Analysis of the Groundwater Resource Pollution of Coal-Fired Power Plants and Its Impact on Geotechnical Engineering Properties by Numerical Simulation Technology

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Abstract. Objective: The objective is to investigate the impact of groundwater resource pollution of coal-fired power plants and its impact on the properties of geotechnical engineering based on numerical simulation technology, thereby proving the effectiveness and superiority of numerical simulation technology in preventing groundwater resource pollution and forecasting the related information, which would provide direction and guidance for the treatment and management of groundwater resource pollution. Method: First, the regions to be investigated are divided and generalized. Then, relevant experiments are carried out for the calculations of hydrogeological parameters to establish the hydrogeological conceptual model. Next, the real-time water level data recorded by the observations are used to identify and verify the model effectively. Afterward, the numerical simulation of groundwater solute transportation is carried out again. During the process, the establishment of the groundwater quality model is the focus, followed by the application of numerical simulation technology to forecast the environmental impacts of groundwater pollution, including the forecasting of groundwater environmental pollutions caused by Chemical Oxygen Demand (COD) leakage, ash yard, and power plants. Results: Through the application of numerical simulation technology, the current information about groundwater pollution, such as the scope of impact and the movement law of pollution, can be understood clearly and timely. Conclusion: By applying the numerical simulation technology in forecasting groundwater pollution, the groundwater pollution problems can be prevented effectively, which offers great help to the correct and reasonable operation and development of coal-fired power plants, which provides a significant reference for the preventive treatment of groundwater pollution.

Keywords: Numerical simulation; water resource pollution; water quality model; movement law.

1. Introduction
With vast land areas and abundant natural resources, China has rich coal resources. In addition, due to its low-cost investment and mature development and construction technologies, the application of coal
for power generation has become the major means of power generation in China [1-3]. In recent years, the application of coal in power generation has become the core of the Chinese electric power industry, accounting for more than half of the total power generation in China [4-6]. With the continuous advancement and development of society, the application of coal is increasing in both scale and assumption, which also causes a series of negative effects, especially the pollution of groundwater resources [7-9].

The application of coal in power generation cannot avoid the exploitation of groundwater. However, due to the uncontrolled and incorrect mining of developers, a series of serious problems that are difficult to be solved has been caused, such as seawater intrusion and ground subsidence, in which the most serious problem is the groundwater pollution that poses great threats to the lives of residents [10, 11]. Therefore, the prevention and treatment of groundwater pollution are of great significance. Most importantly, prevention is an essential link [12, 13]. In recent years, experts and scholars have conducted in-depth research on the issue, providing a certain reference and direction for the prevention of groundwater pollution [14, 15]. It is believed that the focus of pollution prevention is the combination of basic theory and technology. Therefore, it is possible to effectively forecast and analyze the time and space of pollution [16, 17]. With the continuous development and advancement of science and technology, numerical simulation technology has been widely applied. In addition, it has become a key technology and means for people to prevent and control groundwater pollution. Numerical simulation not only can predict the movement characteristics and laws of groundwater pollutants but also is of great significance to predict the extent of the impact of pollutants and other important information, which is of great significance in preventing the pollution of groundwater resources caused by the development and operation of coal-fired power plants [18-20].

In this study, the impact of groundwater resource pollution of coal-fired power plants and its impact on the properties of geotechnical engineering is investigated by using the numerical simulation technology. First, the regions to be investigated are divided and generalized. Then, relevant experiments are carried out for the calculations of hydrogeological parameters to establish the hydrogeological conceptual model. Next, the real-time water level data recorded by the observations are used to identify and verify the model effectively. Afterward, the numerical simulation of groundwater solute transportation is carried out again. During the process, the establishment of the groundwater quality model is the focus, followed by the application of numerical simulation technology to forecast the environmental impacts of groundwater pollution, including the forecasting of groundwater environmental pollutions caused by Chemical Oxygen Demand (COD) leakage, ash yard, and power plants. Through the application of numerical simulation technology, the current information about groundwater pollution, such as the scope of impact and the movement law of pollution, can be understood clearly and timely. By forecasting the groundwater pollution, the groundwater pollution problems can be prevented effectively, which offers great help to the correct and reasonable operation and development of coal-fired power plants, providing a significant reference for the preventive treatment of groundwater pollution.

2. Establishment of the hydrogeological conceptual model

By collecting geological and hydrogeological data, the regions to be investigated are divided, the three-dimensional geological models are constructed, and the hydrodynamic conditions, boundary conditions, and source-sink terms are generalized and calculated. Besides, corresponding to different stratigraphic conditions in different regions, the hydrogeological experiments are carried out and the hydrogeological parameters are calculated through the recorded data. Eventually, the hydrogeological conceptual model is established.

2.1. Division of hydrogeological conditions

The hydrogeological conceptual model is established. Since the hydrogeological parameters have different values at different locations, these parameters must be divided first. In other words, based on the different hydrogeological conditions, the regions to be investigated are divided in the horizontal
direction. According to the topography, aquifer characteristics, and hydrogeological conditions, the groundwater enrichment in the regions to be investigated is divided into three divisions, as shown in the following table:

**Table 1. Division of hydrogeological conditions**

| Divisions                               | Distribution                      | Aquifer                                                                 | Spatial distribution                                                                 |
|-----------------------------------------|------------------------------------|------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Division I: Pore groundwater water      | Yalu Valley alluvial plain         | Alluvial Gravel soil, single-layer aquifer group                       | A horizontal tendency of gradually being thickened from the North to the South     |
| wealth poor area                        |                                    | A two-layered gravel and brecciated cohesive soil layer, and a volcanic  | Characteristics of the spatial distribution of the Quaternary aquifer group: on the |
|                                        |                                    | elastic rock weathering fissure of the Jurassic system upper series.   | horizontal direction, there is a law of thinning from the middle of the river to    |
|                                        |                                    | Mixed aquifer group                                                   | the mountains on both sides, and the distribution of weathered fissure aquifers is   |
|                                        |                                    |                                                                        | irregular.                                                                         |
| Division II: Pore-weathering fissure    | Shaligou tributary mountain valley area |                                                                        |                                                                                     |
| groundwater water-poor area            |                                    |                                                                        |                                                                                     |
|                                        |                                    |                                                                        |                                                                                     |
| Division III: Weathered fissure         | Hilly area (factory sites and ash yard areas) |                                                                        |                                                                                     |
| groundwater water-poor area            |                                    |                                                                        |                                                                                     |
|                                        |                                    |                                                                        |                                                                                     |

2.2. Generalization of hydrogeological conditions

According to the lithology characteristics and distribution characteristics of the aquifer, considering the accuracy and feasibility of the simulation, the simulation object is generalized into a three-layered aquifer system, as shown in Table 2:

**Table 2. Generalized stratification of hydrogeological conditions**

| Layering | Aquifer                      | Characteristic                                                                 |
|----------|------------------------------|-------------------------------------------------------------------------------|
| Layer I  | Sandy clay and gravel layer | Pore water This layer is affected by external conditions such as atmospheric  |
|          |                              | precipitation and evaporation and is relatively large in depth. It is the     |
|          |                              | first aquifer affected by pollution.                                          |
| Layer II | Mudstone aquifers exist in   | The water permeability is poor. It can be regarded as the water-repellent     |
|          | Divisions I and II           | bottom plate of the upper layer and the water-proof roof of the lower        |
|          |                              | aquifer according to its characteristics.                                     |
| Layer III| Deep and moderately          | Fissure water It is generalized into a confined aquifer.                      |
|          | weathered volcanic clastic   |                                                                                 |
|          | formations                  |                                                                                 |

2.3. Calculation of hydrogeological parameters

The calculated hydrogeological parameters mainly include permeability coefficient (K), water supply (μ), and influence radius (R). The above-measured data are calculated. In addition, the corresponding empirical equation is used in different situations. The calculation of the steady flow of the groundwater and confined water is carried out by using the deformed Dupuit equation. The solution of the unsteady flow of the groundwater and confined water is calculated by the Theis equation. The solution is solved by using the Theis wiring method and the Jacob linear graphic method. The mathematical solution equations for various hydrogeological experiments are as follows:

\[ K = \frac{0.336Q(\lg r_i - \lg r_w)}{(s_w - s_i)(2H - s_w - s_i)} \]  \hspace{1cm} (1)

\[ K = \frac{0.732Q}{(2H - s_w)s_w} \cdot \frac{\lg R}{r_w} \]  \hspace{1cm} (2)
In the above equations, $Q$ represents the capacity of water yield, $R$ represents the radius of influence, $r_1$ and $r_w$ represent the distance from the observation hole to the main hole and the radius of the pumping well, respectively. In addition, $B$ represents the slope of the line, $h_2$ and $h_1$ represent the waterhead of water level to the bottom of the hole after stopping the pump (m), $H$ represents the waterhead (m) between the still water level and the bottom of the pumping hole. Also, $t_2$ and $t_1$ represent the corresponding time (min) with $h_2$ and $h_1$, respectively. $M$ represents the thickness of the confined water aquifer (m), $\Delta S$ represents 10 times time difference corresponding to the waterhead difference on the $S$-$\log t$ curve.

$$K = \frac{2.30Q}{2\pi B}$$  \hspace{1cm} (3)

$$K = \frac{2.30Q}{2\pi(h_2^2-h_1^2)} \log \frac{t_2}{t_1}$$  \hspace{1cm} (4)

$$K = \frac{0.183Q}{\Delta S \cdot M}$$  \hspace{1cm} (5)

In the above equations, $a$ represents the positional conduction coefficient, $r$ represents the water level observation distance (m), $A$ represents the $h_2$-$\log t$ line and the longitudinal axis intercept (m$^2$), $B$ represents the $h_2$-$\log t$ line slope, $H$ represents the waterhead between the still water level and the bottom of the pumping hole. In addition, $h_1$ and $h_2$ represent the waterhead (m) of the moving water level to the bottom of the hole after stopping the pump, while $t_1$ and $t_2$ represent the time (min) corresponding to $h_1$ and $h_2$.

$$a = \frac{r^2}{2.25} \log \frac{h_2^2-h_1^2}{h_2^2} \frac{t_2}{t_1}$$  \hspace{1cm} (6)

$$a = \frac{r^2}{2.25t_1} \log \frac{h_2^2-h_1^2}{h_2^2} \frac{t_2}{t_1}$$  \hspace{1cm} (7)

In the above equations, $K$ represents the permeability coefficient (m/d), $Q$ represents the stable seepage flow (m$^3$/d), $Z$ represents the water infiltration depth (m), $H$ represents the in-loop head, $H_a$ represents the capillary water rise height, and $F$ represents the inner ring area, $F=490.625$ cm$^2$.

$$K = \frac{Q \cdot Z}{F \cdot (H + Z + H_a)}$$  \hspace{1cm} (8)

$$K = \frac{Q}{F}$$  \hspace{1cm} (9)

In the above equations, $K$ represents the permeability coefficient (m/d), $Q$ represents the stable seepage flow (m$^3$/d), $Z$ represents the water infiltration depth (m), $H$ represents the in-loop head, $H_a$ represents the capillary water rise height, and $F$ represents the inner ring area, $F=490.625$ cm$^2$.

2.4. Parameter calculation results

According to the above calculations, the preliminary hydrogeological parameters (permeability coefficient, water supply rate, and water storage rate) can be obtained. The value can be used as the initial input value of the simulation. However, the actual data for the deep aquifer is limited. Parameters that are not collected or calculated will be given according to empirical values based on the formation lithology. According to the relationship between the site scale $L_s$ and the longitudinal dispersion $\alpha L$ obtained through the research, it is estimated that the shallow porous aquifer has a dispersion of 50 m and the bedrock fissure aquifer has a small dispersion of 20 m. The flow velocity in the aquitard is slow, and the convection is not obvious. The transportation of solute is mainly dominated by dispersion. Therefore, the dispersion in the aquifer is relatively large at 70 m. Due to the shallow depth of the simulated horizon (<100 m), the dispersion anisotropy caused by the ground lamination is negligible. According to the lithology characteristics of each layer, the effective porosity of the shallow porous aquifer is taken as 0.30 (the gravel and rubble layer), the effective porosity of the aquitard is 0.10 (silt and clay), and the bedrock fissure aquifer is 0.07.
Through the above steps, parameters affecting the transportation of pollutants can be obtained, as shown in Table 3:

Table 3. Calculation parameters of the solute transportation forecasting model

| Parameters                      | Active porosity | Dispersion degree |
|---------------------------------|-----------------|-------------------|
| Shallow porous aquifer          | 0.3             | 50 m              |
| Deep bedrock fissure aquifer    | 0.07            | 20 m              |
| Aquitard                        | 0.1             | 70 m              |

3. Numerical simulation of groundwater solute transportation

In this section, based on the previously established hydrogeological conceptual model, a mathematical model corresponding to the partial differential equation is established. Then, the groundwater quality model is calculated in the GMS software.

3.1. Groundwater quality model

Based on the principle of maximum environmental impact risk, the following assumptions are made on the pollutant transportation model: Contaminant transportation is only affected by convection and dispersion. The hydrogeochemical reaction of pollutants in the aquifer is not considered. The proposed power plant is located in the hilly area, and the permeability of the pore aqueous medium is excellent. Therefore, the barrier function of aeration area on pollutants is ignored. A mathematical model describing the transportation of contaminants in groundwater can be expressed as:

\[
\frac{\partial}{\partial x_i} \left( \theta D \frac{\partial c}{\partial x_i} - \frac{\partial (\theta v_i c)}{\partial x_i} \right) + I = \theta \frac{\partial c}{\partial t}, x_i \in \Omega, t \geq 0, i = 1, 2, 3
\]

\[
c(x, 0) = c_0(x), x_i \in \Omega, t = 0
\]

\[
\theta D \frac{\partial c}{\partial x_i} - q_c \bigg|_{x_i = \Gamma^3} = g(x, t), x_i \in \Gamma^3, t \geq 0
\]

In the above equations, \( c \) represents the concentration of the pollutant (mg/l), \( \frac{\partial c}{\partial t} \) represents the initial concentration distribution (mg/l) for the initial conditions, \( D \) represents the hydrodynamic dispersion coefficient (m²/d), \( v_i \) represents the groundwater seepage velocity tensor, m/d, \( I \) represents the solute (mg/m²·d) entering the unit area of the aquifer per unit time, and \( q \) represents the water flux (m/d) at the boundary.
The water quality model is solved by using the MT3DMS module in GMS software. The simulation uses the eigenvalue method to calculate the concentration change caused by hydrodynamic dispersion by using the finite difference approximation. The spatial distribution of pollutants can be obtained by jointly solving the water flow equation and the solute transportation equation.

3.2. Model identification and verification
Due to the lack of a deep bedrock fissure aquifer water level test, the simulation considered that the shallow and deep aquifers formed a mixed water level. The model is identified, and the identification duration lasts a total of 86 days. The collected and calculated data are input into the model. By repeatedly adjusting the hydrogeological parameters, the water level at the same time as the model is consistent with the measured value. The calculated water level at each time is largely different from the measured value, which may be caused by sudden changes in the water level of the observation well well caused by sudden pumping. Then, the water level data are verified, and the verification period is 60 days. After the adjustment, the satisfactory simulation results are obtained. After analysis, the absolute value fitting error of most time is less than 0.5 m, and the model better simulates the actual situation of the studied regions.

4. The forecast of the environmental impacts of groundwater

4.1. Forecasting of the impact of power plants on groundwater environment
Through the previous groundwater flow and solute transportation model, the spatial and temporal distribution characteristics of each pollutant under natural abnormal conditions and anti-seepage measures are predicted. For the two forecasting designs of different periods, i.e., the discharge under the natural conditions and the discharge under the anti-seepage conditions, the maximum influence distance prediction results are shown in Figure 2:

![Figure 2](image-url)

**Figure 2.** Forecasting of the maximum influence distance of groundwater environment under the ammonia nitrogen environment of power plants.

The results show that after 100 days of operation, the ammonia nitrogen pollutants in the groundwater have begun to affect the groundwater; however, the impact is slight, and the concentration of the pollutants does not exceed the minimum detection limit. After 1000 days, within the range of 0.079 km² near the power plant, the ammonia nitrogen concentration changed beyond the minimum detection limit, resulting in the emergence of small sensitive areas. In 20 years, the maximum impact distance of pollutant leakage is 1087.6 m, which has exceeded the distance between the power plant and its nearest water supply well (Pf) (130.7 m); however, it is less than the distance between the nearest well of the power plant and the neighboring village (1949.7 m). Therefore, it can be known that ammonia nitrogen
will have a certain impact on the water quality of Pf wells after 20 years of natural non-normal conditions. However, it will not affect the water quality of the adjacent village water supply wells.

According to the results, it can be known that the concentration of petroleum pollutants in groundwater exceeds the minimum detection limit after 100 days of operation of the power plant, and the affected area appears accordingly. After 1000 days, sensitive areas appear, but the smaller area is 0.039 km$^2$. As shown in Figure 3, the maximum impact distance during the 20-year operation period is approximately 990 m. The impact range extends to the Pf well but does not affect the water quality of water supply wells in the adjacent village. In each calculation period, the area exceeding the standard is 0 km$^2$, and the petroleum pollutants discharged from the power plant will not cause the concentration of groundwater pollutants to exceed the standard, and the area that exceeds the pollutant concentration standard is none.

![Figure 3. Maximum impact distance forecasting results of petroleum pollution](image1)

**Figure 3.** Maximum impact distance forecasting results of petroleum pollution

![Figure 4. Forecasting of the maximum influence of petroleum pollution in groundwater after seepage prevention measures](image2)

**Figure 4.** Forecasting of the maximum influence of petroleum pollution in groundwater after seepage prevention measures
After the seepage prevention measures were taken, the degree of petroleum pollution in the groundwater decreased during each period. After the 20-year operation period, only the concentration of pollutants in the area of 0.04 km$^2$ near the power plant has increased significantly, with the appearance of sensitive areas. However, the final concentration of the petroleum pollutants in the groundwater does not exceed the standard value with no over-standard areas. As shown in Figure 4, the maximum influence distance is reduced from 990 m before seepage prevention to 726 m after seepage prevention, but the impact range still covers the Pf water supply wells. Therefore, the discharge of petroleum pollutants will have a certain impact on the Pf wells. However, they will not cause the concentration of petroleum-based pollutants in the Pf well to exceed the standards.

4.2. Forecasting of the impact of ash yard on groundwater environment

The pollutants of the ash yard are mainly fluoride and arsenic. In the ash yard, the input of fluoride and arsenic is lower without any seepage prevention measures, which is 0.56 g/d and 0.008 g/d respectively. The numerical simulation results show that the impact range of fluoride leakage increases with the increase of leaching time. During the 20-year operation of the plant, the maximum impact of fluoride is 190 m, which is much smaller than the distance between the ash yard and the nearest pumping well (Pf) (2240 m). During the forecasting period, the fluoride concentration in the groundwater has not exceeded the standard. After the seepage prevention measures are taken, the maximum migration distance of fluoride in the 20-year ash yard operation time is less than 10 m, which can be considered as not affecting the quality of groundwater. Since the highest concentration of arsenic in the ash yard leachate is 0.003 mg/l, which is lower than the lower limit of groundwater arsenic detection (0.005 mg/l), it is considered that the arsenic leaching solution infiltration does not cause the groundwater quality to exceed the standard during the forecasting period.

| Forecast time | Before seepage prevention | After seepage prevention | The distance of excessive pollutants (km) |
|---------------|---------------------------|--------------------------|------------------------------------------|
| 100           | speed=auto duplex=auto     | 0                        | 0                                        |
| 1000          | 65                        | 0                        | 0                                        |
| 7300          | 190                       | <10                      | 0                                        |

4.3. Forecasting of the impact of Chemical Oxygen Demand leakage on groundwater environment

The range of Chemical Oxygen Demand (COD) concentration in groundwater increases largely. As shown in Figure 5, the affected area is expanded from 2.56 km$^2$ at 100 d to 11.2 km$^2$ at 20 years. The sensitive area has appeared at 100 days, which is 0.015 km$^2$; at 20 years, the sensitive area has reached 1.04 km$^2$. Compared with other kinds of pollutants, the COD concentration in groundwater is affected by three sources of pollution at the same time. In addition, the source strength is the largest so that the risk is the highest. Pollutant emissions from power plants will affect adjacent Pf water supply wells, and potential water pipeline leaks will affect the quality of the main water supply wells in neighboring villages along the route. However, in the absence of seepage prevention measures, the concentration of COD in groundwater still does not exceed the standard; therefore, it will have a certain impact on the water quality of the water supply wells around the power plant and the water pipelines.

After the seepage prevention measures are taken, the plane dispersion of COD pollution in each calculation period is shown in Figure 5. The results show that after 20 years of operation of the power plant, due to the seepage prevention measures taken around the power plant, the COD pollution range is reduced, and there is no sensitive area before 1000 days. At 20 years, the range of sensitive area is reduced from 1.04 km$^2$ to 0.65 km$^2$, and the impact range is reduced from 11.20 km$^2$ to 9.86 km$^2$. The COD input still affects the water quality of the water supply wells and Pf wells in adjacent villages. However, the increase rate of COD concentration is still lower than the minimum detection limit. There is no over-standard area during the operation of the power plant so that the impact can be considered low.
5. Conclusions
The utilization of coal for power generation has become a mainstream means of power generation. In recent years, the application of coal in power generation has become the core of the Chinese electric power industry, accounting for more than half of the total power generation in China. With the continuous advancement and development of society, the application of coal is increasing in both scale and assumption, which also causes a series of negative effects, especially the pollution of groundwater resources. In recent years, experts and scholars have conducted in-depth research on the issue, providing a certain reference and direction for the prevention of groundwater pollution. The introduction of numerical simulation technology has solved certain difficulties and has become a critical key technology for people to prevent and control groundwater pollution.

In this study, the impact of groundwater resource pollution of coal-fired power plants and its impact on the properties of geotechnical engineering is investigated by using the numerical simulation technology. First, the regions to be investigated are divided and generalized. Then, relevant experiments are carried out for the calculations of hydrogeological parameters to establish the hydrogeological conceptual model. Next, the real-time water level data recorded by the observations are used to identify and verify the model effectively. Afterward, the numerical simulation of groundwater solute transportation is carried out again. During the process, the establishment of the groundwater quality model is the focus, followed by the application of numerical simulation technology to forecast the environmental impacts of groundwater pollution, including the forecasting of groundwater environmental pollutions caused by Chemical Oxygen Demand (COD) leakage, ash yard, and power plants. Through the application of numerical simulation technology, the current information about groundwater pollution, such as the scope of impact and the movement law of pollution, can be understood clearly and timely. By forecasting the groundwater pollution, the groundwater pollution problems can be prevented effectively, which offers great help to the correct and reasonable operation and development of coal-fired power plants, providing a significant reference for the preventive treatment of groundwater pollution.
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