Analysis of Groundwater Environment Evaluation and Prediction

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Abstract: In accordance with the requirements of Technical guidelines for environmental impact assessment—groundwater environment (HJ 610-2016), the process of groundwater environmental impact assessment and prediction was analyzed. Groundwater Model System (GMS) was used to simulate groundwater flow field and solute transport, the following main conclusions were draw. As long as the project conforms to the specifications and design and the management is in place during operation, the production area and tailings area in normal working conditions will not cause obvious adverse effects on the quality of groundwater. Under different assumptions, groundwater pollution of the production area and tailings area in abnormal conditions will not directly affect the drinking water, farmland irrigation water and surface water of surrounding residents.

1. Introduction
Groundwater resources refer to surface water that enters the stratum and are stored in it through the recharge of aquifers, and exist below the surface in different forms with the influence of gravity and the influence of external conditions. Groundwater has the advantages of high quality, large reserves, and wide distribution. It is an important part of human living space. According to statistics, one-third of Chinese total water resources are natural groundwater resources. At present, there are about 400 cities exploiting groundwater, and about 70% of the population uses groundwater as their main source of drinking water. It can be seen that groundwater resources play a vital role in the social and economic development of our country in terms of quantity and quality [1].

At the same time, in China, mining resources play a pivotal role in economic development, and the development of mining is closely related to groundwater resources. Mine mining is one of the main causes of groundwater pollution in China [2]. Underground mining in mines will destroy the original balance of replenishment and discharge of groundwater, and change the regional groundwater circulation. Especially in the underground mining of non-ferrous mines, large-scale drainage of groundwater is required, causing the regional groundwater level to drop, forming a drop funnel. In addition, the “cascade” pollution caused by the mixing of mine water will worsen the quality of groundwater. Mining waste rock piles carry a lot of harmful substances, entering the aquifer through various ways, polluting groundwater resources [3]. Contaminated groundwater contains a lot of toxic substances, affecting the health of people in the surrounding area.
and harmful substances, such as lead, zinc, cadmium and other heavy metal elements. It will harm the human kidneys and even induce cancer [4]. Therefore, the implementation of groundwater environmental impact assessment is particularly important. This article mainly analyzes the process of groundwater environmental impact assessment and prediction by studying a manganese mining area in Chizhou City.

2. Mathematical model

2.1. Flow field model

The groundwater prediction model system GMS (Groundwater Model System) is used to simulate the groundwater flow field. GMS is developed by the environmental model laboratory of Brigham Yong University and the U.S. Military Waterway Experimental Station. Its core calculation program is the MODFLOW model developed by McDonald and Harbaugh in 1988 and continuously modified and perfected by the US Geological Survey. It adopts a variable finite difference network and a unit center algorithm to solve the steady and unsteady three-dimensional flow of groundwater [5]. The differential equations are as follows.

\[
S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left( K\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y} \left( K\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z} \left( K\frac{\partial h}{\partial z}\right) + \varepsilon \quad x, y, z \in \Omega, t \geq 0
\]

\[
\mu \frac{\partial h}{\partial t} = K\left(\frac{\partial h}{\partial x}\right)^2 + K\left(\frac{\partial h}{\partial y}\right)^2 + K\left(\frac{\partial h}{\partial z}\right)^2 - \frac{\partial h}{\partial x}(K + p) + p \quad x, y, z \in \Gamma_0, t \geq 0
\]

\[
h(x, y, z, t) \big|_{t=0} = h_0 \quad x, y, z \in \Omega, t \geq 0
\]

\[
\frac{\partial h}{\partial t}\big|_{\Gamma_1} = 0 \quad x, y, z \in \Gamma_1, t \geq 0
\]

\[
K_n \frac{\partial h}{\partial z}\big|_{\Gamma_2} = q(x, y, t) \quad x, y, z \in \Gamma_2, t \geq 0
\]

\[
\frac{h-h_0}{\sigma} - K_n \frac{\partial h}{\partial z}\big|_{\Gamma_3} = 0 \quad x, y, z \in \Gamma_3, t \geq 0
\]

Where \( \Omega \) is the seepage area, \( h \) is Aquifer height, \( K \) and \( K_n \) are hydraulic conductivity and hydraulic conductivity in normal direction of variable section, \( S \) is water storage coefficient of aquifer below free surface, \( \mu \) is gravity specific yield of the diving aquifer on the diving surface, \( \varepsilon \) is source sink term of aquifer, \( P \) is evaporation and rainfall on the diving surface, \( h_0 \) is initial water level distribution of aquifer, \( \Gamma_0, \Gamma_1, \Gamma_2 \) and \( \Gamma_3 \) are upper boundary of seepage area, water level boundary of seepage area, flow boundary of seepage area and mixed boundary of seepage area. \( q(x, y, z, t) \) is defined as discharge per unit width of the second-class boundary.

2.2 Numerical model of solute transport

The mathematical model of solute transport in groundwater uses MT3DMS calculation module of GMS, which is a three-dimensional finite difference numerical model used to analyze the numerical simulation of convection, diffusion and chemical reaction between solutes in groundwater. MT3DMS begins to compute when the MODFLOW’s simulation is completed. In this process, the grid head value and the inter-grid flux value provided by the flow field established by MODFLOW are used to solve the solute diffusion and transport equation to calculate the solute transport process [6]. The solute transport and diffusion equation can be expressed by the following formulas, solute diffusion is a process that changes with time:

\[
n_e \frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(nD_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y} \left(nD_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z} \left(nD_z \frac{\partial C}{\partial z}\right) \pm CV_i
\]
Where \( D_{ij} = \alpha_{ij} \frac{V_{ij}}{V_n} \), \( V_m \) and \( V_n \) is dispersion of aquifer, \( |V| \) is the speed absolute value, \( C \) represents simulate the concentration of pollutants, and then \( n_e \) refers to effective porosity. What’s more, \( W \) is flux per unit area of source sink, \( V_i \) is seepage velocity, and \( C' \) is pollutant concentration of source sink.

The spatial distribution of pollutant concentration can be obtained by jointly solving the water flow equation and the solute transport equation.

### 3. Case study

This paper evaluates the groundwater environment in the production area and tailings area of a manganese mining area in Chizhou City. The terrain of the study area is generally inclined from east to west, with large undulations in the southeast and gentle slopes in the northwest.

#### 3.1. Conceptual hydrogeological model

The conceptual hydrogeological model is a scientific generalization of the groundwater system and is the basis for solute transport simulation. After surveying and mapping the hydrogeology of the study area, combining the collected site soil geology, river hydrology and water quality and other statistics, it is highly scientifically generalized, and the site hydrology conceptual model is obtained through the topological relationship [7]. The study area is a half-hill and half-mountain area. Based on the regional hydrogeological characteristics and the current groundwater environment, the aquifer is generalized into an isotropic medium. The groundwater in the study area is mainly recharged by atmospheric precipitation and surface water seepage. However, due to the shallow groundwater level and the thinner simulated aquifer, this evaluation generalized it as a steady flow.

In summary, the conceptual model of the groundwater system in the study area can be generalized into a heterogeneous, isotropic, spatial three-dimensional structure, and a stable groundwater flow system.

#### 3.2. Model establishment

According to the conceptual model, the groundwater simulation software GMS (Groundwater Model System) is selected to simulate the groundwater flow field and solute transport. Because the topography and hydrogeological conditions of the site are complex and changeable, the selection of boundary conditions is difficult. Firstly use WMS (Watershed Model System) software to generate watershed with the regional DEM (Digital Elevation Model) data, then determine the boundary conditions of the entire region based on the generated watershed. Import the regional boundary conditions into the GMS, use MODAEM to generate the regional flow field. Then determine the boundary conditions of the simulation area according to the iso-water level of the regional flow field. Use Modflow to simulate the site flow field and MT3D to simulate the solute transport.

According to the geological prospecting statistics and empirical data, combined with reference data, the specific model parameters are selected in Table 1. Based on the conservative principle, the adsorption and natural attenuation of pollutants are not considered into the simulation.

| Parameter                        | Average thickness of aquifer (m) | Horizontal hydraulic conductivity (m/d) | Regional rainfall infiltration replenishment (×10^{-4}m/d) | Dispersion coefficient (m) | Horizontal vertical (m) | Effective porosity |
|----------------------------------|----------------------------------|----------------------------------------|----------------------------------------------------------|--------------------------|------------------------|-------------------|
| Value                            | 3.0                              | 1.0                                    | 3.9                                                      | 2.0                       | 5.0                    | 0.3               |

The regional watershed and boundary conditions generated by WMS are shown in Figure 1. The simulated regional flow field is shown in Figure 2.
3.3. Groundwater pollution prediction scenarios setting and results

3.3.1 Analysis of groundwater environmental impact under normal working conditions
The sewage produced by the project is pre-treated in the plant and incorporated into the sewage pipe network, and discharged after being connected to the sewage treatment plant to meet the standards. As the sewage storage tank and emergency pool and other structures are all waterproof, anti-corrosion, anti-seepage, and anti-overflow, the leachate can be effectively prevented from seeping into the ground. As long as the project is implemented in strictly accordance with national regulations during the design and construction processes, and management is in place during operation, it will not cause groundwater pollution in normal working conditions.

3.3.2 Analysis of Groundwater Environmental Impact under Abnormal Conditions
Abnormal working conditions refer to the situation where a leakage accident is discovered in a production unit of the project through routine monitoring well data analysis.

1. Production area
In this study, the following representative accident scenarios were selected for quantitative prediction: continuous leakage of sewage in the sewage storage tank, with a daily leakage of 10 cubic meters, and prediction of groundwater pollution after 1, 2, and 5 years of continuous leakage. According to the analysis of the project, the concentration of pollutants in the industrial wastewater produced is shown in Table 2 below.

Table 2. Concentration of main wastewater pollutants in the production area

| Pollution factor | NH$_4$ | Mn  | Cr  | Cr$^{6+}$ |
|------------------|--------|-----|-----|-----------|
| concentration (mg/L) | 556.7  | 405.4 | 63.8 | 20.0      |

According to the above hypothetical scenario, the wastewater in the sewage tank leaks into the ground and then enters the shallow groundwater. The contaminated groundwater migrates and spreads northward along the northern ravine, and flows out of the factory boundary of the production area within 1 year and continues to migrate downward, and reaches the Xiufeng Reservoir downstream impacting the water quality.

Figure 3 shows the changes of groundwater quality entering Xiufeng Reservoir over time. It can be seen from the figure that the contaminated groundwater reaches the Xiufeng Reservoir in 2 years, and the concentration of pollutants entering the reservoir reaches the maximum in 3.8 years and stabilizes in 4.9 years. When stable, the concentration of NH$_4$ entering Xiufeng Reservoir is about 1.15mg/L, the concentration of Cr is 0.135mg/L, the concentration of Cr$^{6+}$ is 0.04mg/L, and the concentration of Mn is 0.8mg/L.

Figure 3. Change of groundwater quality in Xiufeng reservoir after leakage of sewage treatment pond

Under the predict scenario, the pollution plume basically stabilizes after 4-5 years of continuous leakage from the sewage pond. According to the Class III standard of Environmental Quality of Groundwater, analyze the range of groundwater quality exceeding the standard value when the pollution plume reaches a stable level. Since there is no groundwater quality standard value for total chromium, the over-standard range of total chromium is not analyzed.

It can be obtained that when the pollution plume is stable, NH$_4$, Cr$^{6+}$ and Mn all appear in the downstream groundwater exceeding the standard area, and the exceeding range is the narrow zone between the production area and Xiufeng Reservoir. The area is woodland and open land, without residential areas and farmland. Therefore, groundwater pollution will not directly affect the drinking water and farmland irrigation water of surrounding residents.

2. Tailings area
The impacts of tailings area on groundwater under abnormal conditions include that leachate seepage into the ground caused by damage of the anti-seepage layer at the bottom of the tailings area. The anti-seepage layer of the tailings area dam is damaged, and the leachate leaks through the dam foundation to below the dam. Leakage or overflow occurs in the leachate collection pond downstream of the tailings area. Pollutants enter the ground and migrate and spread downstream with groundwater. This paper conducts a quantitative simulation of groundwater pollution under the following two scenarios:

1) The anti-seepage layer at the bottom of the tailings area is damaged, and 10 cubic meters of leachate is leaked to the downstream area of the dam every day, and the groundwater pollution is predicted after the continuous leakage for 1, 2, and 5 years;

2) Leakage occurs due to the damage of the seepage prevention layer of the leachate collection pool of the tailings area, and 5 cubic meters of leachate are leaked every day. Forecast the groundwater pollution situation after 1 year, 2 years and 5 years of continuous leakage.

The simulation prediction of the pollutant concentration in the tailings area leachate is shown in Table 3 below.

Table 3. Concentration of main wastewater pollutants in the tailings area

| Pollution factor | NH₄⁺ | Mn | Cr | Cr⁶⁺ |
|------------------|------|----|----|------|
| concentration (mg/L) | 250.0 | 45.0 | 0.5 | 0.1 |

1) Leakage at the bottom of tailings area

Due to the large hydraulic gradient in the tailings area, the contaminated groundwater quickly migrates and diffuses under the main dam after the leakage occurs, forming a long and narrow groundwater pollution plume along the flow of groundwater, which quickly spreads to the downstream of the tailings area and enters 100 meters downstream Creek. The change of groundwater quality with time is shown in Figure 4. It can be seen from the figure that due to the large hydraulic gradient downstream of the tailings area, the sand gravel layer in the downstream area has good permeability, and the contaminated groundwater reaches the downstream river in a short time. The concentration of pollutants entering the river will continue to increase, and the concentration of pollutants entering the river will stabilize after about 3 years. When stable, the concentration of NH₄⁺ is about 0.55 mg/L, the concentration of Cr is 0.0011 mg/L, the concentration of Cr⁶⁺ is 0.00022 mg/L, and the concentration of total Mn is 0.10 mg/L.

Figure 4. The change of groundwater quality after the bottom of the tailings area continues to leak into the unnamed River
Under the predicted scenario, the pollution plume will basically stabilize after 1-2 years of continuous leakage from the sewage pond. According to the Class III standard of *Environmental Quality of Groundwater*, analyze the range to which the quality of groundwater exceeds the standard value when the pollution plume reaches a stable level. It can be seen that when the pollution plume reaches a stable level, both NH₄ and Mn exceed the standard in the downstream groundwater, and the exceeding area is in the narrow zone between the tailings area and the nameless river. The existing residents under the main dam of the tailings area will be relocated, and the farmland between the main dam and the unnamed river will also be requisitioned for the construction of leachate collection and disposal sites. Therefore, the formation of groundwater pollution will not affect the drinking water and irrigation water. Due to the low concentration of Cr⁶⁺ in the leachate of the tailings area, the leakage of leachate will not cause areas where Cr⁶⁺ is significantly exceeded in groundwater.

② Leakage of leachate collection pond

The leachate collection pond is located under the tailings dam, about 40 meters away from the river. If the leachate collection pond leaks, the contaminated groundwater will soon enter the small river. The water quality of the groundwater entering the unnamed creek after the leak occurred over time is shown in Figure 5. It can be seen from the figure that after the leakage of the leachate collection pond, the pollutants quickly reach the nameless river, and the concentration of pollutants in the groundwater that flows into the nameless river increases rapidly. After 2 years, the pollutant concentration in the contaminated groundwater entering the nameless river is stable, the concentration of Mn is 0.21425mg/L, the concentration of Cr is 0.0023805mg/L, the stable concentration of NH₄ is 1.19025mg/L, and the concentration of Cr⁶⁺ At 0.0004mg/L, the Cr⁶⁺ concentration hardly changes.

![Graphs showing change in groundwater quality](image)

Figure 5. Change of groundwater quality in the unnamed river after continuous leakage of the leachate collection pond

Analyze the range of groundwater quality exceeding the standard value when the pollution plume reaches a stable level. It can be seen that when the pollution plume reaches a stable level, both NH₄ and Mn exceed the standard in the downstream groundwater, and the range of excess is in the narrow strip between the tailings area leachate collection pond and the nameless river. The existing residents...
under the main dam of the tailings area will be relocated, and the farmland between the main dam and the unnamed river will also be requisitioned for the construction of leachate collection and disposal sites. Therefore, the formation of groundwater pollution will not affect the drinking water and irrigation water. Due to the low concentration of Cr$^{6+}$ in the leachate of the tailings area, the leakage of leachate will not cause areas where Cr$^{6+}$ is significantly exceeded in groundwater.

3.4. Environmental impact analysis of surface water

It can be seen from the prediction results of groundwater environmental impact under abnormal working conditions where if the leachate of the tailings area continues to leak, the contaminated groundwater will continue to migrate and diffuse downstream along the groundwater flow. If the leakage time is longer and the leakage of leachate is large, the pollutants in the leaked leachate will continue to diffuse downstream and eventually enter the unknown river, which will affect the water quality of the unknown river. If the wastewater pool in the production area continues to leak and a relatively large amount of pollutants enter the groundwater, the pollutants will migrate north along with the groundwater flow and eventually enter the Xiufeng reservoir. Under different leakage scenarios, the stable concentrations of pollutants in surface water are shown in Table 4. It can be seen from the table that the concentration of Cr$^{6+}$ entering unnamed river and Xiufeng reservoir in several leak scenarios is lower than the standard III of surface water, but the concentration of NH$_4$ entering is slightly higher than the standard III of surface water. As mentioned in the previous, this groundwater solute transport model is based on conservative principles. It does not consider the adsorption and degradation of pollutants after entering the groundwater, but only considers the migration and diffusion of pollutants. According to the research results of related literature, NH$_4$ in shallow groundwater will be degraded, and a considerable part of NH$_4$ will be oxidized into nitrate in an aerobic environment. Therefore, after considering the degradation effect, the NH$_4$ concentration in the surface water will be lower than the predicted result of the model, and it should not have obvious adverse effects on the surface water.

Table 4. Stable concentration of pollutants in surface water under different scenarios (mg/L)

| Pollutants | Sewage pond leakage in production area | Leakage at the bottom of tailings area | Leakage in the sewage pond of the tailings area | Standard III for surface water |
|------------|---------------------------------------|---------------------------------------|-----------------------------------------------|-------------------------------|
| NH$_4$     | 1.15                                  | 0.55                                  | 1.19025                                       | 1.0                           |
| Cr         | 0.135                                 | 0.0011                                | 0.23805                                       | N/A                           |
| Cr$^{6+}$  | 0.04                                  | 0.00022                               | 0.0004                                        | 0.05                          |
| Mn         | 0.8                                   | 0.10                                  | 0.21425                                       | N/A                           |

Note: N/A — No corresponding reference standard

Unnamed river and Xiufeng reservoir are both standard III of surface water, and there are no limit standards for total chromium and manganese concentrations. According to the prediction results of the model, the concentration of total chromium and manganese in the groundwater entering the surface water is also very low, which will not have obvious adverse effects on water quality. It can be seen that under the set accident scenario, after a long period of continuous leakage, the leaked pollutants will eventually enter the downstream of surface water through the groundwater, but the concentration of groundwater that flows into the surface water is low. Taking into account that the surface water is diluted and mixed with a large amount of surface water, the groundwater pollution generated under abnormal working conditions will not have a significant adverse effect on the surface water quality.

4. Conclusion

In this study, field investigations were conducted in the research area. Combined with the current hydrology and water quality of the study area, a simulation and prediction model of the ground
The prediction results show that in abnormal working conditions, the leakage of toxic and hazardous substances in the production area will cause shallow groundwater pollution, and the contaminated groundwater will migrate and spread northward along the groundwater flow. If the leakage is large enough, the contaminated groundwater will eventually enter the Xiufeng reservoir about 500 meters to the north of the site, and form a long and narrow over-standard area of NH$_4$, Cr$^{6+}$ and Mn between the production area and the Xiufeng reservoir. The damage of the impervious layer at the bottom of the tailings area or the impervious layer of the dam, and the overflow or leakage of the downstream leachate collection pond will cause shallow groundwater pollution. The contaminated groundwater will migrate and diffuse in the downstream direction of the main dam. An excessive NH$_4$ and Mn area will be formed between the tailings area and the river in the downstream. As the surrounding water sources are not within the scope of groundwater pollution, the groundwater pollution caused by the production area and tailings area under abnormal working conditions will not adversely affect the drinking water of surrounding residents. Meanwhile, in abnormal conditions, the concentration of groundwater pollutants entering the Unnamed river and the Xiufeng reservoir is low. Groundwater pollution will not cause obvious adverse effects on the surface water.

This paper uses the GMS model to simulate and predict the hydrological and water quality of groundwater. This is conducive to learn the status of groundwater pollution and taking reasonable control and maintenance measures. However, the speed of pollutant migration and the size of the diffusion range are closely related to the amount and intensity of groundwater extraction. Therefore, when predicting the migration of pollutants, the influencing factors should be considered.

References:
[1] YANG, J.F., WAN, S.Q., CHEN, X.H. (2007) An Evaluation of Groundwater’s Role in Regional Economic and Social Development in China. J. Resources Science, (05): 97-104.
[2] HAN, F.P., HUANG L. (2017) Analysis of groundwater environmental impact assessment of a lead zinc mine in Ankang. J. Underground Water, 39(6): 40-43.
[3] HUNAG X. (2015) The Numerical Simulation of the Mining Groundwater Environmental Impact Study. D. Guangdong University of Technology.
[4] ZENG Y. (2017) Study on the Environmental Impact of Groundwater in Metal Tailing Reservoir. J. Resources Economization & Environment, (12): 70-70.
[5] TONG X.X., NING L.B., DONG S.G. (2012) GMS Model for Assessment and Prediction of Groundwater Pollution of a Garbage Dumpling Site in Luoyang. J. Environmental Science & Technology, 35 (7): 197-201.
[6] TAN W.Q., SUN C., HU J.M., et al. (2008) Application of GMS in simulation of pollutants migration for ground water. J. Water Resources & Hydropower of Northeast China, (5): 54-55,59.
[7] LI J., LI Y., SHEN B., et al. (2014) Simulation of rain garden effects in urbanized area based on SWMM. J. Journal of Hydroelectric Engineering, (4):60-67.