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Research Article

Defects and Improvement of Predicting Mine Water Inflow by Virtual Large Diameter Well Method

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In order to prevent the occurrence of water inrush accidents, it is particularly important to predict the mine water inrush, especially the accurate prediction of the mine water inflow in the coal mining process. Mine water inflow is caused by mining disturbance, groundwater flows into mining panels along the mining-induced fissures, and a depression cone of water table is formed in certain range around the mining sites. Mining panel is usually regarded as an irregular "virtual large diameter well" so as to calculate mine water inflow in China. However, in the mining process, the area, shape, and cross section of goafs are constantly changing, so is the water inflow. Therefore, the central position and influence radius of the "virtual large diameter well" in the spatial and temporal distribution are in a dynamic process of continuous movement and expansion, rather than being confined to a static position. This paper firstly analyzes the formation mechanism of coal mine roof water inflow and the errors and defects in the calculation of mine water inflow by virtual large diameter well (VLDWM). Then, based on the theory of steady flow and combined with the dynamic change process of goaf area and depression cone of water table during mining activities, this paper proposes an improved method and puts forward a concept of dynamic virtual large diameter well (DVLDWM) and establishes a theoretical model of the central position and influence radius of the "mining large diameter well" moving forward. The first (periodic) caving step is taken as the calculation unit and generalized as the "dynamic large diameter well," which is used to calculate the dynamic water inflow in the process of mine advancing. Taking the No.7208 mining panel in Zhangshuanglou Coalmine in Xuzhou City, Jiangsu Province, as the study area, the mine water inflow was calculated dynamically by using the DVLDWM. The results show that the mine water inflow calculated is similar to the actual mine water inflow of the No.7208 mining panel observed, thus proving the reliability and credibility of the DVLDWM.

1. Introduction

China is one of the world's largest mining economies and the number, scale, and difficulty of China's mine water problems are unique. Compared with those of other countries, the coal mining areas in China are characterized by complex hydrogeological conditions and various mining depths [1, 2], and the roof and floor rocks of coal seams are greatly affected by the groundwater from the confined sandstone aquifer, loose sandy and soil aquifer, limestone-karst aquifer and goafs water [3, 4]. Water inrush accidents not only lead to heavy casualties and property losses, but also the increasing cost of mine water treatment in coal mines [5–7]. According to the data released by the State Coal Mine Safety Supervision Bureau, 1027 water inrush accidents occurred in coal mines from 2000 to 2021, resulting in 4390 deaths. In 2021, a total amount of 7.3 billion m^3 mine water from aquifer and mining activities was formed, and more than 10 billion CNY was used to prevent, control, treat, and rehabilitate mine water [8]. In this case, it is particularly important to explore a method of predicting mine water inflow so as to prevent the occurrence of mine water inrush accidents [9, 10], especially with regard to how to enhance the accurate prediction of mine water inflow in mining panel [11, 12].

Many researches have been carried out on the prediction method of mine water inflow, including water balance method, hydro-geological analogy method, correlation analysis method, numerical method, and conventional analytical method [13–17]. Miladinovic et al. used a multiple linear regression model to simulate the situation of mine water flowing into the mine and conducted short-term prediction of mine water inflow [18]. Wu et al. proposed the variable weight model (VWM) to evaluate the hydrodynamic process of groundwater inflow [19]. Yao et al. analysed the change of mine water inrush by establishing a numerical model of the roof fracture and seepage development law [20]. Sun et al. used Visual Modflow software and numerical simulation method to evaluate the flow field of karst water under large-scale mining conditions [21]. Surinaidu et al. established a numerical model of groundwater flow based on finite difference and predicted ground-water inflow at different stages of mine advancement [22].

Darcy's Law [23], which was obtained through seepage column experiments by Darcy in 1856, has led to the transition of hydrogeology from qualitative descriptions to quantitative calculations, and it is an important milestone in the history of hydrogeology. Seven years later, Dupuit established the Dupuit steady flow model based on Darcy's Law and derived the steady flow formula known as the Dupuit formula [24]. Thiem [25] extended the Dupuit model to a horizontal infinite aquifer using an approximate hypothesis and thus established the Thiem model. Generally, when the principle of the Dupuit model and the Thiem model is used to calculate mine water inflow in China, it is called the virtual large diameter well method (Figure 1). After a long period of water gushing, relatively steady flow field with goaf as the discharge point is formed in the mining panel. At this time, the groundwater runoff basically meets the steady runoff condition, which can be regarded as steady runoff flow field. On this basis, the VLDWM regards the complex system as steady runoff discharge system with the central large well, and the irregular pit system as the area of the large well, and summarizes a complex geological condition as homogeneous strata of the same medium. Then, the water inflow of the large diameter well can be regarded as the water inflow of the whole mining area [26, 27]. Accordingly, the Dupuit steady flow equation can be used to predict the water inflow of the mining area. In recent years, some scholars have optimized the calculation parameters, aquifer conditions, and influence radius of the VLDWM [28] or revised the formula according to real water inflow, but the theoretical equations for the evolution of dynamic water inflow is not presented yet, for its changing process is fuzzy [29, 30].

On the ground of analyzing basic theories, assumptions and calculation errors of the existing calculation methods of mine water inflow and groundwater flow field, this paper exploratorily puts forward the scientific concept and calculation principle of dynamic virtual large diameter well method (DVLDWM). Then, the DVLDWM was utilized to calculate water inflow at the No.7208 mining panel of Zhangshuanglou Coalmine and reveal the dynamic water inflow process of the Quaternary bottom gravel aquifer of the coal mine roof in the study area. The calculation results were also compared with the traditional the VLDWM and the actual mine water inflow observed in the No.7208 mining panel, which could be applied to verify that the DVLDWM is reliable for the calculation of dynamic water inflow during the mining process.

2. Study Area

Zhangshuanglou Coalmine is located in Pei County, 79 km away from Xuzhou City to the northwest, Jiangsu Province, China. As is shown in Figure 2, it is located in the range of the Yellow River alluvial plain, with the geomorphology being relatively flat. The weather conditions of the Zhangshuanglou Coalmine belong to the south temperate Huanghuai region-monsoon continental climate, with the annual average temperature and precipitation being 13.8 °C and 811.7 mm, respectively. The maximum and minimum of annual precipitation are 1178.9 mm (1977) and 550 mm (1968), respectively. The Dasha River passes through the study area from north to south, with Xupei River in the east and Fengpei River in the south. The frozen soil depth is 19 cm, with an average of 12 cm.

There are no faults, collapse columns, and other structures in the No.7208 mining panel, so mining activities has no in situ stress effect. Moreover, the mining panel is located in the shallow part of the mining area, and there is no impact of rock burst.

3. Theories and Methods

3.1. Formation Mechanism of Mine Roof Water Inflow. The example of water inflow from coal seam roof rocks is shown in this paper. When the coal seam is to be mined out, the roof rock collapse and fracture development would occur consequently [31]. The rock collapse and fracture zones can be divided into three stages in the mining panel, and the phenomenon lasts through the whole mining period from the formation of panel to the first weighting, periodic pressure stage, and the end of mining [31].

The area of the goaf is small, and its surrounding rock bears less but relatively concentrated stress from the upper rock mass when the first weighting occurs above the roof of mining panel [32]. At the beginning, the mining influence of coal seam is weak, which is mainly manifested in concentrated stress and caving rock stratum; and the range of rock movement, deformation, cracking, and collapse is small, so the panel water inflow is relatively small. After entering the periodic pressure stage, the roof rock mass collapses downward, further developing fractures upward, and the upper rock stratum bends and sinks until all the coal seams are mined out. The water conducted fissure zone of stable roof will be formed in the roof rock stratum of the stope and the coal seam. When the fracture zone connects the roof aquifer of coal seam with the mining panel, the groundwater

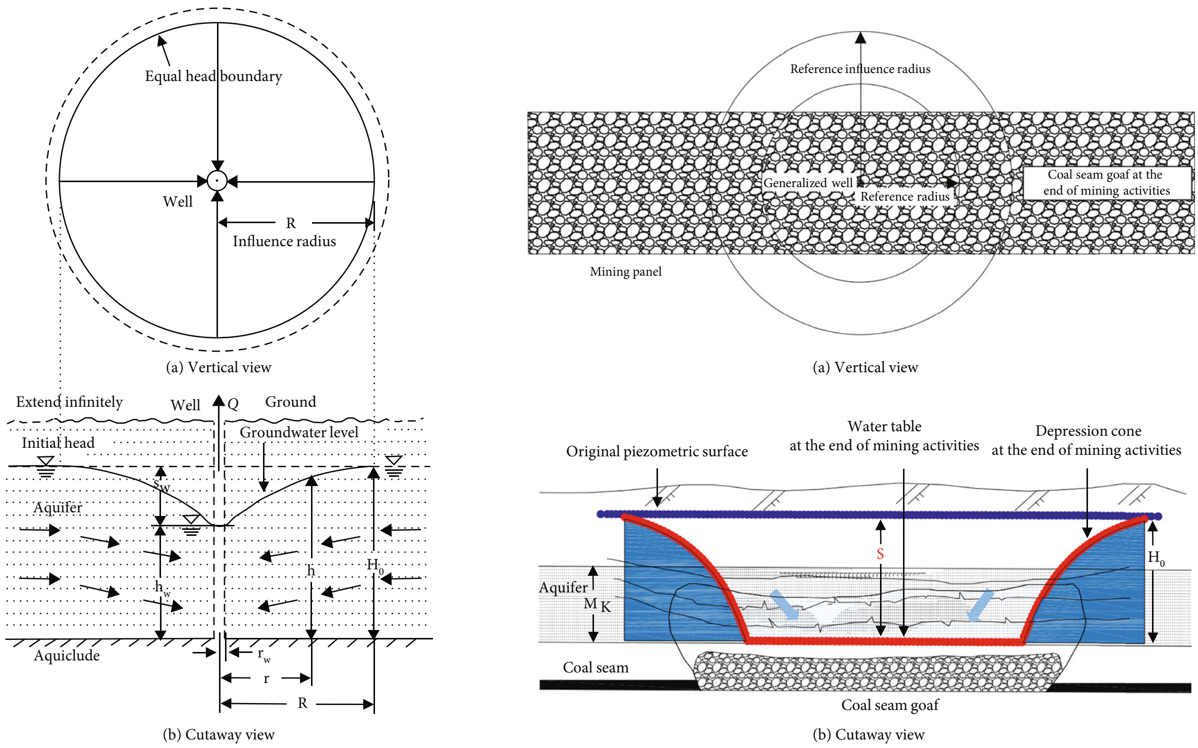


FIGURE 1: Schematic diagram of Thiem model and VLDWM.

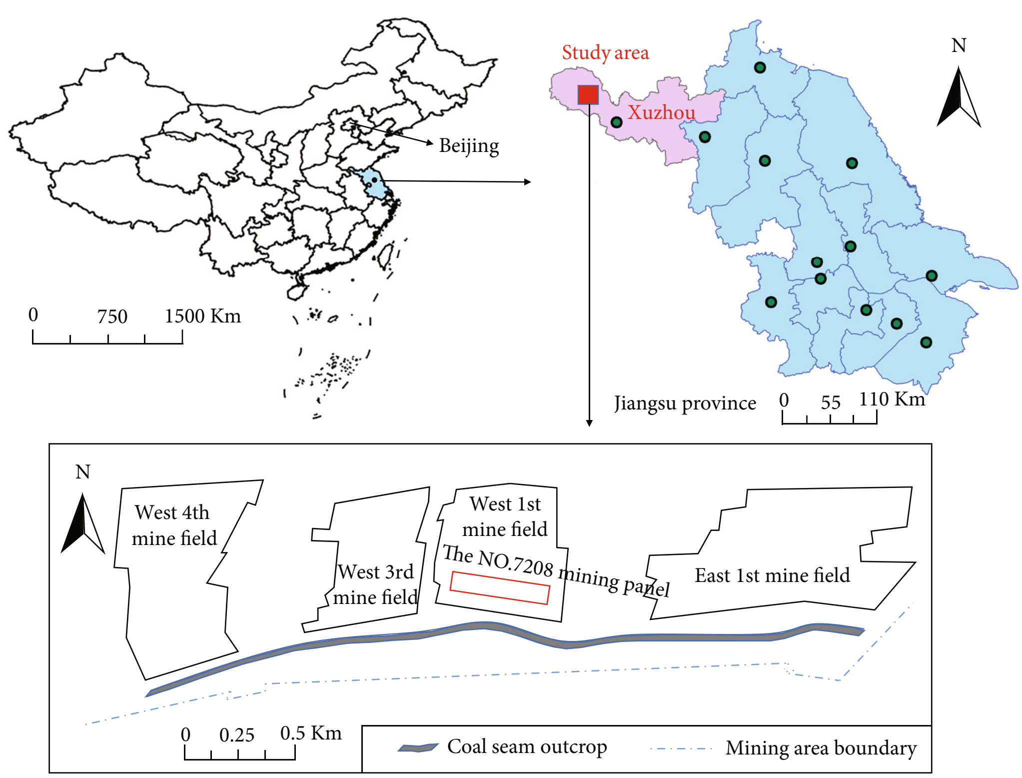


FIGURE 2: Location of the study area.

in the aquifer flows into the goaf, roadway, and mining system along the mining fissures to form mine water inflow, as shown in Figure 3.

3.2. Theoretical Defects of VLDWM. The theoretical formula of steady flow has strict assumptions, which makes it unadaptable to the complex actual hydrogeological

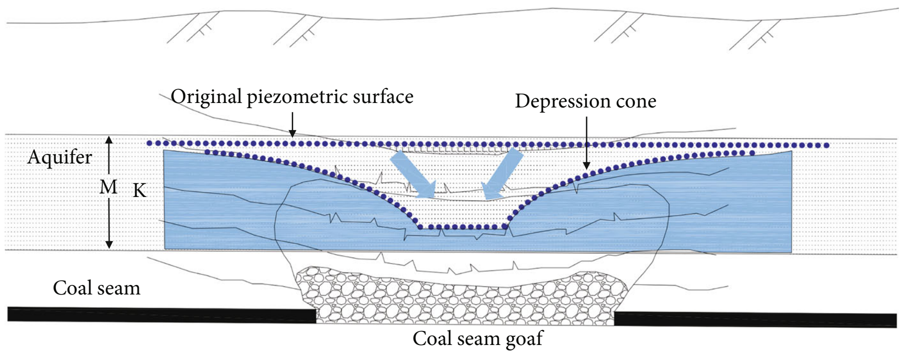
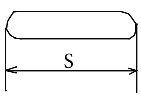
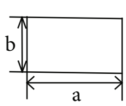
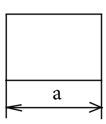


Figure 3: Formation mechanism of mine roof water inflow.

Table 1: Generalization of large diameter wells with different sketches.

Plane figure of mine pit		r_0 expression	Explanation
	Long strip	$r_0 = S/4 = 0.25S$	S is length, Only when width/length →0 is used
	Rectangle	$r_0 = \eta(a + b/4)$	a and b are the rectangular side lengths; η can be seen in Table 2
	Square	$r_0 = 0.59a$	a is the edge length of square

conditions. The generalized hydrogeological conditions of the mining area are usually named as "hydrogeological conceptual model" [33], which is the qualitative description of the groundwater system movement in mining area. "Virtual large diameter well" is in nature a hydrogeological conceptual model. In order to apply the theoretical formula of steady flow, it is necessary to reasonably summarize and simplify the hydrogeological conditions of the mining area, without distorting the original conditions in certain range.

A depression cone with a certain shape centered on the goaf area is to be formed around the mine site when the mine water drainage is conducted, which is similar to the formation of a depression cone of water table around the pumping well. Therefore, the distribution range of the panel goaf area can be assumed to be an ideal large diameter well.

It is assumed that the circular section area of the large diameter well is equivalent to the area of the goaf area distribution. Therefore, the equation of groundwater dynamics can be directly used to calculate the water inflow of mining panel, and the calculation equation for confined aquifer is used:

$$Q = 2.73K\frac{MS}{\lg R_0 - \lg r_0}, \tag{1}$$

$$R = 10S\sqrt{K}, \tag{2}$$

$$R_0 = R + r_0, \tag{3}$$

Table 2: The relationship between b/a and η.

b/a	0	0.20	0.40	0.60	0.80	1.00
η	1.00	1.12	1.14	1.16	1.18	1.18

where Q denotes the water inflow of the mining panel (m^3/s); K is the hydraulic conductivity (m/s); M refers to the thickness of aquifer (m); S is the water table drawdown caused by mine water drainage (m); R_0 stands for the reference influence radius (m); r_0 is the reference radius (m); and R denotes the influence radius (m).

It should be noted that the variable R is only related to the water table drawdown and hydraulic conductivity. R depends on the shape and sketch of the goaf area of mining panel η [34]. The calculation methods of large diameter well and reference radius with different profiles are shown in Tables 1 and 2.

Based on the steady well flow theory, the VLDWM generalizes the whole mining panel into a "large diameter well," and the predicted mine water inflow refers to the flow formed when the water flow reaches an approximately steady state at the end of the mining panel. This theory does not consider the transition of large well flow from steady flow to transient flow, and the way and time of releasing water stored in the aquifer to the mining panel. In fact, the mining process in the mining panel (or mining area) is a

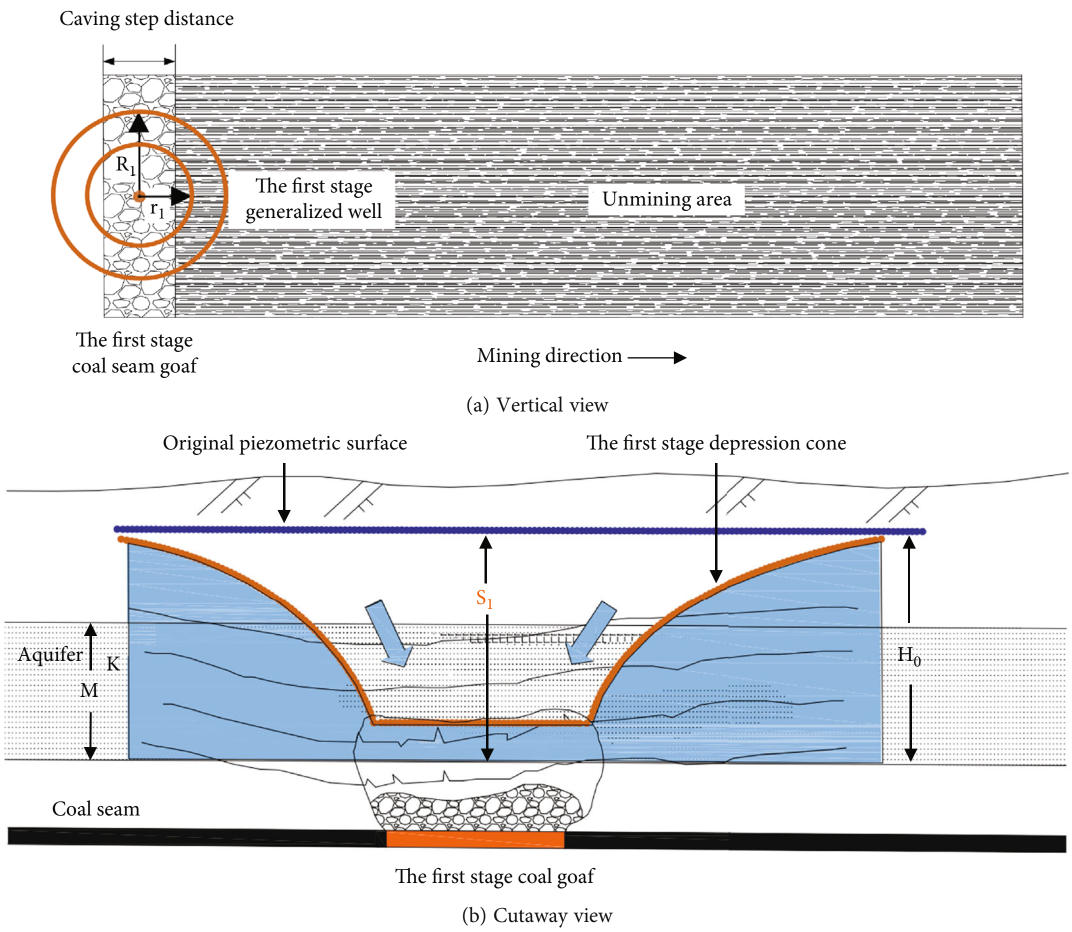


Figure 4: The first stage of the depression cone.

step-by-step process, which does not form the goaf at once. In fact, at the beginning of mining activities, the affected area by mining is small, the water flow section is limited, and the water inrush quantity is relatively little. Therefore, using conventional the VLDWM to calculate water inflow often leads to larger results, even exceeding the warning magnitude.

3.3. The Improved Method of VLDWM. Groundwater flow in mine area is transient, because it is not only affected by seasonal climate changes, but the mining activities. Groundwater often forms transient flow centered on the goaf when the depression cone becomes larger during the mining process. Transient flow theory displays better practicability because it can describe the whole process of groundwater moving to goaf. However, there still exists the steady flow condition in the process of mining activities. For example, the aquifer has abundant supply water, or the mine water inflow and supply are approximately equal in the early stage of mining activities.

In field experiments, the area and shape of the goaf are constantly changing, and water flow section is also constantly increasing with the continuous advancement of the mining panel. Accordingly, depression cone is expanding, and water inflow is also increasing. The central position and influence radius of "large diameter well" in spatial and temporal distribution is in a dynamic change process of continuous movement and expansion, rather than being confined to a static position. Besides, since steady flow formula does not contain time variables, the transient flow theory should be used so as to understand the dynamic change process of mine water inrush.

Based on the theory of steady flow and combined with the dynamic change process of goaf area and depression cone in the mining process, the concept and method of the DVLDWM are proposed. On this basis, the theoretical model is established of the central position and influence radius of "mining large diameter well" which moves forward continuously. With this improved method, the initial (periodic) collapse step is taken as the calculation unit, and the "mining large diameter well" is generalized as "dynamic large diameter well" so that the dynamic mine water inflow advancing with the mining panel can be calculated more accurately.

4. Discussion and Results

4.1. Calculation Principle and Method of the DVLDWM. Assumption: The aquifer is an infinite boundary, and the infinite distance is a constant head boundary. With the excavation of the mining panel, the local water table in the goaf will drop [35–38].

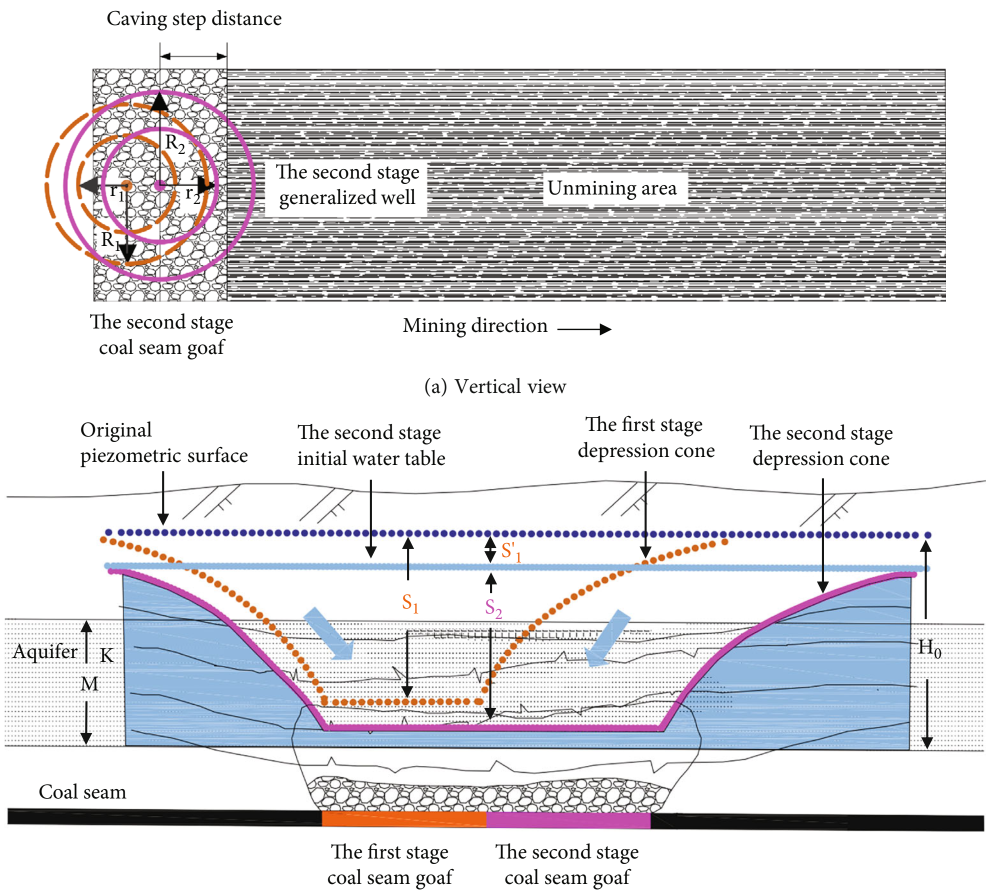


Figure 5: The second stage of the depression cone.

In the first stage, the first collapse and the aquifer form the first depression cone during the excavation of the mining panel (as shown in Figure 4). The confined aquifer calculation formula is used to calculate the water inflow Q_1 of the mining panel at the end of the first stage:

$$Q_1 = 2.73K\frac{MS_1}{\lg R_1 - \lg r_1}, \tag{4}$$

$$R_1 = 10S_1\sqrt{K} + r_1, \tag{5}$$

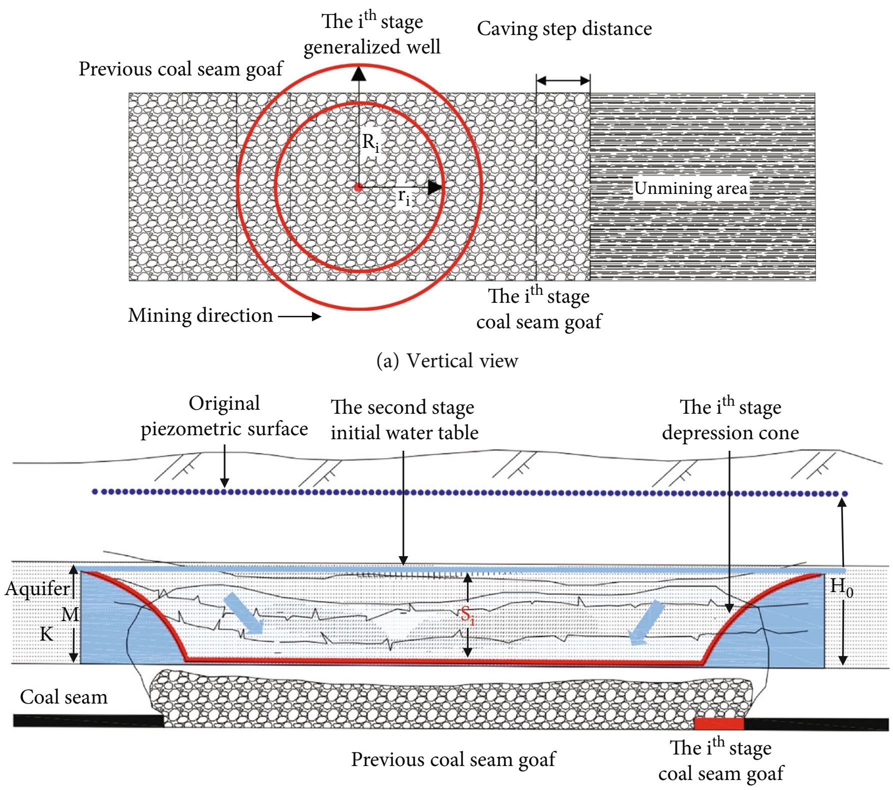
where Q_1 denotes the water inflow of the mining panel at the end of the first stage (m^3/s); H_0 means the initial water table of the aquifer (m); K refers to the hydraulic conductivity (m/s); M is the thickness of aquifer (m); S_1 stands for the water table drawdown caused by mine drainage in the first stage (m); R_1 denotes the reference influence radius of the first stage (m); and r_1 means the reference radius of the first stage (m).

(1) The drawdown in the first stage (S_1): The traditional VLDWM is used to predict the mine water inflow [39, 40], and the depression cone is usually taken from the roof to the floor of the aquifer. However, the aquifer water table is difficult to drain to the floor, and the maximum depression cone value will change with the excavation of the mining panel in field processing, especially in western China. Therefore, it is assumed that the first stage drops $S_1 = \lambda H_0$ and λ can be obtained by the following two methods:

(a) When the first stage of mining is completed, the approximate theoretical formula of transient flow (Jacob's formula) is used to calculate the flow at the center of the "generalized-well" of the mining panel. To be specific, the drawdown of the water table is observed through the long observation hole in the aquifer adjacent to the mining panel; and then the water inflow in the center of "large diameter well" in the first stage can be obtained by the following formula:

$$Q' = \frac{S_r T}{0.183 \lg\left(2.25Tt_1/r_1^2\mu^*\right)}, \tag{6}$$

where Q' denotes the water inflow in the center of "large diameter well" in the first stage



(a) Vertical view

(b) Cutaway view

FIGURE 6: The i^th stage of the depression cone.

calculated from observation logging (m^3/s); S_r means the drawdown of observation well (m); T refers to transmissivity (m^2/s); t_1 means the time required for the first stage of mining (s); r_1 is the distance from observation point to well center (m); and μ^* denotes coefficient of storage (dimensionless).

According to the flow rate at the center of the "generalized-well" in mining panel, the water table drawdown of the aquifer at the center of the "generalized-well" can be reversely deduced by using the confined aquifer formula of the Dupuit's law, and then λ can be obtained:

$$Q' = \frac{2.73KMS_1}{\lg\left(10S_1\sqrt{K} + r_1\right) - \lg r_1}, \quad (7)$$

$$\lambda = S_1/H_0. \quad (8)$$

(b) According to the existing mine water inflow caused by the initial collapse of mining panel, the drawdown of aquifer water table at the center of "generalized-well" can be deduced by using the Dupuit's law confined aquifer formula, and then $\lambda = S_1/H_0$ can be obtained

(2) Initial water table of aquifer (H_0): The natural water table elevation of confined aquifer within the water-conducting fracture zone of coal seam roof is based on coal seam floor

(3) Hydraulic conductivity (K): The hydraulic conductivity value is calculated according to the steady flow Dupuit's law formula based on the test data of pumping (draining) water from boreholes in field tests

(4) Aquifer thickness (M): It refers to the accumulated thickness of aquifer within the water-conducting fracture zone of coal roof

(5) Substitute influence radius of the first stage (R_1): It is obtained according to the "generalized-well" after the first collapse of the mining panel

(6) Reference radius of the first stage (r_1): It is obtained by the generalization of "large diameter well" contour after the first collapse of the mining panel

In the second stage, the depression cone expands, and the drawdown decreases compared with that in the first stage (Figure 5). The drawdown formed by the mine inflow generated in the first stage is used to push back the "initial" water table in the center of the "large diameter well" before the end of the second stage and the periodic collapse. The drawdown formed here by the mine water inflow in the first stage can be calculated by Jacob's formula of the approximate theory of transient flow:

$$S_1' = \frac{0.183Q_1}{T} \lg \frac{2.25Tt_1}{r_1^2\mu^*}, \quad (9)$$

where S_1' means the actual drawdown of water table caused by mine water inflow in the first stage (m); Q_1 denotes the water inflow in the first stage (m^3/s); T means transmissivity (m^2/s); t_1 refers to the time required for the first stage of mining (s); r_1 stands for the reference radius of the first stage (m); and μ^* means coefficient of storage (dimensionless).

The water table drawdown in the second stage (S_2): The water inflow Q_2 at the end of the second stage and after the cycle collapse can be obtained by repeating the calculation of mine water inflow with the following formulas:

$$S_2 = \lambda\left(H_0\text{-}S_1'\right), \quad (10)$$

$$Q_2 = 2.73K\frac{MS_2}{\lg R_2 - \lg r_2}, \quad (11)$$

$$R_2 = 10S_2\sqrt{K} + \text{r}_2, \quad (12)$$

where Q_2 means the water inflow of mining panel at the end of the second stage and backward cycle collapse (m^3/s); H_0 denotes the initial water table of aquifer (m); S_2 means the water table drawdown caused by mine drainage in the second stage (m); R_2 refers to the reference influence radius of the second stage (m); and r_2 means the reference radius of the second stage (m).

With the continuous advance of the mining panel, when the water table of the aquifer decreases below the roof (Figure 6), the following equation shall be adopted to calculate the water inflow of the mining panel:

$$Q_\text{i} = 1.366K\frac{(2H - M)M - \text{h}^2}{\lg R_i - \lg r_i}, \quad (13)$$

where Q_i means the water inflow of mining panel after the first stage is over and the cycle collapses (m^3/s); R_i denotes the substitute influence radius (m) in the i^{th} stage; and R_i means the reference radius (m) in the i^{th} stage.

The caving step is introduced as the calculation unit to calculate the mine water inflow by stages during the mining process. Then, repeat the similar calculations until the end.

The mining scope and influence radius ("large diameter well" radius) gradually expand during the mining process, and a new depression cone and water table drawdown will be formed in each mining stage. The DVLDWM for mine water inflow calculation is based on the new initial water table formed by the drainage of aquifer by previous mining stage, which greatly corrects the error of mine water inflow calculated by the traditional VLDWM. The key point of the DVLDWM is that the water table and the influence radius caused by coal mining, which are used to calculate the mine water inflow, will both be affected by the previous stage.

Generally, both the VLDWM and the DVLDWM are based on the theory of steady flow to predict mine water inflow. The difference is that the VLDWM can only calculate the total mine water inflow when the mining-induced aquifer reaches steady state at the end of the mining process in a panel, and then, the changes of the water table and the influence radius in each stage during the mining process were not considered. However, the above defects are totally considered in the DVLDWM, and a great improvement is achieved.

Table 3: Comparison between the DVLDWM calculation and actual observed results.

The excavated distance of the mining panel (m)	Mine water inflow (m^3/h)	
	Calculation results	Actual observed results
15	5.19	3.1
30	5.41	3.5
45	5.91	3.4
60	6.43	4.0
75	6.92	4.8
90	7.42	6.9
105	8.50	8.4
120	8.28	7.0
135	8.78	8.5
150	9.16	8.7
165	10.43	8.4
180	10.79	7.0
195	11.17	10.1
210	11.62	11.1
225	12.07	10.4
…	…	…
390	18.65	16.2
405	19.11	24.8
420	19.58	19.1
435	19.88	19.3
450	20.36	19.1
465	20.83	19.0
480	21.29	21.0

4.2. Case Comparison and Superiority Analysis. Both methods are employed to calculate the water inflow of the target mining panel in the study area. The NO.7208 mining panel is 105 m in width and 480 m in length. The length for periodic roof weighting is 15 m. Moreover, M (aquifer thickness) = 14 m, K (hydraulic conductivity) = 0.0033 m/s,

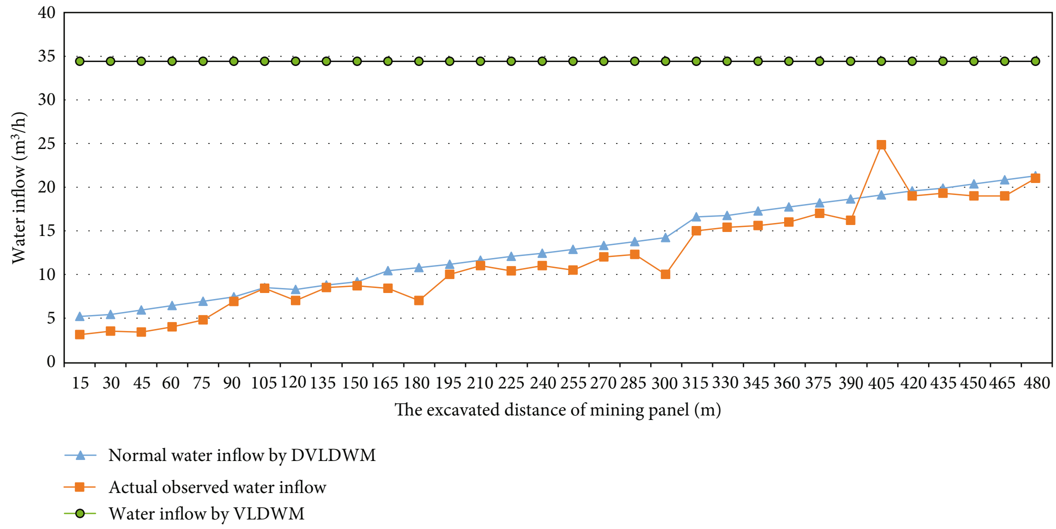


FIGURE 7: Prediction of water inflow variation curve of the mining panel by two methods and actual observed water inflow.

μ^* (coefficient of storage) = 1.8×10^{-4}, T (transmissivity) = $0.0467\ m^2/s$, and H_0 (initial water table) = 150 m.

(1) According to traditional VLDWM:

$$Q = 2.73K \frac{MS}{\lg R - \lg r}, \quad (14)$$

$$R = 10S\sqrt{K} + r. \quad (15)$$

The mining panel water inflow is $Q = 34.4\ m^3/h$ ($0.00956\ m^3/s$).

(2) In the light of DVLDWM, the dynamic change of water inflow during the whole mining process of the NO.7208 mining panel is confirmed. Besides, the λ values can be calculated as 1/10, 1/6, and 1/3, respectively, by using the observed water inflow during the real mining process of the mining panel. The calculation results and their change trends are shown in Table 3 and Figure 7

The observed water inflow during the mining process of the panel is about 3-10 m^3/h (0.000833-0.002778 m^3/s) in the initial stage, 15 m^3/h (0.004167 m^3/s) in the middle stage, and at most 21 m^3/h (0.005833 m^3/s) in the later stage. The calculation results obtained by DVLDWM are consistent with the actual mine water inflow, which proves that the calculation theory, method, and results of the DVLDWM are more reliable than before.

Summarily, the results obtained by the VLDWM are obviously larger than the observed ones, and the DVLDWM results are closer to the observed ones. Moreover, the calculation accuracy of mine water inflow by using the DVLDWM is greatly improved compared with that of the traditional VLDWM. In this sense, the DVLDWM achieves the goal of dynamically predicting the mine water inflow finally. These are also the innovative aspects of this paper.

5. Conclusions

(1) It is particularly important to predict the mine water inrush for preventing the occurrence of water inrush accidents, especially the accurate prediction of the mine water inflow in the coal mining process. In this paper, the defects of the widely used VLDWM were analyzed. We improved the VLDWM based on the actual water inflow principles during mining processes, and a calculation method of water inflow quantity with higher accuracy was named as DVLDWM

(2) The DVLDWM proposed in this paper for mine water inflow calculation is based on the new initial water table formed by the drainage of aquifer by previous mining stage, which greatly corrects the error of mine water inflow calculated by the traditional VLDWM. The key point of the DVLDWM is that the water table and the influence radius caused by coal mining, which are used to calculate the mine water inflow, will both be affected by the previous stage. Generally, the defects of the VLDWM are totally considered in the DVLDWM and a great improvement is achieved

(3) According to the principle and calculation of the DVLDWM, and combined with the groundwater inflow observed at the NO.7208 mining panel in the study area, the λ values in the first, middle, and later stage are calculated, and the water inflow in each stage of the mining panel advancement is dynamically presented. Compared with the calculation results obtained by the traditional VLDWM, the calculation results of DVLDWM greatly reduce

the calculation error and are consistent with the actual observation records of mine water inflow in the mining panel. The quantitative comparison result proves that the calculation principle of the DVLDWM displays higher reliability than the traditional VLDWM

Data Availability

The (data type) data used to support the findings of this study are included within the article.

Conflicts of Interest

There is no conflict of interest regarding the publication of this paper.

Acknowledgments

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