in the secondary land conservation area of the reservoir is not connected with the surface subsidence fracture. However, coal mining induces partial aquifer drainage in the roof of the coal seam, increasing the amount of surface water flowing to groundwater. Therefore, the maximum drop in the water level of the reservoir is 0.19 m, and the maximum recharge of the reservoir is 52,900 m$^3$/a, accounting for 0.89% of the total recharge. It demonstrates that coal mining in the secondary land conservation area has little effect on the recharge of the reservoir. On the basis of good ecological compensation, water saving and comprehensive utilization of mine water, coal mines need to further carry out research on mitigating the adverse effects of coal mining on the reservoir’s land conservation area.

**Keywords:** Numerical simulation, reservoir land conservation area, water-conducting fracture zone, surface subsidence, recharge capacity.

### 1 Introduction

As one of the main energy sources of social production, coal mining plays an important role in economic activities. China is increasingly aware of development with environmental protection, and has issued strict environmental protection policies for coal mining in the first and second land conservation areas under the reservoir, requiring mines to set up protective coal pillars to reduce surface subsidence and secondary hazards in the mining area [1]. Presently, China has a huge amount of coal under various water bodies. Scholars have conducted a lot of research on coal mining under water bodies, and have accumulated rich experience in coal mining under reservoirs and rivers [2–4]. However, there are few studies on the impact of coal mining in the reservoir protection area on the reservoir recharge, which is a new issue of environmental protection.

The coal mine field is located on the west side of the northern section of Taihang Mountain. There are two reservoirs in the mine field, Qinshan and Guanshan. In addition, coal resources are heavily overburdened because of the coal pillars in the reservoir, which affects the normal connection and economic benefits of the mine. The research collected the mine geology and reservoir data, based on the field survey, and took the Qinshan Reservoir secondary land conservation area as the research scope, using FLAC3D and Visual MODFLOW to simulate the development height of the roof water-conducting fracture and the development depth of surface subsidence cracks [5]. Moreover, this study also predicts that the drainage
of the groundwater in aquifer affected by mining-induced water-conducting fractures will cause the overflow of upper groundwater and surface water to recharge the lower aquifer. In order to provide scientific support for mining technology selection, and formulate effective compensation measures, the variation of reservoir recharge and reservoir water level in the secondary land conservation area is analyzed and calculated.

2 Overview of Coal Mines and Land Conservation Area

The coal mine is located in Xiyang County, Shanxi Province, which belongs to Qinshui coal field. It is high in the west and low in the east, high in the south and low in the north, with a total area of 120.25 km$^2$ and a mining elevation of +760 ∼ +280 m. The mine adopts the comprehensive excavate method of inclined shaft and vertical shaft, full seam one passing cutting mechanized mining and full-caving method is adopted [6]. The main aquifer group in the mine consists of five layers from top to bottom: gravel aquifer of Holocene, interlamination sandstone aquifer of Shihezi formation (K10, K8), interlamination sandstone aquifer of Shanxi formation (K7), thin limestone karst aquifer of Taiyuan formation (K2, K3, K4), thick limestone karst fracture aquifer of Middle Ordovician [7]. Among them, there are two main aquicludes: arenaceous mudstone, mudstone, aluminous mudstone aquicludes of Benxi formation, and interlamination mudstone, sandy mudstone aquicludes of Permian [8].

Qinshan reservoir is located in the middle reaches of Bazhou river, with normal water level of +958.25 m and flood level of +959.76 m. The bottom of the reservoir is in contact with the strata of the upper Shihezi formation in upper Permian. The level 1 water area of the reservoir is within the normal water level +958.25 m, and the area is 0.28 km$^2$. The level 2 water area is the water level below the flood level +959.76 m minus the scope of the level 1, and its area is 0.20 km$^2$. The land scope of the level 1 land conservation area is within 200 m from the level 1 water area. The land scope of the level 2 land conservation area is above the level 1 land conservation area to the watershed area. The total area of the land conservation area is 50 km$^2$, of which the overlapping area with the coal mine field is 17 km$^2$. In order to protect the water source of the reservoir, protection coal pillars with a width of 280 ∼ 400 m are reserved in the level 2 land conservation area according to the requirements. The protection coal pillars range up to 21.9 km$^2$ in the mine field. The positional relationship between the mine field and the reservoir’s land conservation area is shown in Figure 1.
3 Impact Analysis of Coal Mining Under the Level 2 Land Conservation Area

3.1 The Growth Law of Water-Conducting Fracture Zone in Coal Seam Roof

The mining process in the coal seam will cause disturbance and damage to the roof rock layer, forming a roof water-conducting fracture zone and becoming the most important water-filled channel for the roof aquifer in the working seam [9, 10]. For fully and truly reflects the roof disturbance and damage effect induced by mining on working face, FLAC3D three-dimensional calculation model is adopted for the numerical simulation. On the basis of actual situation of typical working face in coal mine and rock mechanical parameter, the strike length of the working face is 280 m, the dip width is 220 m, the height of the model is 175.4 m, and the thickness of coal seam is
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5.67 m. Furthermore, an analytical simulation model is established to limit its boundary conditions. Growth height of “two zones” is judged by the distribution law of tensile failure and shear failure in the plastic zone [11].

As coal mining face advances to 30 m, the direct roof is mainly subjected to tensile failure, while the overlying rock above the coal wall of the working face is mainly subjected to shear failure. The caving zone is the fine sandstone of the direct roof of the coal seam, with a height of 5.2 m and a growth height of the fracture zone of 10.39 m, as shown in Figures 2(a), 3(a) and 4(a). Whereas the growth height of the fracture zone continues to increase with the advancement of the working face. When advancing to 240 m, the growth height of the fracture zone reached a maximum value of 108.5 m, reaching 19.1 times the mining height, and basically remained at this position, no longer changed significantly with the advancement of the working face [12], as shown in Figures 2(b), 3(b) and 4(b). The thickness of coal seam in the level 2 land conservation area of the reservoir is 3.45 ~ 7.36 m, and the growth height of roof water-conducting fracture zone after mining is 65.89 ~ 140.58 m.

3.2 Dynamic Law of Surface Subsidence

According to the coal mining plan, the FLAC3D three-dimensional calculation model is used to simulate the coal seam extraction. Combined with the
Figure 3  Distribution law of vertical displacement field of stope roof under different pushing mining progress.

Figure 4  Distribution law of failure height and fracture of stope roof under different pushing mining progress.

ageology, terrain and borehole data of the mine field, the rock structure, split position and direction of each calculated section are confirmed to establish a numerical calculation model. Take 1-1’ as an example, the lower left corner of the model is the coordinate origin, the horizontal direction to the right is the X-axis direction (cross-section direction), and the vertical direction upward is the z-axis direction. The vertical displacement at the bottom of
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Figure 5  1-1’ cross-section model.

Figure 6  Structural model of rock mass (7 adjacent working faces).

the model is zero, the horizontal displacement at both sides of the model is zero, and the top of the model is the free boundary, as shown in Figures 5 and 6. By simulating the monitoring of surface displacement, the surface deformation law of the working face affected by the level 2 land conservation zone is analyzed [13].

The 1-1’ section model simulates the interval mining between 7 adjacent working faces in the following order: 1-mining face ∼ 3-mining face ∼ 5-mining face ∼ 7-mining face ∼ 2-mining face ∼ 4-mining face and 6 mining face. The surface deformation law of the vertical displacement after mining is shown in Figure 7. According to the simulation analysis, the maximum surface subsidence value is 1.5 m after the mining of the mining face 1. When the mining face 1, 3, 5 and 7 is finished, the maximum surface subsidence value increases to 1.9 m and tends to be stable. It demonstrates that during the first stage of mining, due to the mining of a working face is separated in the middle, each mining face is superimposed in the affected boundary, but the respective maximum subsidence value does not change significantly. After the second stage of mining in the mining face 2, the previously formed stable subsidence basin was affected by secondary mining and new surface subsidence occurred. The surface subsidence value increased to 2.8 m, and it increased to 3.3 m after mining in mining face 4, forming a continuous subsidence basin, as shown in Figure 8. The surface subsidence value tends to be stable and has reached full mining at this time. Subsequent to the mining of the mining face 6, the surface subsidence value no longer increased evidently, and the surface subsidence basin range gradually
Figure 7 Continued

(a) 1-mining face

(b) 3-mining face

(c) 5-mining face

(d) 7-mining face
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Figure 7  Diagram of surface deformation law when skip-mining in working face.

expanded with mining [14, 15]. In addition, in terms of the measured data of surface rock movement on the working face in the first mining area, the average thickness of the coal seam in the first working face is 5.5 m, and the maximum value of surface subsidence after mining is 3.4 m, which is close to the numerical simulation results. The depth of fracture, caused by surface subsidence, is 11.2 m, about twice the mining thickness.
3.3 Coal Mining Impact Analysis

After coal mining, the roof overburden is damaged to form water-conducting fracture zone. Surface subsidence and cracks are formed under the influence of coal mining, which have a certain impact on safe mining [16]. According to the minimum thickness calculation formula of waterproof coal pillars in coal mining,

\[ H_a > H_{li} + H_b + H_{bi} \]  

(1)

where:

- \( H_a \) – thickness of safe waterproof coal pillar, m;
- \( H_{li} \) – water-conducting fracture zone, m;
- \( H_b \) – thickness of protection layer, m;
- \( H_{bi} \) – crack depth of surface subsidence, m.

As shown in Figure 9, since there is no clay layer at the bottom of the loose layer in the mine field, the thickness of the protective layer is generally about 6 times of the mining height, and the average mining height of the secondary land conservation area is 5.00 m. The thickness of the waterproof coal pillar \( H_a > 95.50 + 30 + 10 = 135.50 \) m, while the depth of the coal seam in the secondary land conservation area of the reservoir is 447.50~801.07 m, which is far greater than \( H_a \). Therefore, the water-conducting fracture zone of coal seam roof will not be in connected with the surface subsidence cracks, and the atmospheric precipitation and surface water will not directly flow into the mine from the coal mining subsidence cracks [17, 18].
On the basis of comprehensive statistics of geological (hydrological) drilling data in the mine field, the average distance from the coal seam to the limestone aquifer of Taiyuan formation K2, K3 and K4, the sandstone aquifer of Shanxi formation K7, the sandstone aquifer of lower Shihezi formation K8, and the bedrock of upper Shihezi formation K10 is 17.66 m, 35.45 m, 52.94 m, 93.11 m, 164.71 m and 282.64 m, respectively. After mining, the growth height of the roof water-conducting fracture zone is 65.89 ~ 140.58 m, which can affect the K2, K3, K4 limestone and K7 sandstone aquifers. The groundwater is drained into the mine, causing groundwater and surface water in the unaffected K8 and K10 sandstone aquifer to recharge layer by layer downward, resulting in changes in the recharge of the reservoir and the water level of the reservoir in the secondary land conservation area.

4 Dynamic Prediction and Analysis of Reservoir Replenishment

To predict the impact of coal mining in the secondary land conservation zone on the reservoir water level and recharge, the groundwater dynamic simulation software Visual MODFLOW is adopted to establish a numerical model of groundwater flow in the simulation area. Use the actual measured water level of the mine to draw the measured flow field, and correct the numerical simulation parameters and models [19, 20]. Finally, the corrected numerical model is used to predict the size and effect of the recharge of
groundwater and surface water flowing down layer by layer in the K8 and K10 sandstone aquifers [21].

4.1 Groundwater Numerical Simulation Model

4.1.1 Outline of the simulation area and its conditions

The rectangular area with an extension of 1.5 km outside the overlapping area between the mine field and the secondary land conservation area of the reservoir is the groundwater simulation area, with an area of about 81.6 km$^2$. From top to bottom, the model aquifer can be classified as: upper Shihezi formation, lower Shihezi formation, Shanxi formation and Taiyuan formation. The Shanxi formation and Taiyuan formation are the aquifers connect with the water-conducting fracture zone of the roof after coal mining, and the two layers share the same water head. The lower Shihezi formation is a composite water-bearing rock formation with sand and mudstone interbedded. The sandstone aquifer is relatively thin, with good vertical water-proof performance, which is characterized as water-proof layer.

The boundary condition of the simulated area is generalized as the head boundary of the reservoir. The four boundaries of the upper and lower Shihezi formation, the south and north boundaries of the Shanxi and Taiyuan formations are generalized to flow boundaries, and exchange water with the outside. The eastern and western boundaries of Shanxi formation and Taiyuan formation, and the bottom boundary of the model are generalized as the water-proof boundary [22]. In the model, the mine water inflow is 68 m$^3$/h, which is expressed by the pumping capacity of the hole well.

4.1.2 Groundwater flow model

According to the characteristics of hydrological parameters such as the thickness and lithology of the water layer in the secondary land conservation zone, the simulation area is a hydrogeological conceptual simulation model of heterogeneity, anisotropy, spatial three-dimensional structure and unsteady flow [23]. Its mathematical model is expressed as follows.

\[
\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial H}{\partial z} \right) + W = S_s \frac{\partial H}{\partial t} \\
(x, y, z) \in \Omega \quad t > 0 \quad (2)
\]

\[
H(x, y, z, t)|_{t=0} = H_0(x, y, z) \quad (x, y, z) \in \Omega \quad (3)
\]

\[
H(x, y, z, t)|_{\Gamma_1} = H_1(x, y, z, t) \quad t > 0 \quad (4)
\]
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\[ K \frac{\partial H}{\partial n} \bigg|_{\Gamma_2} = q(x, y, z, t) \quad t > 0 \]  
\[ \frac{\partial H}{\partial n} \bigg|_{\Gamma_3} = 0 \quad t > 0 \]  

\[ H(x, y, z, t)|_{t=0} = H_0(x, y, z), (x, y, z) \in \Omega \]

Where:

- \( H \) – The water level elevation, m;
- \( q \) – Unit seepage flow at the boundary, m\(^3\)/d;
- \( H_0 \) – The initial flow field, m;
- \( H_1 \) – The head height of fixed head boundary, m;
- \( t \) – time, d;
- \( n \) – The normal direction outside the boundary;
- \( K \) – Permeability coefficient, m/d;
- \( \Gamma_1, \Gamma_2, \Gamma_3 \) – Head boundary, flow boundary and water barrier boundary;
- \( \Omega \) – Computational domain;
- \( W \) – Vertical recharge or discharge intensity, l/d;
- \( S_s \) – Specific storage, l/m;
- \( K_{xx}, K_{yy}, K_{zz} \) – Aquifer permeability coefficient, m/d;

The model is divided by a discrete method with equal spacing and finite difference. The row \times column \times layer of the grid unit is divided by 102 \times 80 \times 4, and the elevation data of the top and bottom of each layer, as shown in Figure 10, are imported into the model according to the drilling data.

### 4.1.3 Model correction and parameters adjustment

In order to reflect the hydrogeological parameters of the groundwater flow system as accurately as possible, takes the flow field measured in June 2018 as the initial flow field, and the running model is adopted to calculate the flow field. In October 2018, hydrogeological parameters after the model correction, the results are shown in Table 1. After adjusting the parameters, the calculated flow field fits the measured flow field as shown in Figure 11, and it can be seen that the fitting effect of water level contour is better [24, 25].

### 4.2 Recharge Flow Forecast of Reservoir

The coal mining roof water-conducting fracture zone directly affects the K2, K3, K4 of Taiyuan formation and the K7 sandstone aquifer of Shanxi formation, resulting in the gradual draining of the aquifer underground in
(a) Surface elevation          (b) Floor height of upper Shihezi formation

**Figure 10** Elevation contour map.

**Table 1** The model parameter list

<table>
<thead>
<tr>
<th>Aquifer</th>
<th>$K_{xx}$</th>
<th>$K_{yy}$</th>
<th>$K_{zz}$</th>
<th>$S_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>The upper Shihezi formation</td>
<td>0.5851</td>
<td>0.5849</td>
<td>0.0059</td>
<td>$8 \times 10^{-5}$</td>
</tr>
<tr>
<td>The Shanxi formation</td>
<td>0.2122</td>
<td>0.2124</td>
<td>0.0213</td>
<td>$6 \times 10^{-5}$</td>
</tr>
<tr>
<td>The Taiyuan formation</td>
<td>0.1391</td>
<td>0.1392</td>
<td>0.0138</td>
<td>$6 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

the mining area. Therefore, the original hydraulic gradient of the unaffected K8 and K10 sandstone groundwater is changed and overflowed downward to recharge. In terms of mining range of the planned working face in the three areas, the numerical model of underground water flow is established. It is predicted that the overflowing vertical recharge of groundwater in K8 and K10 aquifers of the lower and upper Shihezi formations is about 146 m$^3$/d, and the maximum water level drops to 0.25 m. The water level change curve is shown in Figure 12.

According to the survey and statistics over the years, the average annual inflow of the reservoir is 5.95 million m$^3$, and the recharge is mainly from atmospheric precipitation, surface water and groundwater. Moreover, the bottom of the reservoir is in direct contact with the strata of the upper Shihezi formation, and the upper Shihezi formation is more exposed in the secondary land conservation area, and there are some groundwater spring discharge areas.
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**Figure 11** Flow field fitting diagram.

**Figure 12** Schematic diagram of water level drop depth of aquifer.
Through the above research and analysis, coal mining under the secondary land conservation area of Qinshan reservoir will lead to the drainage of the sandstone aquifers of K2, K3, K4 Taiyuan formation and K7 Shanxi formation, causing groundwater in sand aquifer of K8 lower Shihezi formation and K10 upper Shihezi formation recharges downward. As the amount of groundwater in the upper aquifer decreases, atmospheric precipitation surface water recharge to and groundwater of the Shihezi formation increase. Then the amount of recharge to the reservoir will be reduced, the maximum amount of reduction is 52,900 m$^3$/a, accounting for 0.89 % of the total recharge, and the water area of the reservoir is 0.28 km$^2$, the maximum decrease of the reservoir water level is 0.19 m. Affected by coal mining, the elevation of the water level is +958.06 m, and the change of the water level is unapparent.

5 Conclusion and Suggestion

Based on the data of mine geology and reservoir, and on the basis of reconnaissance survey, the secondary land conservation area of Qinshan reservoir is taken as the research area. The FLAC3D software is adopted to simulate and analyze the maximum growth height of the roof water-conducting fracture zone after mining the coal seam is 19.1 times of the mining thickness, the maximum surface subsidence is 3.4 m, and the depth of the surface subsidence cracks is twice of the mining thickness. It is calculated that the thickness $H_a$ of the coal mining safety waterproof coal pillars should be greater than 135.50 m, and the coal seam burial depth in the secondary land conservation area of the reservoir is 447.50 ~ 801.07 m, which is much greater than $H_a$. The water-conducting fracture zone in the roof of the coal seam will not connect with the surface subsidence fracture, or causes surface water to flow into the mine. The water-conducting fracture zone can only affect the groundwater of the K4, K3, K4 limestone of the Taiyuan formation and the K7 sandstone aquifer of the Shanxi formation, resulting in the unreached groundwater and surface water of the K8 sandstone aquifer of the lower Shihezi formation and the K10 sandstone aquifer flow down layer by layer. According to the Visual MODFLOW software simulation and prediction of recharge flow, the vertical downflow recharge water of the aquifer of the upper Shihezi formation K8 and K10 is about 146 m$^3$/d. Indirectly, the atmospheric precipitation and surface water recharge of the reservoir is reduced by 52,900 m$^3$/a, accounting for 0.89 % of the total annual recharge of the reservoir, and the maximum water level decline is 0.19 m.
Therefore, the effect of coal mining on the recharge and water level of the reservoir in the secondary land conservation is less changed. The water-conducting fracture zone of the coal mining roof in the Qinshan Reservoir’s land conservation area will not connect with the surface subsidence cracks in the mining area. The surface water of the reservoir’s land conservation area will not collapse into the pit. However, it will increase the content of mud and sand in of surface water and the intensity of soil and water erosion on the surface to a certain extent, which will affect the water quality of the reservoir. This is also an important aspect that needs further research.

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Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

References


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