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Quantitative Evaluation Method and Response Mechanism of Shallow Groundwater in Multi-Mine Mining of "Soil–Rock" Composite Water-Resisting Strata

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Abstract: The sustainability of shallow groundwater systems, pivotal to maintaining ecosystem equilibrium and facilitating the sustainable development of mine sites, is the core of various dynamic indicators in response to mining activity and mining area planning. This study quantitatively evaluates the impact of mining activities on shallow groundwater systems at the orefield scale, taking the equivalent permeability coefficient (EPC) of "Soil–Rock" composite water-resisting strata and the response mechanism of shallow groundwater in multi-mine mining as the entry points. A modified six-step evaluation method for the response mechanism of shallow groundwater in multi-mine mining is proposed using mathematical statistics, numerical simulation, and theoretical analysis methods. The method is used to evaluate the sustainability of the shallow water system in the Yushen mining area, to study the distribution characteristics of the water resource carrying capacity (WRCC) in different mining areas of the Yushen area, and to analyze the number of mines allowed to be mined under geological conditions with a WRCC of more than moderate bearing capacity. The results show that when the mining area of a mine in the Yushen area is set to 1×10^8, 7.5×10^7, 5×10^7, and 2.5×10^7 m^2, as the mining area of the designed mine decreases, the area bearing surplus gradually increases, with values of 1.70×10^9, 1.98×10^9, 2.28×10^9, and 2.58×10^9 m^2. The number of mines allowed to be mined under geological conditions with a WRCC above moderate capacity is 20, 31, 51, and 112, respectively.

Keywords: "Soil–Rock" composite water-resisting strata; shallow groundwater; quantitative evaluation method; multi-mine mining

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1. Introduction

The conservation of water resources in the northwest coal bases is a significant challenge. The Yellow River Basin has 57 nationally planned coal mining areas, but the intensity of coal mining in certain areas, such as Yuheng, Yushen, and Liliu, does not align with the environmental carrying capacity [1–3]. Prioritizing ecological protection and promoting high-quality development in the Yellow River Basin has been elevated to a major national strategy. However, the existing water-retaining mining methods, such as fill-in mining, short-wall mining, and parallel mining and charging, face issues of low efficiency, high cost, and poor effectiveness [4–6]. The long-term accumulation of mining activities in large-scale multi-mining spaces aggravates the impact on shallow groundwater. Thus, with the yearly increase in coal production in the western mining area, identifying an optimal solution that effectively reconciles the scale of scientifically conducted coal mining with the WRCC assumes paramount significance in the conservation-oriented mining of water resources within northwest coal bases.

In recent years, researchers and experts have delved into comprehensive investigations surrounding the theory and technology of water-preserved mining [7–10]. However, the majority of research findings have been centered around the mining processes of individual working faces [11]. The shallow water system, characterized by a unified hydraulic connection and consistent groundwater circulation laws [12], requires a more comprehensive analysis than what is offered by examining the impact of mining solely on a single working surface [13]. It is pertinent to explore the intricate relationship between the coal mining intensity and the WRCC, viewing it from the broader perspective of an entire mining area [14,15]. It is imperative to move beyond the conventional approach of first developing and subsequently protecting, or worse, dealing with pollution after its occurrence when addressing the issue of environmental sustainability. There is an urgent demand for a strategic layout of mining areas prior to excavation and judicious regulation and control measures during the mining process [16,17]. The overarching goal is to chart a course that avoids historical pitfalls, striving to minimize the adverse impact of coal resource exploitation on shallow water systems. This necessitates achieving a delicate balance: promoting coal resource development while simultaneously safeguarding water resources, thus fostering a harmonious and coordinated development framework [18,19]. To accomplish these objectives, it is crucial to delve deeper into the quantitative evaluation of shallow water systems and establish precise mining thresholds at the scale of the entire mining area.

In summary, the Yushen area is taken as the research background, a quantitative evaluation method for shallow groundwater is proposed, the WRCC is used as the evaluation index, and mining planning based on the sustainability of the shallow water system is realized. Based on the quantitative evaluation model of shallow water (QEMSW) and combined with the numerical calculation results, the shallow water seepage model under the mining disturbance is further modified to obtain a shallow aquifer seepage model that can reflect the mining disturbance at the scale of the Yushen mining area. The number of mines allowed to be mined under geological conditions with a WRCC of more than moderate bearing capacity was identified to study the distribution characteristics of the WRCC in different Yushen mining areas. The quantitative evaluation of the shallow groundwater response of mining was realized, and the mining threshold of the mine number based on shallow groundwater sustainability was determined.

2. Materials and Methods

2.1. Hydrogeological Conditions

The Yushen mining area is located north of Yulin City, Shaanxi Province, under the jurisdiction of Shenmu County and Yulin City Yuyang District. The mining area is close to the Inner Mongolia Autonomous Region, and the northwest boundary of the mining area is the border between Shaanxi and Inner Mongolia, the northeast boundary is the western boundary of the Shenfu mining area, and the southwest is the northern boundary of the Yuheng mining area. The shape of the mining area is irregular, and the maximum distance between the north and south of the mining area is approximately one hundred kilometers. The maximum distance from east to west is approximately one hundred kilometers. The mining area is divided into four planning periods, namely, the first, second, third, and fourth planning areas, of which the exploration and exploitation degree of the first and second planning areas is relatively high. The overall surface of the Yushen mining area shows a change from high to low from northwest to southeast, with the western part of the mining area being the aeolian sand landform, the loess Liang'an hilly landform in the east, and the loess Liang'a hilly landform in the north. The location and planning area of the Yushen mining area are shown in Figure 1.

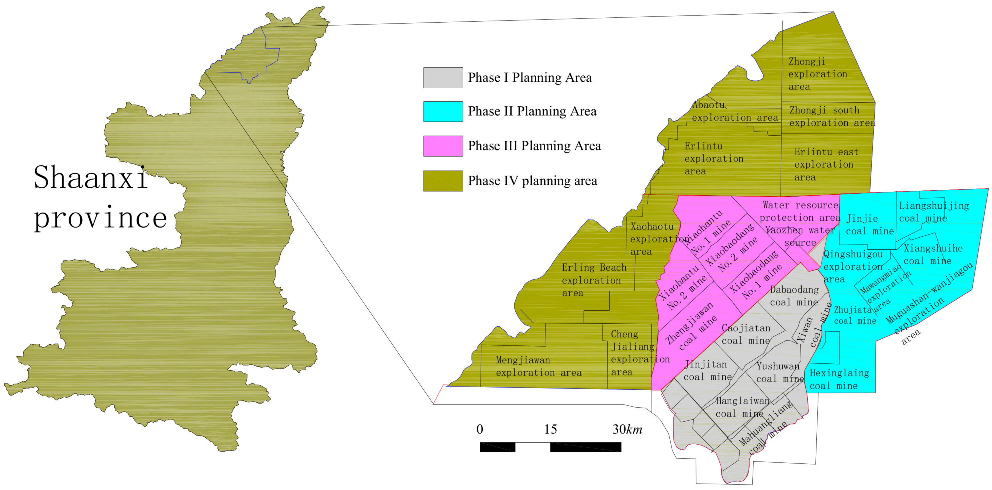


Figure 1. Location of Yushen mining area.

The drilling data of the Yushen mining area and the data of the coal seam thickness, shallow aquifer thickness, soil thickness, bedrock thickness in the area were organized. In the collation of the Yushen mining area, the density of the drill hole is relatively small, and the data need to be interpolated. The corresponding distribution feature map is generated using the GIS data spatial analysis function to meet the calculation needs and improve the accuracy, as shown in Figure 2.

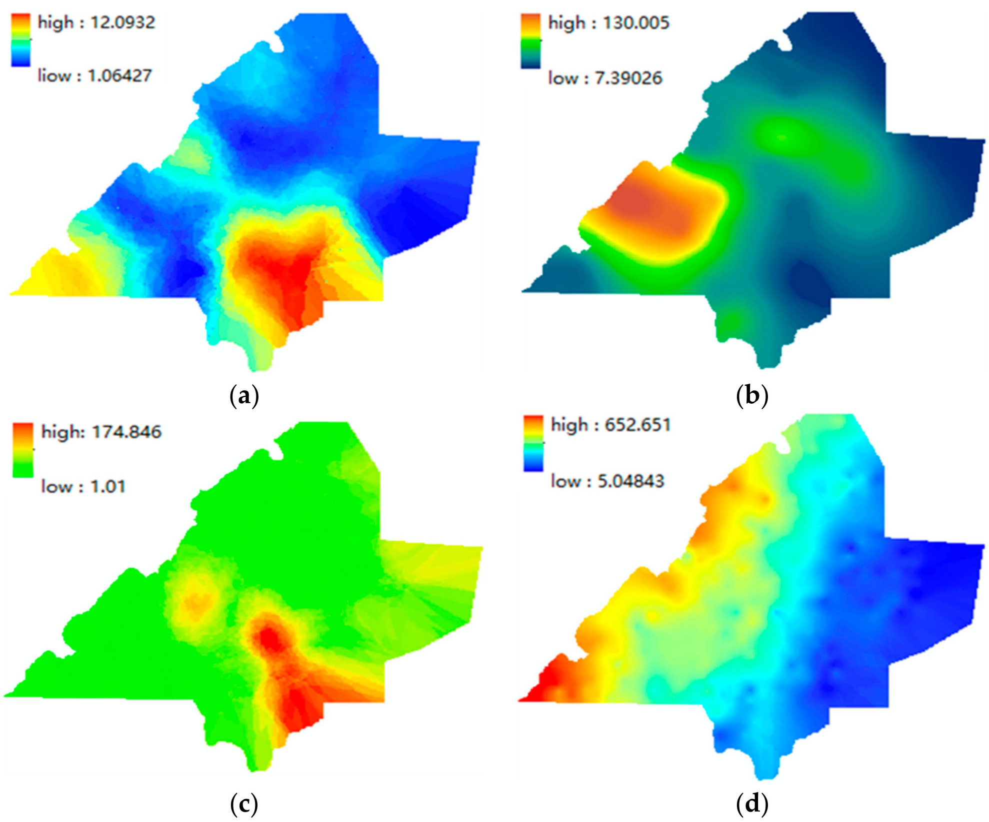


Figure 2. Thematic map. (**a**) Coal seam thickness/m; (**b**) aquifer thickness/m; (**c**) thickness of soil layer/m; and (**d**) bedrock thickness/m.

The first coal seam thickness in different areas of the Yushen mining area varies greatly, with the maximum thickness of a single layer reaching 12 m, located at the southeast boundary of the mining area. The minimum coal seam thickness is 1 m, located at the eastern boundary of the mining area. The structural characteristics of shallow aquifers are as follows: The fourth series of the Aeolian sand + Sarawusu formation aquifer is widely distributed in the Yushen mining area. The aquifer between the Aeolian sand layer and the Sarawusu formation often forms a well-linked diving aquifer. The thickness significantly changes in the range of 0 to 130 m. The lithology is mainly silt sand and fine coarse sand, belonging to the permeable rock group. The water level is buried at a depth of 0.50~3.28 m. Due to weathering and ablation, the thickness of the bedrock in the mining area gradually thins from the northwest to the southeast. The maximum thickness of the overburden is 652.7 m, and the minimum thickness is 5 m. The place with the largest thickness of the insulation soil layer is at the southeast boundary of the mining area, with a value of approximately 110 m, and the place with the smallest thickness of the insulation soil layer is at the northwest boundary of the mining area, with a minimum value of 1 m. The largest distance between coal and water space is located at the western boundary of the mining area, with a value of approximately 663.6 m, and the smallest distance is located at the eastern boundary of the mining area, with a value of 32.6 m.

According to the geological exploration data, the stratigraphic geological profile of the Yushen mining area is shown in Figure 3. The minimum value of coal seam thickness is 1.08 m (XH76 borehole), the maximum value of coal seam thickness is 12.36 m (P49 borehole), the maximum value of coal seam depth is 551.05 m, and the minimum value of coal seam depth is 105.8 m.

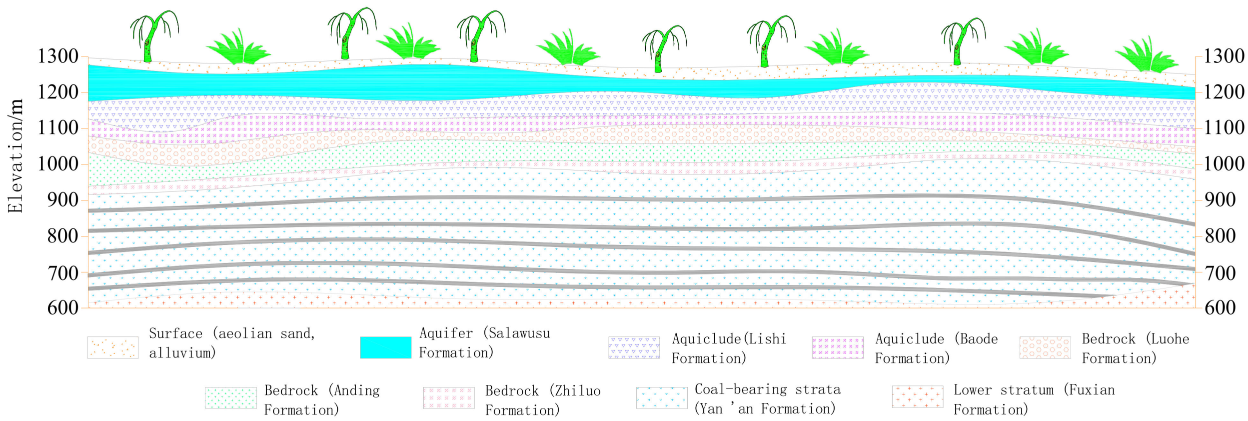


Figure 3. Stratigraphic geology profile.

2.2. Method Overview

Based on the planning method [20,21], the quantitative evaluation model was modified, and the WRCC was introduced. Methods for mining planning mainly consist of six steps, as shown in Figure 4.

(1) The basic data(coal seam thickness, aquifer thickness, thickness of soil layer, bedrock thickness/m) were obtained. (2) The empirical formula for the height of the water-conducting fractured zone (HWCFZ) was derived. (3) The equivalent permeability coefficient (EPC) of the "Soil–Rock" was determined. (The first three steps are detailed in References [20,21]).

The EPC of the overburden rock is K_e, where the single formation thickness is H_i, the total thickness of the "Soil–Rock" formation is H, and the permeability coefficient of the soil or rock layer is K_{ei}:

$$K_e = \frac{H}{\sum_{i=1}^{m} \frac{H_i}{K_{ei}}} \tag{1}$$

(4) The calculation formula for the shallow water leakage with different mining areas: Combined with the conditions of J. Dupuit and the principle of water pressure equilibrium, the formula for the change in the water head under different equivalent permeability

coefficients was obtained. Combined with the numerical calculation results, the calculation formula for the shallow water leakage with different mining areas at the Yushen mining area scale was given.

(5) The evaluation indicators of the WRCC of 3 levels and 11 indicators were used to evaluate the sustainability of shallow water in the research area.

(6) The mine planning was carried out as follows: The calculation formula for the shallow water leakage with different mining areas was adopted. Combined with the water head values, WRCC, mining planning was realized.

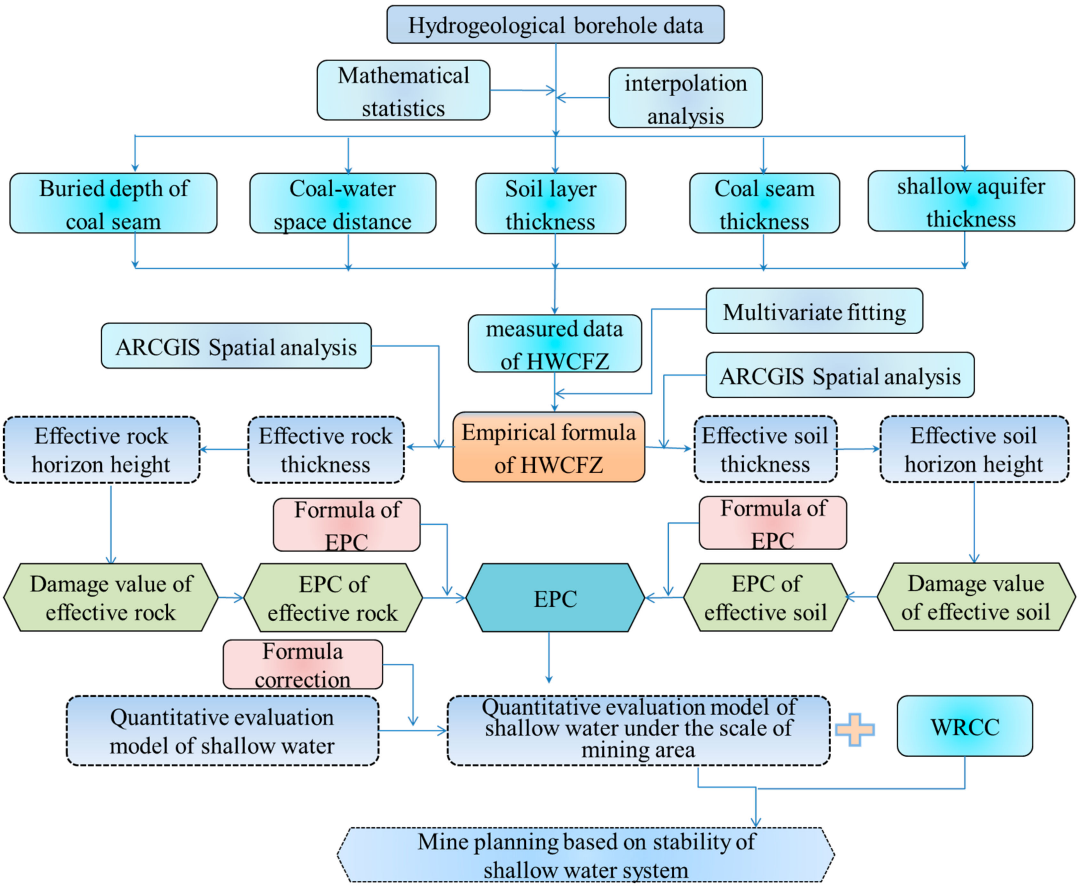


Figure 4. Mine planning method (modified based on references [20,21]).

2.3. Hydraulic Model for Shallow Water in Mining Area

(1) Correction based on water level fall

Based on the QEMSW (Figure 4) given in References [20,21] and combined with the numerical calculation results, the shallow water seepage model under mining disturbance was modified to obtain a shallow aquifer seepage model that can reflect the mining disturbance at the Yushen mining area scale. The shallow water leakage is related to the water head value, EPC, rock and soil layer thickness, and mining range. The correction of these four influencing factors is considered herein.

The water head value and the EPC were then corrected (Figure 5) in the form of $f(H_1, Ke) = (a \times \exp((H_1 - b)/c + d))) \times (e \times \exp((Ke - f)/g + h))$, where the variable was the water head value and EPC. The correction formula was introduced into the QEMSW, and then the model was modified. The data fitting results using the McCot method + the universal global optimization algorithm [22] are shown in Figure 5a, and the fitting correlation coefficient (R) was 0.976. The fitting effect was better in the case of a coal–water spacing of 350 and 400 m. However, the error was large when the coal–water spacing was 200 and 300 m.

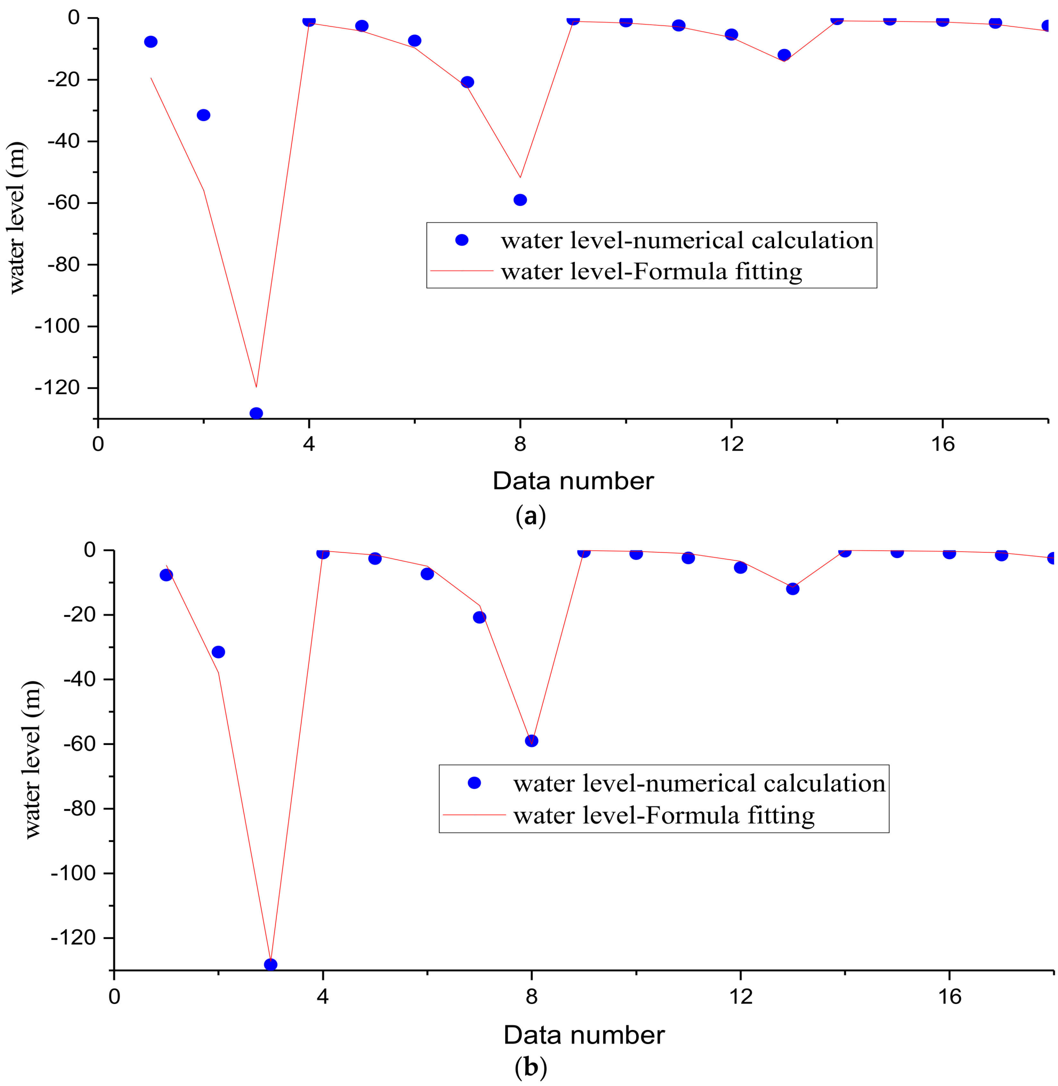


Figure 5. Correction based on water level fall. (**a**) Correction of water head value and EPC; and (**b**) correction of water head value, EPC, and rock and soil layer thickness.

The water head value, EPC, and rock and soil layer thickness were then corrected in the form of f(H_1, Ke, Le) = ($a \times \exp((H_1 - b)/c + d)) \times (e \times \exp((Ke - f)/g + h)) \times (i \times \exp((Le - j)/k + l)$), where the variable was the water head value, EPC, and rock and soil layer thickness. The correction formula was introduced into the QEMSW, and then the model was modified. The data fitting results using the McCot method + the universal global optimization algorithm [22] are shown in Figure 5b, and the fitting correlation coefficient (R) was 0.9986. The overall fitting effect of the data was better, and the revised formula is as follows.

$$H = \sqrt{H_1^2 - \frac{H_1^2 - H_2^2}{l}x + \frac{Wl}{K}x - \frac{Ke}{2K}\frac{H_1 + H_2}{Le \times f\left(\frac{H_1+H_2}{2}, Ke, Le\right)}lx - \frac{W}{K}x^2 + \frac{Ke}{2K}\frac{H_1+H_2}{Le \times f\left(\frac{H_1+H_2}{2}, Ke, Le\right)}x^2} - H \tag{2}$$

$$a : 0.457294330561178,\ b : 25.9532271913645,\ c : -70.8004969865701,\ d : 5.1937426460841,$$
$$e : 58.7851023452796,\ f : 2.43358318433559 \times 10^{-7},\ g : 5.02473148732882 \times 10^{-9},\ h : 0.562696013357747,$$
$$i : 124.239738437762,\ j : -245.488329148918,\ k : 36.057711309322,\ l : 0.212017930891133$$

where H: the water head values, H_1 and H_2: the water head values at boundary, l: the spacing between the boundary, Ke: the EPC, Le: the thickness of the "Soil–Rock" layer, K: the permeability coefficient of aquifer, and W: the recharge intensity at upper boundary.

The above formula is based on the fitting result of the shallow groundwater level depth reduction data with a mining range of 1×10^8 m^2. Then, the two formulas were combined according to the sensitivity coefficient of the water level in different mining areas, and the shallow groundwater leakage calculation formula with different mining parameters within the mining area was determined.

(2) Correction based on different mining areas

The mining areas of 1.00×10^8 m^2, 7.50×10^7 m^2, and 5.0×10^7 m^2 were compared and analyzed to explore the influence of the mining range of the mine in the mining area on the shallow water level. The mining height was 6 m; the simulated mining times were 70 years, 54 years, and 35 years; the measurement point was arranged in the middle of the aquifer; the numerical simulation period was 3 years; the simulation results were taken as the initial value of the next step; and the simulation was carried out in turn for the whole cycle (Table 1).

Table 1. Simulation parameters of different schemes [21].

Mining Height/m	EPC/m/s	Mining Area/m^2	Water Head/m
6	3.05438×10^{-8}	1.00×10^8	40
6	3.05438×10^{-8}	7.50×10^7	40
6	3.05438×10^{-8}	5.00×10^7	40

Under the conditions of 1.00×10^8 m^2, 7.50×10^7 m^2, and 5.0×10^7 m^2 in the mining range, the shallow groundwater level decrease gradually increased over the entire simulation period, reaching the maximum depth reduction after 70, 54, and 35 years, respectively. As the mining range increased, the decline in shallow water levels gradually increased during the same mining period. The mining range was 1.00×10^8 m^2 as the benchmark value, which was recorded as 1. The ratio of the other two mining ranges to the benchmark value was taken as the basic parameter, and then the maximum water level drop values of different mining ranges were extracted for analysis, as shown in Figure 6. With the increase in the mining range of the mine, the maximum depth reduction in the shallow water after mining gradually increased. The maximum water level of shallow water and the mining range showed a power index function relationship, as shown in Equation (3):

$$y = a\left(1 - e^{-b \times S/1E8}\right) \tag{3}$$

where y is the water level depth reduction, S is the mining area (m^2), and a and b are related parameters.

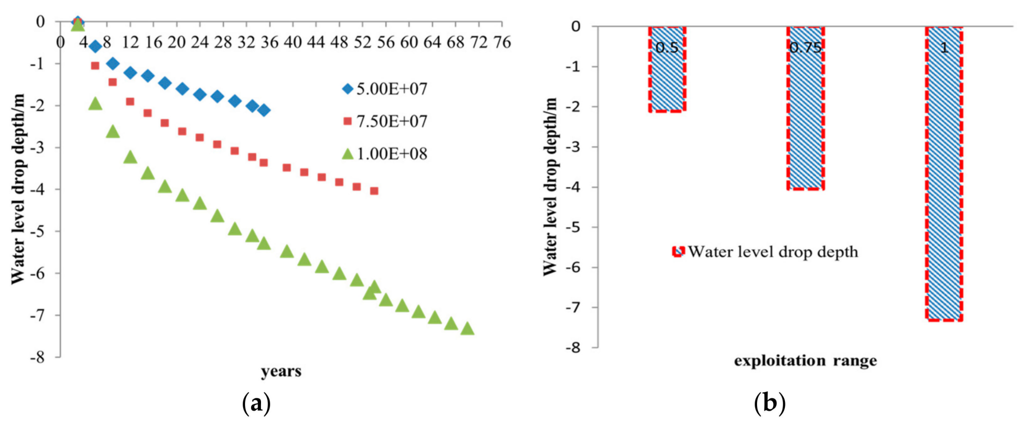


Figure 6. Depth of shallow water level in different mining areas. (**a**) Water level drop depth in different mining years; (**b**) maximum water level drop.

a = 1.34597187097131, b = −1.86021703430486, and R^2 = 0.99994.

Based on the above research findings, in the case of different mining ranges, the water level depth reduction value of the mining area of 1.00×10^8 m^2 was the largest, and the mining area was 7.5×10^7 m^2. The mining area of 5×10^7 m^2 was the smallest. This paper proposed the sensitivity coefficient of water level depth reduction to analyze the water level depth reduction law for different mining ranges and increase the comparativeness of the data, that is, the maximum water level depth reduction with the mining area of 1.00×10^8 m^2 as the benchmark value. The ratio of the maximum shallow water level depth reduction to the benchmark value for different mining areas was calculated as follows:

$$\alpha_m = \frac{H_i}{H_{\max}} \tag{4}$$

Then, the power index relationship between the maximum water level depth reduction and the mining range was transformed, and the fitting formula for the maximum water level reduction in shallow groundwater was constructed:

$$H = \alpha_m \cdot \left(\sqrt{H_1^2 - \frac{H_1^2 - H_2^2}{l}x + \frac{Wl}{K}x - \frac{Ke}{2K}\frac{H_1 + H_2}{Le \times f\left(\frac{H_1+H_2}{2}, Ke, Le\right)}lx - \frac{W}{K}x^2 + \frac{Ke}{2K}\frac{H_1 + H_2}{Le \times f\left(\frac{H_1+H_2}{2}, Ke, Le\right)}x^2} - H \right) \tag{5}$$

2.4. Evaluation System of WRCC

The WRCC evaluation system proposed by scholars was adopted [15], and the impact weights of each factor were taken from Reference [15]. The evaluation of shallow water system sustainability in the study area was carried out. Combined with the bearing state of the ecological environment under the conditions of water resource changes in the northwest mining area of China under the disturbance of mining, the WRCC in the mining area was divided into five levels, as shown in Table 2.

Table 2. Classification table of equivalent WRCC in the mining area.

Classification of Bearing Capacity	I	II	III	IV	V
Classification	Carrying surplus	Capable of carrying	Moderate carrying	Slight over-carrying	Severe over-carrying
Comprehensive evaluation value	[0.9–1]	[0.8–0.9)	[0.7–0.8)	[0.6–0.7)	[0–0.6)

According to the fuzzy comprehensive evaluation principle, the membership function of each influencing factor was determined [23], the F determination criterion was used for the factors under the influence of one factor, and the multivariate membership function was used for the factors under the influence of multiple factors. The membership function of each impact factor was calculated as follows.

According to the discriminant matrix, the weights of each impact factor were calculated:

$W_{A\sim B}$(B1, B2, B3, B4) = (0.0546, 0.5873, 0.1454, 0.2127);

$W_{B1\sim C}$(C1, C2, C3) = (0.1884, 0.0810, 0.7306);

$W_{B2\sim C}$(C3′, C4, C5, C6, C7) = (0.3408, 0.1255, 0.0538, 0.0938, 0.3861);

$W_{B3\sim C}$(C6′, C7′, C8, C9) = (0.3210, 0.5157, 0.1108, 0.0525);

$W_{B4\sim C}$(C7, C9, C10, C11) = (0.1427, 0.1186, 0.4007, 0.3380);

A: WRCC; B1: Geological factors; B2: Mining system; B3: Ecosystem; B4: Water resources system; C1: Relationship of occurrence between coal and water; C2: The buried depth of coal seam; C3: Effectiveness of the aquifer; C4: Development degree of mining fracture; C5: Mining parameters; C6: Degree of surface subsidence; C7: Temporal and spatial variation of groundwater level; C8: Vegetation coverage rat; C9: Ecological water requirement; C10: Total water resources, C11: Water quality. The values of weights and calculation process are detailed in References [15,23].

3. Results

3.1. Determining the Thickness of Effective "Soil–Rock"

This study combined various factors, such as the spatial relationship between coal and water, the allocation of the first coal seam, the contour line of the bedrock thickness, and the formula of the HWCFZ in the Yushen area. Utilizing the GIS software, a map illustrating the distribution of damaged rock and soil layers in the Yushen mining area and the corresponding lithology combination was generated (refer to Figure 7). After coal mining, the thickest damaged geotechnical layer was found at the northwest boundary of the wellfield, reaching 476.4 m. Conversely, the southeast area of the wellfield experienced the least thickness, with a damaged geotechnical layer thickness of 0 m. Overall, there was a gradual thinning trend from the northwest to the southeast. The maximum effective rock thickness measured 465.435 m, while the minimum effective rock thickness was reported as 0 m. For soil layers, the maximum thickness of effective "Soil–Rock" was 109.8 m, with the minimum thickness of effective "Soil–Rock" observed at 0 m.

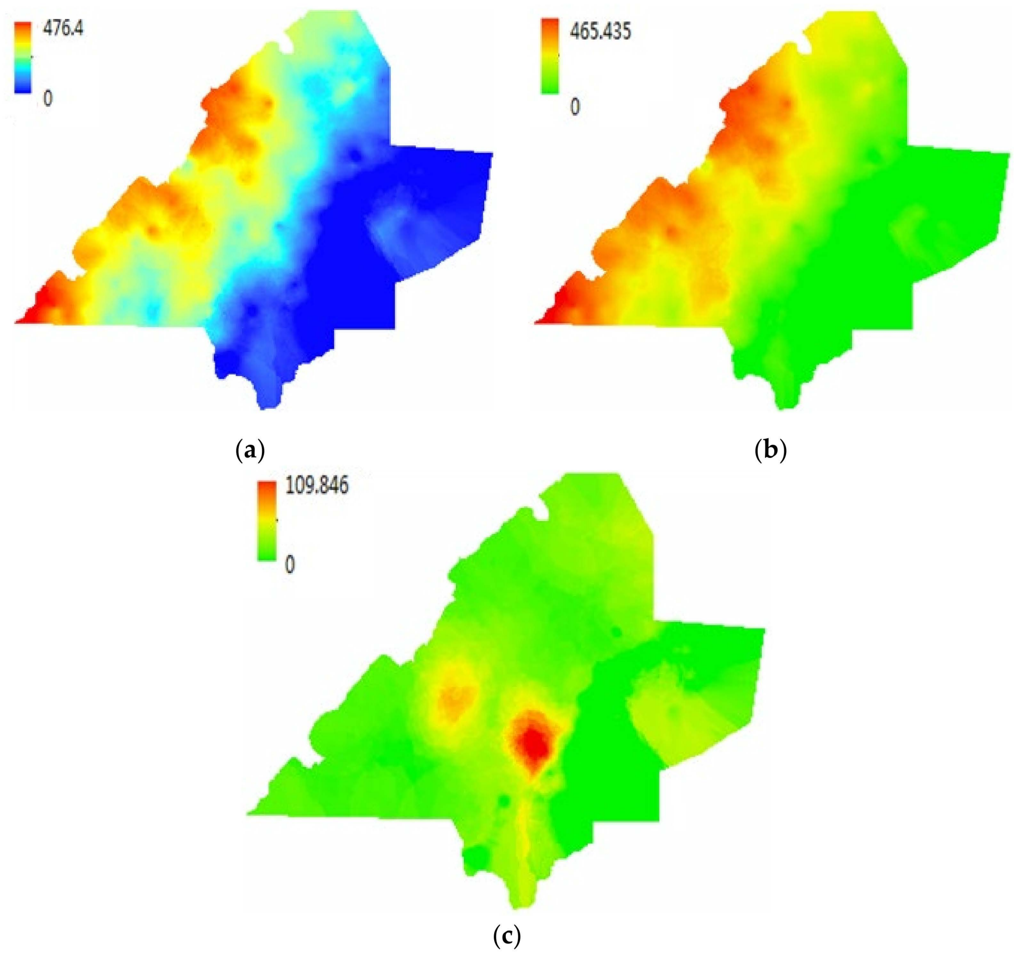


Figure 7. Thickness and assemblage of damaged rock mass in the Yushen mining area. (**a**) Thickness of effective "Soil–Rock"/m; (**b**) thickness of effective bedrock/m; and (**c**) thickness of effective soil/m.

3.2. Determining the EPC

3.2.1. Determining the Damage Values of Effective "Soil–Rock"

The rock damage value is a quantitative index to describe the degree of damage to the rock. It is not only related to the strength and stability of the rock, but rock damage may also lead to the formation or expansion of cracks and pores, affecting the permeability of the rock.

This study applied the quantitative analysis results of the damage deformation of the overburden structure in combination with factors such as the coal–water spatial distance, first coal seam thickness, and the multi-factor empirical formula of HWCFZ. This analysis was used to generate a damage map showing the distribution of damage values in the effective rock and soil layers of the Yushen mining area (Figures 8 and 9). The distribution pattern of the damage values in the effective rock layer was similar to that in the effective soil layer. The highest damage values in the effective rock layer were located at the southeast boundary of the mining area, with a value close to one. The lowest damage value was found in the northwest area of the wellfield, with a value of 1.52×10^{-6}. Similarly, the effective soil layer showed a larger damage value from northwest to southeast, with a maximum value of 1 and a minimum value of 0.06768.

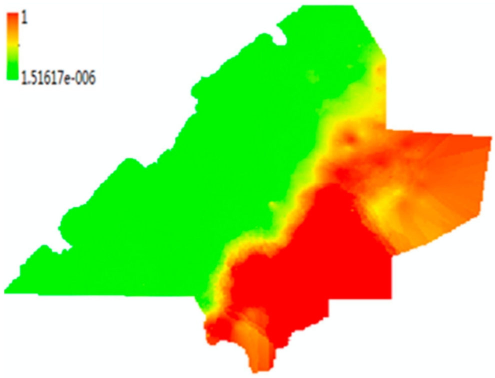


Figure 8. The effective rock layer's damage value.

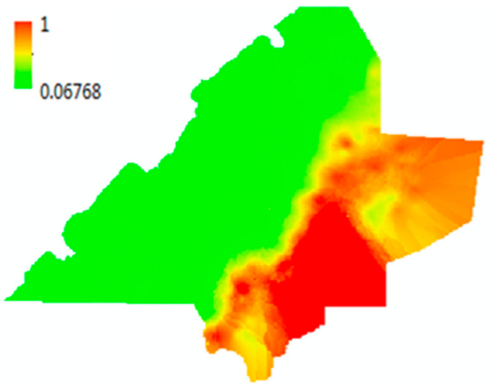
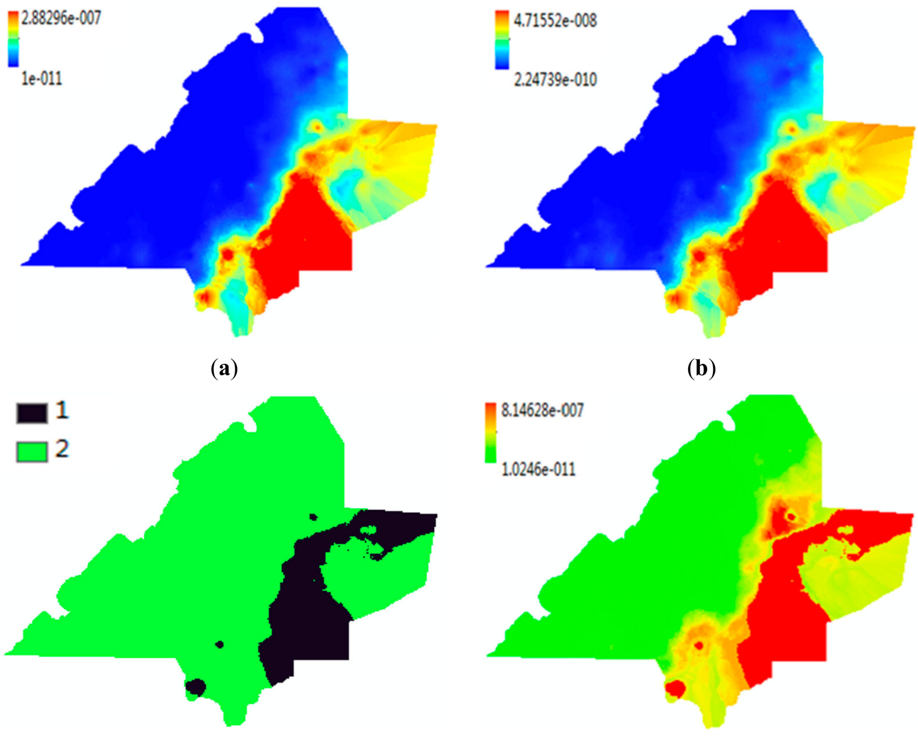


Figure 9. The effective soil layer's damage value.

3.2.2. Determining the EPC

Permeability of the effective "Soil–Rock" layers were then generated using the EPC formula [20,21] (Figure 10a,b). The area was zoned according to the formula of HWCFZ. The thickness of the "Soil–Rock" layer in zone 1 was less than the HWCFZ, and the thickness of the "Soil–Rock" layer in zone 2 was greater than the HWCFZ (Figure 10c). Additionally, the EPC of the damaged geotechnical layer was obtained using the EPC formula. The southeast boundary area near the mine exhibited the highest permeability coefficient in the effective rock mass, with a maximum value close to 2.883×10^{-7} m/s. The lowest permeability coefficient was a value of 1×10^{-11} m/s. As for the effective soil, the maximum permeability coefficient was 4.72×10^{-8} m/s, and the minimum value was 2.25×10^{-10} m/s. Further calculations based on the EPC formula for the entire formation of the Yushen area yielded the EPC distribution (Figure 10d). The maximum EPC value was 8.15×10^{-7} m/s, while the minimum EPC value was 1.02×10^{-11} m/s.

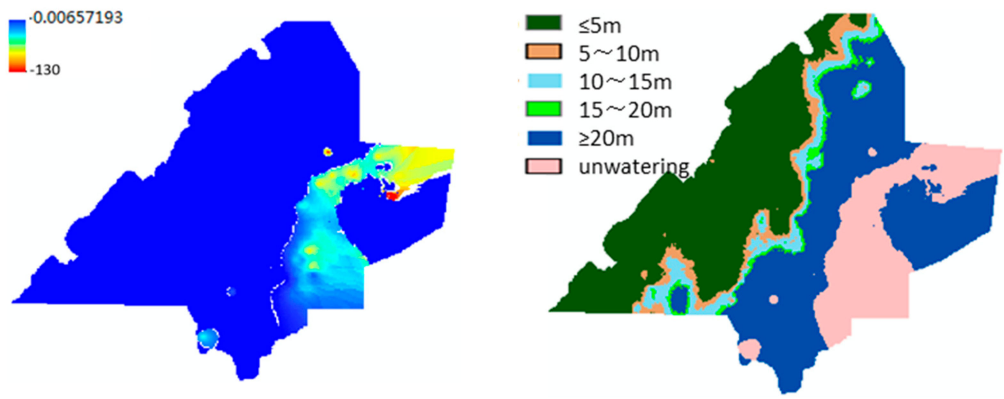


(a) (b) (c) (d)

Figure 10. EPC of the effective barrier layer. (**a**) Permeability of effective rock/(m/s); (**b**) permeability of effective soil/(m/s); (**c**) partition map; and (**d**) EPC/(m/s).

3.3. Mining Planning Based on the Sustainability of Shallow Water Systems

Combining the EPC of the effective barrier layer and the thickness of the equivalent barrier layer, Equation (5) was used to analyze the evolution of the shallow water level. The water head of the Yushen mining area was generated with GIS software (Figure 11a), The characteristic map illustrating the alterations in shallow water levels due to mining disturbances was reclassified and segmented into five distinct categories. The categorization outcomes are displayed in Figure 11b. Areas where the HWCFZ surpasses the coal-water distance are designated as dredging zones and fall outside the designated area. The first type is a water level drop of 0 to 5 m; the second type is a water level drop of 5 to 10 m; the third type is a water level drop of 10 to 15 m; the fourth type is a water level drop of 15 to 20 m, and the fifth type is a water level drop of more than 20 m.



(a) (b)

Figure 11. Depth of the shallow water table and classification. (**a**) Drop depth of shallow water; (**b**) classification of shallow water drop depth.

Based on the classification results and the WRCC evaluation system in the Yushen mining area, the bearing capacity status of water resources in different areas was evaluated and calculated, as shown in Figures 12 and 13. The WRCC in the first, second, and third categories was 0.913, 0.781, and 0.748, belonging to the carrying surplus, capable of carrying, and moderate bearing WRCC divisions in the mining areas, respectively. Therefore, the area of the above moderate carrying was 2.29×10^9 m^2, accounting for 54% of the planned area. The WRCC in the fourth and fifth categories was 0.636 and 0.373, respectively, corresponding to the slight overcarrying and severe overcarrying WRCC divisions in the mining areas. The overcarrying area in the mining area was 1.95×10^9 m^2, accounting for 46% of the planned area.

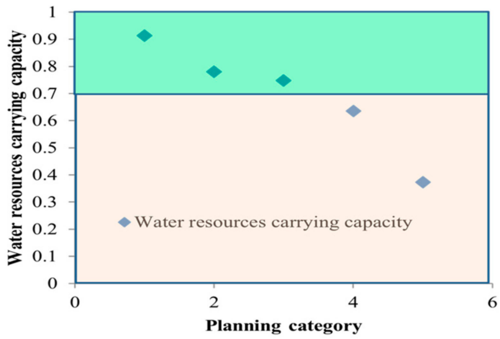


Figure 12. WRCC evaluation results.

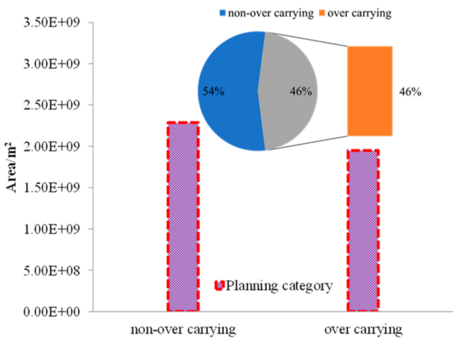


Figure 13. Classified area and proportion of the WRCC.

Combining the thickness of "Soil–Rock" layer and EPC, Equation (5) was used to analyze the water head value change in different mining areas. The mining areas were 1×10^8, 7.5×10^7, 5×10^7, and 2.5×10^7 m^2, respectively. The permeability coefficient of the aquifer was 5 m/d. The water head of the Yushen mining area was generated with GIS software, as shown in Figure 14a. The characteristic map of the distribution of water level changes under the influence of mining disturbance was classified, and the classification thresholds were selected as 5, 10, 15, and 20 m (Figure 14b). In addition, the allowable mining range was obtained. The largest allowable mining range in the Yushen area was based on the shallow water sustainability northwest of the wellfield. When the mining area was 1e8 m^2, the areas of classification 1–classification 5 were 1.77×10^9, 3.33×10^8, 1.86×10^8, 3.33×10^8, and 1.77×10^9 m^2, respectively (Figure 14c). Classification 5 had the largest area, with approximately 43% of the designed mining area; classification 1 came second, with approximately 42% of the designed mining area, and classification 3 had the smallest mining area, with approximately 3% of the designed mining area (Figure 14d). With the decrease in the designed mining area, the area of classification 1 gradually increased. The areas of classification 1 were 1.70×10^9, 1.98×10^9, 2.28×10^9, and 2.58×10^9 m^2, and the number of mines allowed to be mined in classification 1 of geological conditions was 18, 27, 47, and 107, respectively.

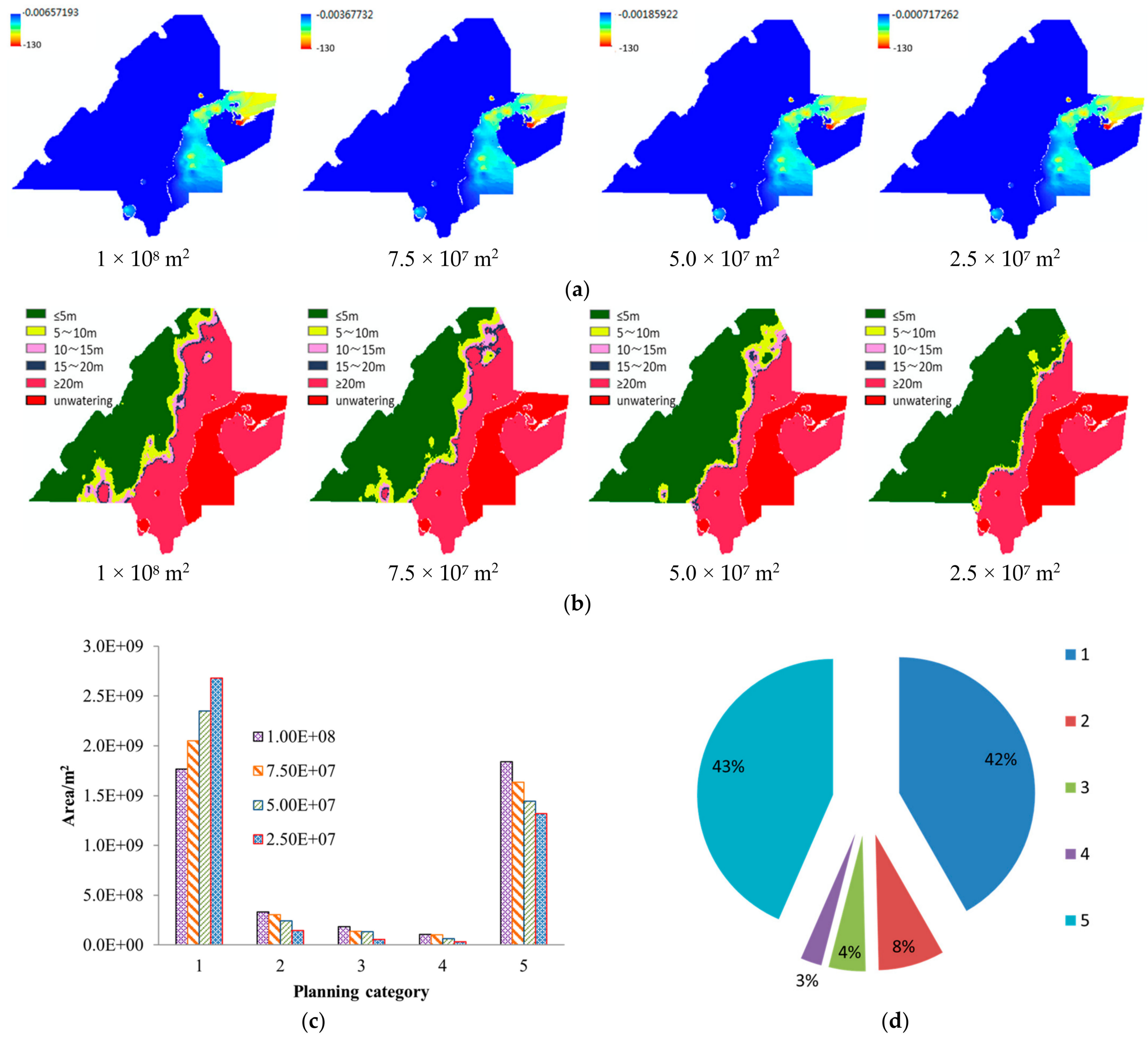


Figure 14. Depth and classification of the shallow water level in different mining areas. (**a**) Shallow water drop depth in different mining areas; (**b**) classification of shallow water drop depth in different mining areas; (**c**) planned areas of different types; and (**d**) proportion of different types of planning (mining area: 1×10^8 m^2).

According to the WRCC evaluation system under the influence of mining, the distribution characteristics of the WRCC of mines in different mining areas in different hydrogeological conditions were analyzed. The mining areas were 1×10^8, 7.5×10^7, 5×10^7, and 2.5×10^7 m^2, respectively. The WRCC of the Yushen mining area was generated with GIS software, as shown in Figure 15a. The characteristic map of the bearing capacity distribution of water resources under the influence of mining disturbance was classified and processed, and the classification thresholds were set as 0.9, 0.8, 0.7, and 0.6 according to the classification table of the equivalent water resource bearing capacity (Figure 15b). The place with the largest WRCC in the Yushen mining area was in the northwest of the wellfield, and the southeast area of the wellfield featured the smallest WRCC of large-scale mining. When the mining area was 1×10^8 m^2, the areas of carrying surplus, capable of carrying, moderate carrying, slight overcarrying, and severe overcarrying were 1.70×10^9, 2.26×10^8, 1.14×10^8, 1.69×10^9, and 4.99×10^8 m^2, respectively (Figure 15c). Classification 1 (carrying surplus) had the largest area, with approximately

40.2% of the designed mining area; classification 4 (slight overcarrying) accounted for approximately 39.98% of the designed mining area, and the mining area of classification 3 (moderate carrying) was the smallest, with approximately 1.7% of the designed mining area (Figure 15d). With the decrease in the designed mine's mining area, the area of classification 1 (carrying surplus) gradually increased. The areas of the carrying surplus were 1.70×10^9, 1.98×10^9, 2.28×10^9, and 2.58×10^9 m^2, and the number of mines allowed to be mined under the geological conditions with a moderate carrying capacity was 20, 31, 51, and 112, respectively.

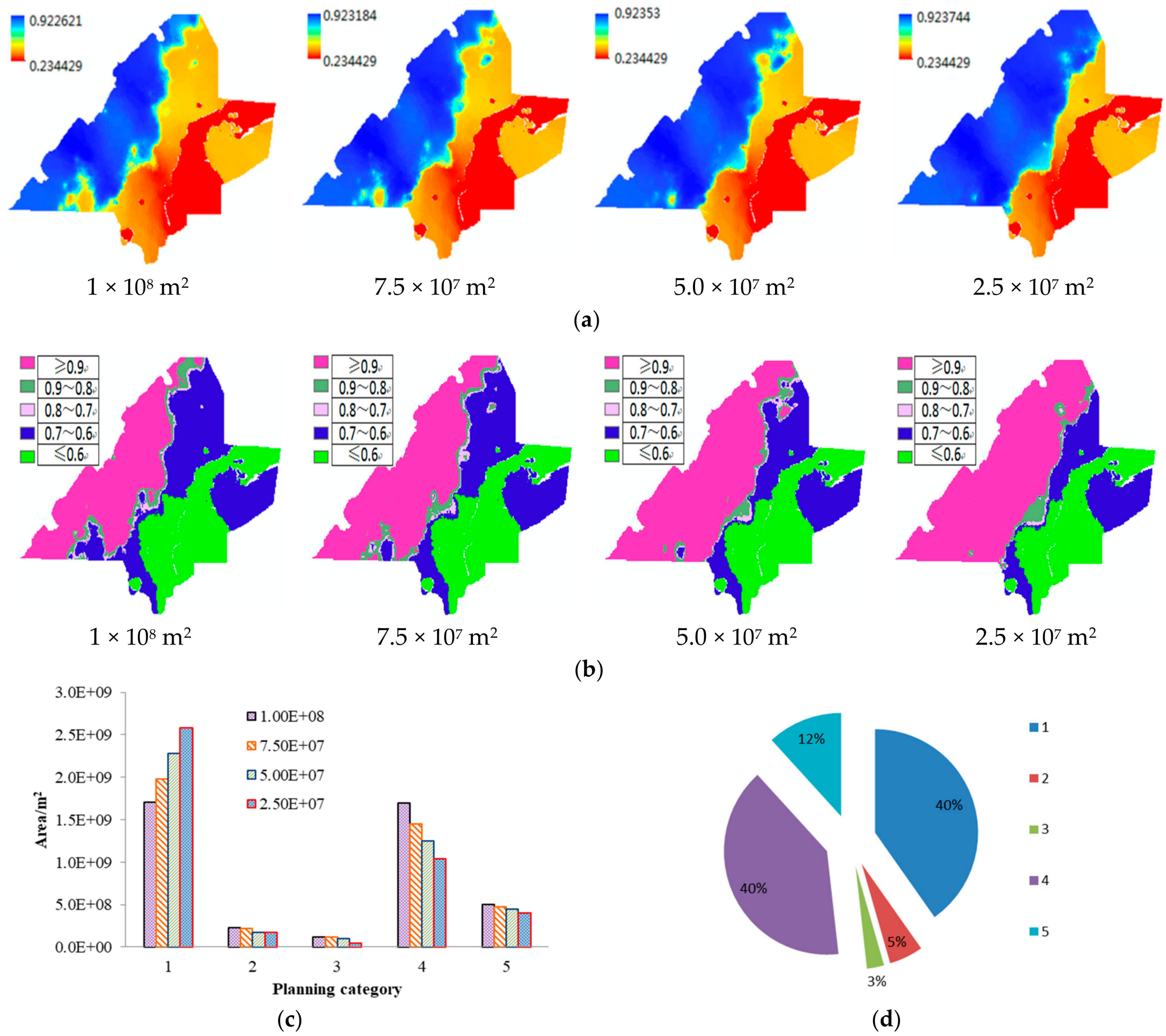


Figure 15. WRCC and classification in different mining areas. (**a**) WRCC in different mining areas; (**b**) WRCC classification in different mining areas; (**c**) planned areas of different types; and (**d**) proportions of different types of planning (mining area: 1×10^8 m^2).

4. Discussion

In this paper, to maintain the groundwater level, we carried out in-depth research on the mechanism and quantitative evaluation of shallow groundwater leakage at the Yushen mining area scale. A calculation method for the EPC of overburden and the planning method were proposed.

Mastering the evolution law of shallow groundwater is an important prerequisite for protecting shallow water systems [24–26]. This study aimed to reveal the evolution law and redistribution characteristics of shallow water flow fields in single/multi-mining units of different sizes at the mining scale [27,28]. The key was to establish a relationship model between shallow water level depth reduction and the shape, size, and quantity of mining units. Clarifying the effects of mining units on shallow water overlays was fundamental [29–31]. A leak model of a shallow aquifer in the mining area was constructed, the leakage mechanism of shallow groundwater leakage in the mining area was analyzed, and the water head changes in the shallow aquifer under the disturbance of exploitation were quantified. The calculation formula for the shallow water leakage of mining parameters within the mining area was given.

However, the degree of shallow water disturbance and recovery process in a mining area is affected by the non-uniform sinking and permeability of the mining insulation rock and soil layer and the cumulative effect of large-scale mining [32–34]. It is necessary to strengthen the understanding of the morphology and permeability of the articulated structure of the overlying rock layer. The elimination and self-healing characteristics of the water insulation of the water-separated rock and soil layers, the superimposed effect of multiple empty mining areas on shallow water, and the recovery time of the shallow water in multi-mining units are key points that must be solved.

5. Conclusions

(1) Utilizing the drilling data from the Yushen area, a thematic map was developed to illustrate the depth of the buried coal seam, the distance between coal and water bodies, soil layer thickness, coal seam thickness, and aquifer depth. Subsequently, a modified six-step mining planning approach was formulated, with a focus on ensuring the sustainability of the shallow groundwater systems.

(2) The EPC calculation method was given, and the EPC of the overburden within the Yushen area was obtained. The maximum EPC was 8.15×10^{-7} m/s, and the minimum value was 1.02×10^{-11} m/s. The calculation formula for the shallow water leakage with different mining areas was constructed. On this basis, the calculation formula for shallow water leakage at the Yushen mining area scale was given.

(3) The area of classification 1 (carrying surplus) gradually increased with the decrease in the mining area of the designed mine. The areas of the carrying surplus were 1.70×10^9, 1.98×10^9, 2.28×10^9, and 2.58×10^9, and the number of mines allowed to be mined under the geological conditions with a moderate carrying capacity was 20, 31, 51, and 112, respectively.

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