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Simulation of Solute Transport in Groundwater of Landfill Site in Zhenjiang New District

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Abstract: The solid waste landfill in Zhenjiang New Area is located at the quarry entrance in the south wing of the beidingmountain of Zhenjiang New Area. Continuous heavy rainfall leads to a sharp rise in the groundwater level, causing swelling and damage to the side wall of the waterproof curtain on the east side of the foundation pit of the landfill site. As a result, the lower water level in the interior of the landfill site rises rapidly, resulting in the flooding of the landfill site and the destruction of the waterproof curtain on the east side of the foundation pit. Therefore, it is of great significance to analyze and evaluate the groundwater pollution in the study area. The main research methods are to investigate the regional hydrogeological conditions in detail and fully analyze the transport channel of groundwater pollutants in the study area. Two modules of Modflow and MT3D in GMS are used to establish groundwater flow model and solute transport model, and nitrate is selected as the sensitive factor to simulate and predict the transport law of groundwater pollutants. In the model, the pollutant leakage is 1% and 2% of the total sewage, and the migration rule, pollution range and concentration distribution of residual pollutants within 1500 days after the pollution source is cut off and the pollutant leakage continues for 180 days are simulated. According to the simulation prediction, the pollutant migrates slowly in groundwater. After the pollution source is cut off, the pollution area increases first and then decreases. The farthest migration of the pollutant is 281m, and the concentration is less than 20mg/L.

Keywords: Solute Transport, Contaminant Plume, The Numerical Simulation, Landfills

1. Introduction

As an important water supply source and an important support of ecological system, groundwater is an important guarantee to maintain the water system benign cycle, and an indispensable precious resource, playing a pivotal position in the total water resource in our country [1]. In recent years, with the increasing density of urban population, the problem of landfill disposal cannot be ignored. The landfill leachate infiltration during the landfill stage and after the sealing of the landfill will cause very serious groundwater pollution [2, 3]. At present, numerical simulation is the main method for evaluating groundwater resources and simulating the occurrence and development of some hydrogeological processes in nature. The development of 3D flow model, the calculation method of velocity field and flow line, the regional generalization of heterogeneous parameters, the optimization of complex data and the application of MODFLOW software in 3D flow have become the mainstream of groundwater numerical analysis. Taking the landfill site of Zhenjiang New District as an example, this paper studies and analyzes the evolution trend of groundwater flow field, discusses the source, migration and spatial distribution of pollutants by sorting out the monitoring data of the landfill, and establishes the groundwater flow model and solute transport model by using two modules of Modflow and MT3D in GMS. Simulate the migration rule of groundwater pollutants, predict the pollution range and pollutant concentration distribution, and provide technical reference for groundwater quality, water quantity management and restoration of groundwater areas contaminated by leakage [4-7]. It is of great significance to control and protect regional groundwater environment [8].

2. Research Background

2.1. Current Situation of the Study Area

The solid waste landfill site of Zhenjiang New Area Solid Waste Disposal Co., Ltd. is located at the quarrying site of the south wing of Beidingshan Mountain in Zhenjiang New Area. Continuous heavy rainfall leads to a sharp rise in the groundwater level, swelling and destruction of the waterproof curtain wall on the east side of the foundation pit of the landfill site, and the rapid rise of the lower water level in the interior of the landfill site, which leads to the landfill being flooded, and the water level is 3.0m higher than the surface of the waste, leading to the leachate and groundwater mixing, and groundwater pollution. Since then, the water level in underground Wells, leachate Wells and detection Wells is basically the same because of the main and secondary impervious membrane leakage. The elevation of groundwater level in the former reservoir area is basically stable between 11.36 and 11.95m.

2.2. Regional Geological Overview

The study area is located in the low hilly region at the east end of the Ningzhen Mountains. It is a hill-hilly landform unit, with the terrain high in the west and low in the east, high on both sides of the north and south, and valleys in between. The south side is a mountain with the original maximum elevation of 81.4m, the north side is a back-top mountain with the original maximum elevation of 81.6m, the east side elevation of 15-20m and the west elevation of 20-40m (see Figure 1). On the north side, due to open-pit mining, the pit is filled with water all year round, which cannot be dredged. The current water level is 11m. The study area is located in the south bank of Zhenyang River section in the lower reaches of the Yangtze River, with abundant rainfall, the average annual rainfall is 1074.1mm, the average annual rainfall is 123 days, the maximum annual rainfall is 1602.1mm, and the maximum daily rainfall is 262.5mm (1972.7.3). The rainfall is concentrated in June, July and August, accounting for 50% of the annual rainfall. The maximum annual evaporation is 1175.9mm, the minimum evaporation is 847mm, and the average evaporation is 1276.7mm.

This area is located in the southern wing of Liangshan-Hengshan complex anticline. The complex anticline is composed of several groups of parallel anticlines and synclines. It strikes northeast, passes through Liangshan Mountain, Qinglongshan Mountain and Guanyin Mountain, and extends east to Hengshan Mountain. It is 12km long and 2-5km wide, and the fold inclines northwest and reverses southeast. There are two north-south striking faults in the reservoir area, among which the F1 fault runs through the reservoir area and the back water pit, extending about 470m with a width of 60-75m. The fracture zone is mainly marble and has good permeability. F2 fault is located in the west side of the reservoir area, with a strike of 315°, a width of about 50m and an extension of about 160m. The fracture zone is rich in water and has good permeability. Both faults have no effect on groundwater runoff.

The strata are mainly composed of the Upper Sinian Series, the western end is occupied by intrusive rocks, and the eastern end is covered by Lower Cretaceous volcanic rocks. The strata in the anticlinal core are the thin limestone (Zd^2) of the upper member of Doushantuo Formation, and the dolomite (Z_2dn) of Dengying Formation in the synclinal core. The fissure karst is generally developed, which is a medium water-rich rock group in the region. The late Pleistocene silty clay (Q_3x) is distributed in the low-lying area around the mountain. It is mainly composed of brown-red silty clay with a small amount of pore water distribution. It can be regarded as the water -insulating layer.

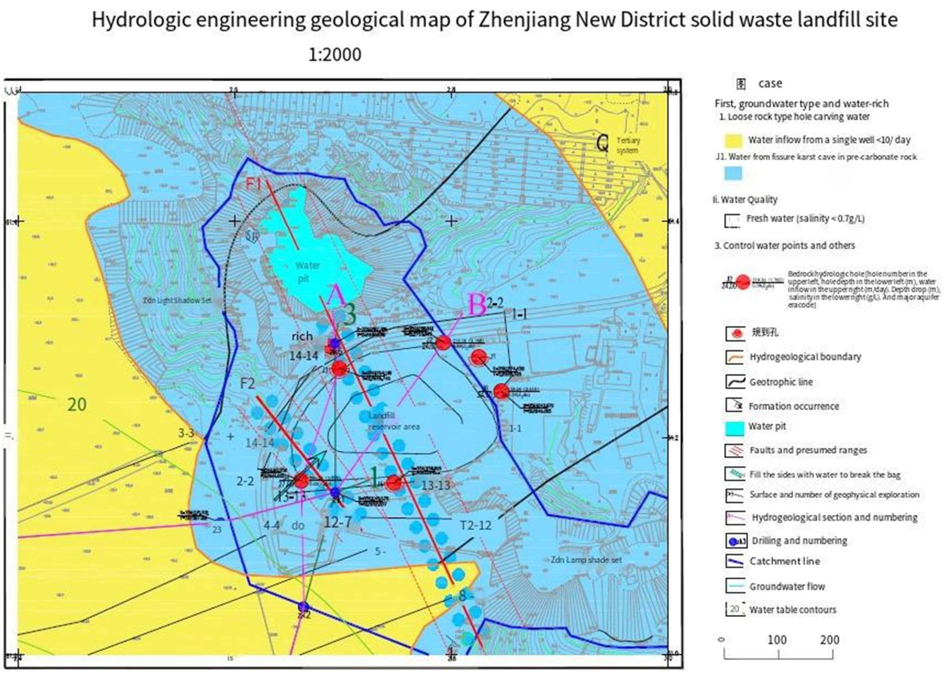

***Figure 1.** Engineering geological map of the reservoir area.*

3. Model Establishment

3.1. Boundary Conditions and Conceptual Models

According to the formation lithology and occurrence conditions of groundwater, hydraulic connection and hydrodynamic characteristics, the study area is generalized into a closed hydrogeological unit, and the Sinian karst aquifer is the main aquifer, with the thickness of about 200-500m. According to the regional hydrogeological conditions, the downstream of the study area is an east-west waterlogging pit, which is also the discharge base of groundwater in the north of the study area, so it is set as the third type boundary. The outcrop layer on the east and west sides is the Quaternary loose layer, mainly silty clay, with weak water permeability and poor permeability, which is the relative water barrier layer. Due to the influence of geological structure and its associated structures, the surface watershed in the south of the study area is close to the east-west trend, and the precipitation on both sides of the surface watershed respectively supplies groundwater on both sides, so the surface watershed in the south of the study area is basically the same as the underground watershed. Therefore, the surface watershed in the south of the study area is generalized as the water-separating boundary of the model. The groundwater flow system in the study area is generalized as heterogeneous anisotropic three-dimensional stable flow, with a total area of $0.72km^2$.

3.2. Mathematical Model of the Study Area

Based on the established hydrogeological conceptual model, a three-dimensional stable flow mathematical model of anisotropic groundwater in the study area was established:

$$\begin{cases} \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial H}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial H}{\partial z}\right)=0 \\ H(x,y,z,t)|s_i=\varphi_i(x,y,z,t),(s,y,z)\epsilon S_i \\ K\frac{\partial H}{\partial n}\Big| S_i=q_i(x,y,z,t),(x,y,z)\in S_i \\ \frac{\partial H}{\partial n}+\alpha H=\beta \end{cases}$$

Where, Kxx is the principal value of the permeability coefficient in the xdirection, Kyy is the principal value of the permeability coefficient in the y direction, Kzz is the principal value of the permeability coefficient in the z direction, m/d; H -- water head of confined aquifer, m. H(x,y,z,t) represents the head of the point (x,y,z) on the boundary section Si at time t under the three-dimensional condition, and is a known function on Sφi(x, y, z, t)i. n is the direction of the outer normal of the boundary Si q is the known function representing the amount of lateral recharge per unit area on Si. Alpha and beta are known functions.

The movement of substances dissolved in groundwater along groundwater current can be described as follows:

$$\frac{\partial c}{\partial t}=\frac{\partial}{\partial x}\left(D_{xx}\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_{yy}\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_{zz}\frac{\partial c}{\partial z}\right)-\frac{\partial(u_x c)}{\partial x}-\frac{\partial(u_y c)}{\partial y}-\frac{\partial(u_z c)}{\partial z}$$

Where, Dxx is the principal value of longitudinal dispersion coefficient, Dyy is the principal value of transverse dispersion coefficient, and Dzz is the principal value of transverse dispersion coefficient. c is solute concentration, mol/l; *u* Is the actual average flow velocity, m/d.

$$c(x,y,0)=c_0(x,y)\ (x,y)\in\Omega, t=0$$

$$\left(c\vec{v}-Dgradc\right)\cdot\vec{n}|_{r}=\varphi(x,y,t)\ (x,y)\in\ \Gamma_2, t\geq 0$$

Is the region where solute percolates; Γ2 is the boundary of the second kind; C0 is the initial concentration; φ is the boundary solute flux.

3.3. Source Sink Term

(1) Supply items

The main source of groundwater recharge in this area is atmospheric rainfall, and its enrichment and migration are mainly controlled by landform, stratigraphic lithology and structural location. According to the relevant meteorological data of Zhenjiang area, the average annual precipitation is about 1900 mm/a. In addition, due to the influence of the topography and two permeable faults in the site, the surrounding groundwater may converge to the study area, but the main source of groundwater recharge is rainfall infiltration. The strata in the study area are SinianDengying Formation (Z_2dn) and Doushantuo Formation (Z_2d^2), and the lithology is carbonate rock. In this area, surface karst is developed and there are downfall caves. Therefore, the maximum rainfall infiltration coefficient is 0.3, and the local rainfall recharge groundwater is 0.0015m/d.

(2) Drainage terms

Mining leads to the formation of a large drainage pit in the northern part of the reservoir area. The water level in the pit remains constant throughout the year and is lower than the minimum elevation of the reservoir area. The water in the pit cannot be drained, and the groundwater flows from southwest to northeast. In the establishment of the model, the upwelling spring point in the area is also taken as the drainage term of the model.

3.4. Parameter Partitioning and Values

According to the stratigraphic lithology information obtained from the regional hydrogeological map and the structural geological map, the structural development status, the reservoir pumping (injection) water test and the mastered hydrogeological data, the permeability coefficient of the study area was divided into 12 main areas (Figure 2). There is a linear relationship between the principal values of the permeability tensor calculated according to the measured fissure. Through linear regression analysis, the permeability ellipsoid has a certain linear relationship between the horizontal axis Ky and the horizontal axis Kx, Ky=0.3015Kx. Therefore, the permeability coefficient can be divided into Kx and Ky values according to the osmotic principal axis direction (Table 1). According to the collected data, predecessors have done a lot of work in the study area. By referring to the pumping test and dispersion test done in the same set of lithology and strata, the empirical values are taken as the vertical permeability coefficient and dispersion coefficient of the study area on the basis of previous studies through analogical analysis.

Table 1. *Permeability coefficients of each main area.*

Serial number	Kx (m/d)	Serial number	Kx (m/d)
Zone 1	1.35	Zone 7	2.1
Zone 2	1.58	Zone 8	1.46
Zone 3	1.56	Zone 9	0.8
Zone 4	1.75	Zone 10	1.5
Zone 5	1.83	Zone 11	0.15
Zone 6	1.56	Zone 12	1.2

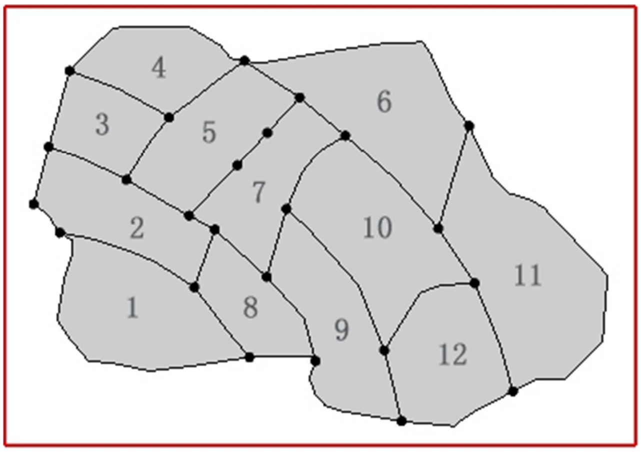

Figure 2. *Partition diagram of permeability coefficient.*

The indoor measurement value of dispersion is not suitable for the numerical simulation [9] of pollutant dispersion in a wide range of study areas. Therefore, the longitudinal dispersion should refer to the research results [10] obtained by predecessors in the site. According to the test data near the study area, the statistical relationship between longitudinal dispersion and observation scale should be calculated, and the value of longitudinal dispersion is 48.375m according to the conservative evaluation principle. The horizontal dispersion is 10% of the longitudinal dispersion. By referring to the existing research results, the average porosity of rock mass in the study area is determined to be 0.30.

3.5. Model Establishment and Identification

(1) Model building

According to the regional hydrogeological survey data, there is no large water source or pumping well for other purposes in the whole hydrogeological unit, and the groundwater rediameter drainage system has little human interference and is still in a natural state. Therefore, the 3D stable flow of aquifer is adopted to simulate the groundwater flow field when the model is established. The topographic elevation is input to the model in 2D scatter mode. And then IDW interpolation method is used to assign its value [11-15].

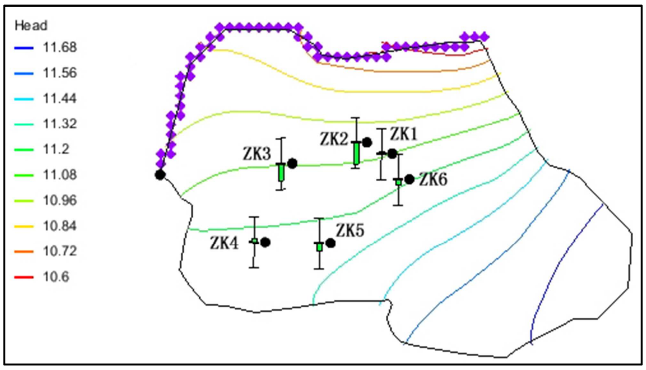

Figure 3. *Steady groundwater flow field (m).*

(2) Model fitting

The relationship between the observed hole data and the calculated data in GMS7.1 software is as follows. If the difference between the observed value and the calculated value is within the checking confidence range, the error bar will be shown as green; If the difference is beyond the check confidence range, but less than 200%, the error bar will be shown as yellow; If more than 200% is exceeded, the error bar will appear red.

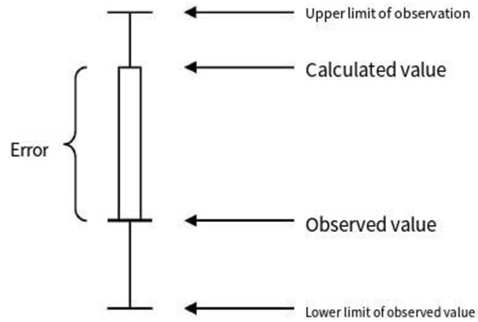

Figure 4. *Schematic diagram of error sticks.*

The groundwater level measured by six groundwater monitoring Wells, ZK1, ZK2, ZK3, ZK4, ZK5 and ZK6, set around the reservoir area of the landfill site, is used as the calibration basis for the steady flow groundwater field. Through reasonable adjustment of parameters, the model is as close to the real groundwater level as possible, so that the model can simulate the current situation of groundwater flow field in a real and effective way. The simulation results of the model are shown in Figure 3, and the calculated water level at each observation hole is within the set error range (see Table 2).

Table 2. *Table of water level fitting results and errors.*

Unit: m

Drill hole number	Observing water level	Calculated water level	Error	Set error (absolute alue)
ZK1	10.99	11.08	-0.09	1
ZK2	11.886	11.027	0.858	1
ZK3	11.765	11.075	-0.689	1
ZK4	11.050	11.230	-0.180	1
ZK5	11.535	11.264	0.270	1
ZK6	11.39	11.190	0.199	1

The calculated water level and observed water level of the model are within the set error, and the model can basically reflect the groundwater flow field under the corresponding conditions, and the established model is reasonable and reliable. It can be known from the model that groundwater flows from south to northeast.

4. Pollutant Migration Rule and Concentration Change Prediction

4.1. Pollutant Type and Source Intensity Setting

Rainfall causes swelling and destruction of the waterproof curtain wall on the east side of the landfill site. Groundwater rushes into the foundation pit and mixes with the seepage. Pollutants enter the aquifer through the groundwater migration channel, thus polluting the groundwater. Landfill common pollutants are mainly ammonia nitrogen, nitrate, nitrite, total hardness, chloride, iron, manganese and volatile phenol, according to the data that has been mastered, the highest concentration of seepage night, the most harmful pollutant is nitrate, according to the most harmful principle, the farthest possibility of pollutant diffusion analysis, without considering adsorption and biochemical action, The simulation uses nitrate as a characteristic factor of pollution to predict its migration rule and concentration change. According to the data obtained, the reservoir pit water inflow is about 4600m^3/d (the center depth is 2.4m), and the nitrate concentration is 1.236g/L. The model considers that pollutants penetrate the quaternary clay layer and enter the aquifer after the reservoir impervious membrane breaks. The model assumes that the water flowing into the reservoir area is uniformly mixed with garbage and polluted into garbage leakage liquid. Two scenarios are set. The total amount of garbage leakage liquid is 1% and 2% of the total sewage, respectively, and the corresponding flow rate is 46 m^3/d and 92 m^3/d. Only the waterproof curtain wall on the east side of the reservoir area was damaged, so the leakage mode was set as point source pollution, and the leakage center was the damage of impervious film on the east side of the reservoir area. The initial concentration of nitrate at the leakage point was 1.236g/L. Landfill is generally half a year to overhaul all facilities once, that is, the waterproof curtain is damaged within 180 days after the repair, assuming that after the repair of impervious film pollutants no longer leak out, that is, pollutants continue to leak 180 days after cut off the source of pollution, simulate the remaining pollutants in the aquifer migration and concentration change. The simulation lasted for 1500 days, simulating the time required when the leakage liquid of different concentrations migrated to ZK2 outside the reservoir area. The process of adsorption, reaction and attenuation of pollutants is not considered in the simulation.

4.2. Analysis of Simulation Results of Pollutant Migration

(1) Simulation results of flow leakage at 46 m^3/d (1%)

After 180 days of continuous leakage of waste leakage at a flow rate of 46 m3/d, the central concentration of the leakage area is about 482.94mg/L. (Figure 5), the square grid side length is 20cm. After 180 days of continuous leakage of waste leakage, the pollutants spread out about 40m. According to the third-class groundwater standard GBT 14848-2017, the limit of nitrate concentration is 20mg/L, so the minimum display range of pollution plume in the model is set to 20mg/L.

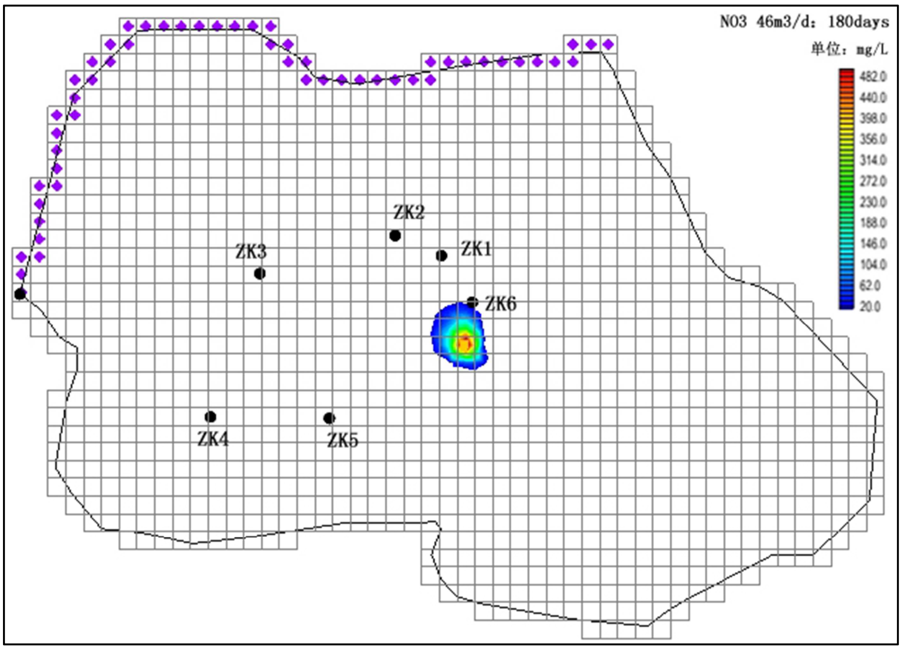

Figure 5. *1% nitrate seeps into the plume for 180 days.*

After the continuous leakage of pollutants for 180 days, the impervious membrane is repaired, the surface pollution source is cut off, and the pollutants no longer enter the groundwater, and the residual nitrate in the aquifer will return to full migration and dilution with the groundwater flow. When the residual pollutants migrated in the aquifer for 100 days after the pollution source was cut off, the pollution plume gradually diffused downstream, and the pollution center migrated about 10m downstream. The concentration of the pollution plume center was 278.29mg/L (Figure 6-a). 500 days after pollutant migration, the plume center concentration decreased to 98.24mg/L and the front concentration was 18.34mg/L. The plume gradually moved downstream (in the direction of ZK2) slowly, with a moving distance of about 30m, and the contaminated area was gradually expanding (Figure 6-b).

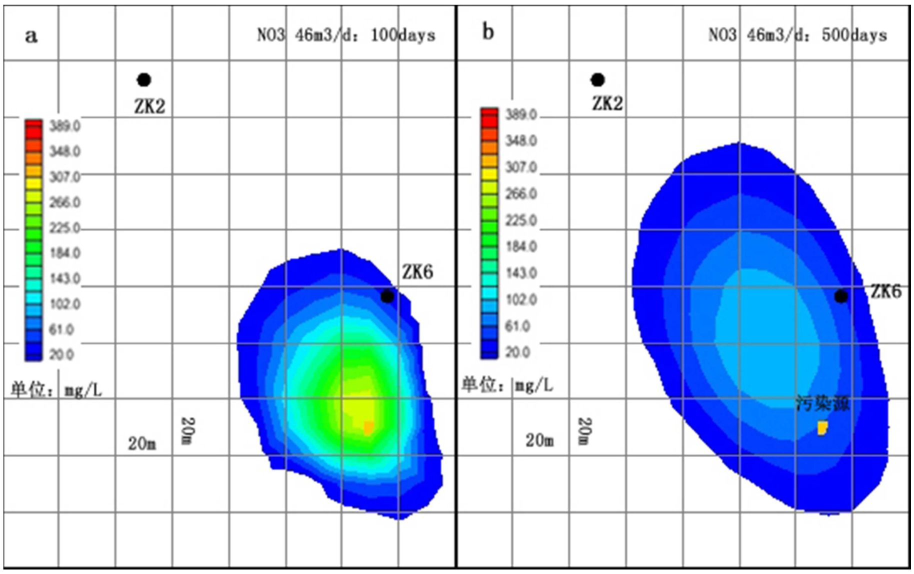

Figure 6. *Simulation chart of residual nitrate migration in 100-500 days with 1% leakage.*

When residual pollutants migrated for 1300 days, the plume reached the downstream edge of the landfill ZK2 and began to migrate outside the landfill. At this time, the core concentration of the plume was 47.61mg/L, the front concentration was 13.02mg/L, and the contaminated area reached the maximum (Figure 7-a). When the plume migrated for 3000 days, the plume area was the smallest and the overall concentration was 20.20mg/L, and the pollutants migrated to 68m downstream of the site (Figure 7-b). According to the trend that the concentration of pollutants remaining in the aquifer gradually decreases with the migration time, the concentration of pollutants in the groundwater will be less than 20mg/L at about 3020 days.

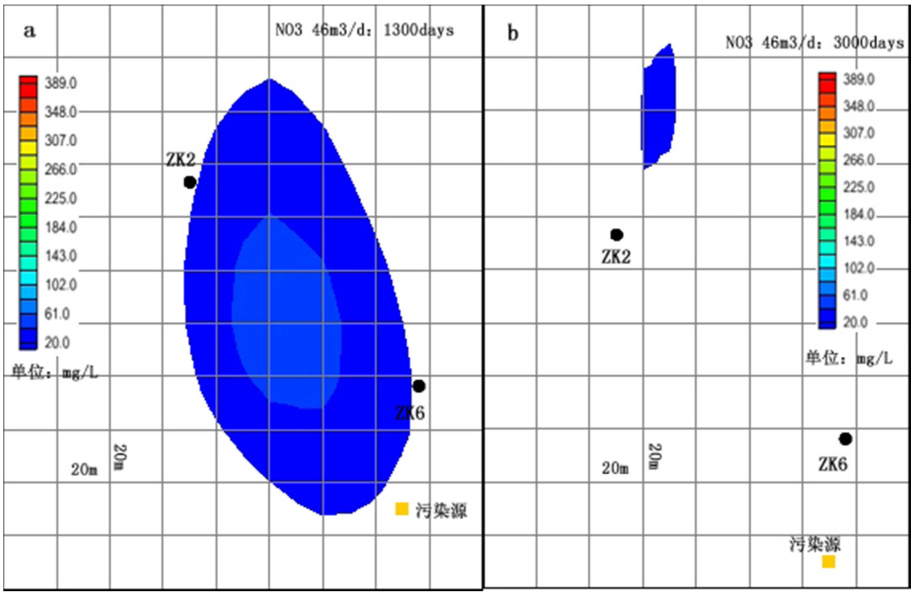

Figure 7. *Simulation chart of residual nitrate migration in 500-3000 days with 1% leakage.*

(2) The flow leakage simulation results were 92 m^3/d (2%)

When the leakage amount is 2% and the pollutants continue to leak for 180 days, the central concentration of the pollution plume is 712.10mg/L, and the pollution plume extends 35m downstream (ZK2 direction). With reference to the third class groundwater standard GBT 14848-2017, the pollution range and concentration greater than 20mg/L are shown in Figure 8.

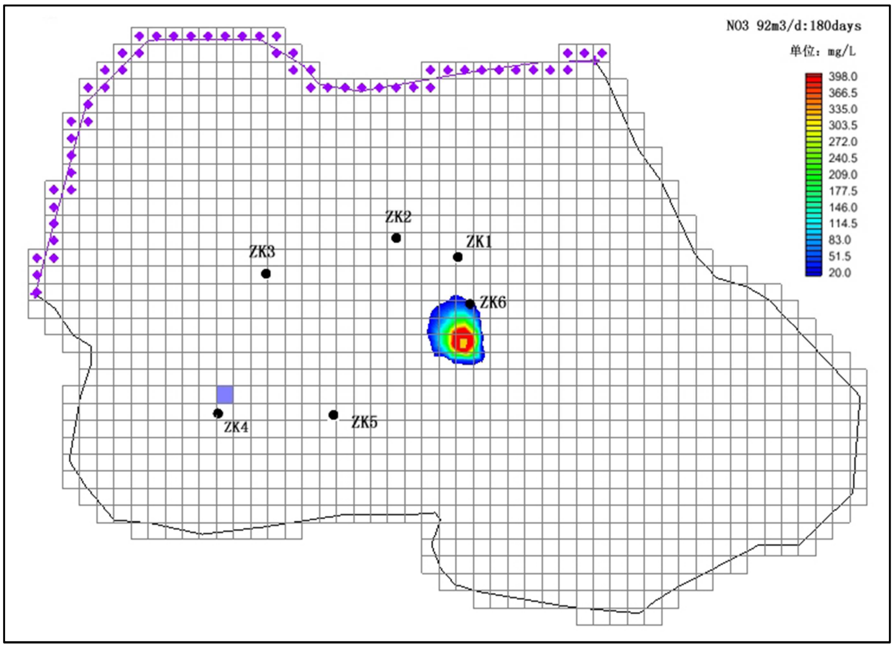

Figure 8. *2% nitrate seeps into the plume for 180 days.*

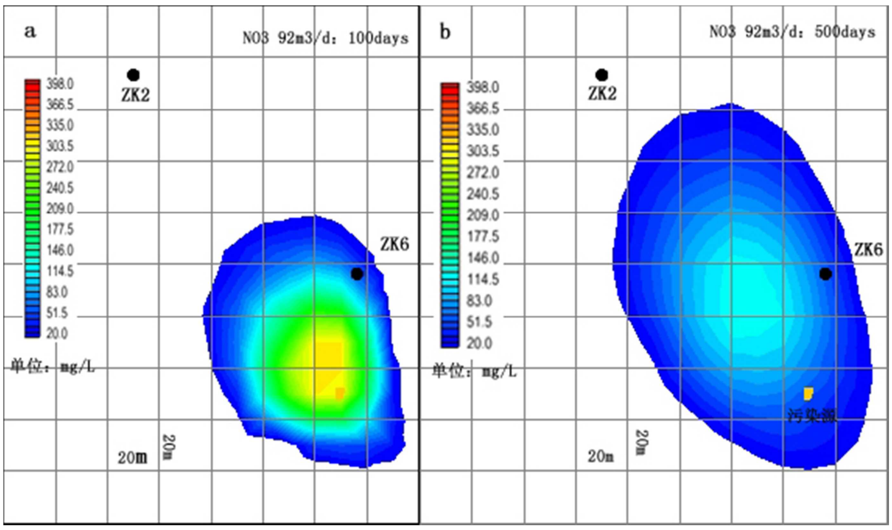

Figure 9. *5% leakage residual nitrate migrates 100-500 days.*

Nitrate leakage at 2% continued for 180 days and cut off the source of pollution, and the remaining pollutants migrated with water flow in groundwater. When the residual nitrate migrated for 100 days after the pollution source was cut off, the plume gradually moved about 25m to the downstream direction of ZK2, with the central concentration of 303.83mg/L and the front concentration of 18.92mg/L, and the area of the plume gradually expanded (Figure 9-a). When the residual pollutants migrated in the groundwater for 500 days, the area of the plume gradually increased and the shape of the plume was oval. At this time, the central concentration of the plume is 121.28mg/L, and the front concentration is 19.91mg/L, indicating that the plume is still within the scope of the landfill plant area (Figure 9-b).

When the residual nitrate migrated in groundwater for 1000 days, ZK2 at the northern edge of the landfill began to be polluted, and the pollution plume front already passed ZK2. At this time, the concentration of the plume center was 72.63mg/L, and the concentration of the plume front was 17.39mg/L. The plume area no longer expanded, and the pollution center gradually moved to the downstream direction of ZK2 (Figure 10-a). When the residual pollutants migrated for 3500 days, the pollution area was the smallest, and the pollutants migrated to about 142m downstream from ZK2, at which time the average concentration of the pollution plume was 20.24mg/L (Figure 10-b). According to the trend of decreasing residual nitrate in the aquifer along with the concentration of groundwater migration, the pollutant concentration is expected to be less than 20mg/L at 3550 days.

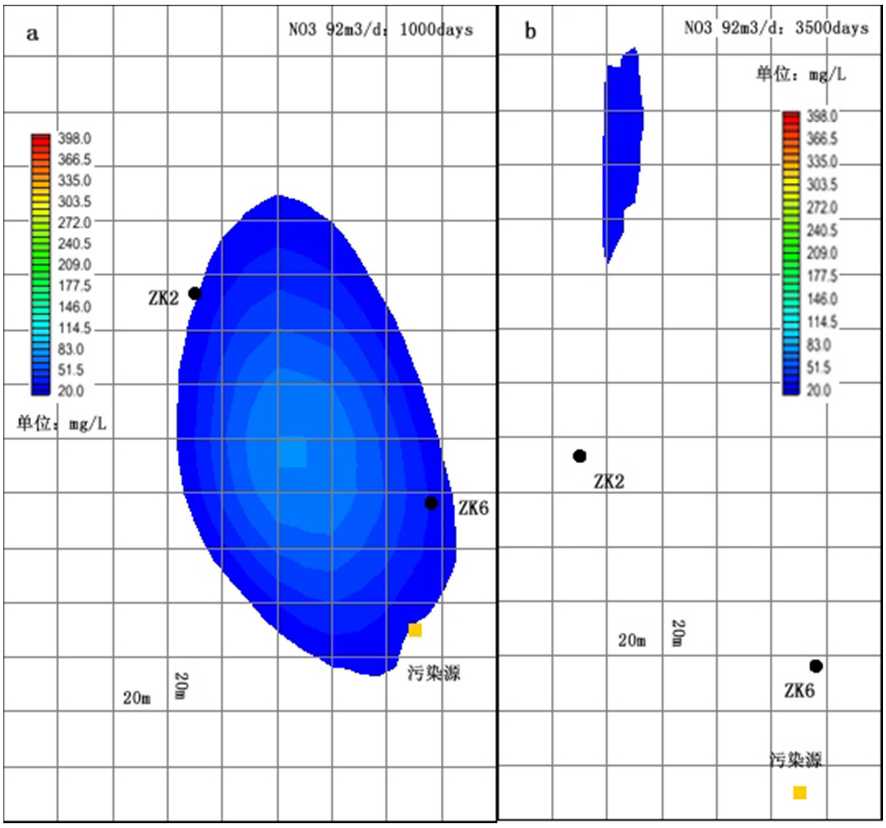

Figure 10. *2% leakage and residual nitrate migrated for 1000-3500 days.*

(3) Simulation and prediction results

The waterproof curtain on the east side of the landfill site in Zhenjiang New District was damaged, and the groundwater flowing into the reservoir area mixed with garbage to form garbage seepage into the aquifer to pollute the groundwater. In this simulation, nitrate in the garbage seepage was selected as the sensitive factor for simulation, and the initial concentration of pollutants was 1236mg/L. It is assumed that the leaking pollutants can enter the aquifer through the groundwater runoff channel. Two simulation scenarios are set without considering adsorption and reaction, and the corresponding flow rates are $46m^3/d$ and $92m^3/d$ when the amount of simulated waste seepage is 1% and 2% of the total sewage. After 180 days of continuous waste leakage, the pollution source is cut off. At this time, the central concentration of the pollution plume is 482.94mg/L and 712.10mg/L. After the pollution source was cut off, the continued migration of residual pollutants in the aquifer was simulated (see Table 3).

Table 3. *Statistical table of simulation results of residual pollutant transport.*

The leakage of the original pollution source is m^3/d		Migration days of residual pollution source (d) and concentration (mg/L)				Time of contamination plume to ZK3 (d)	Maximum migration distance from contaminant plume leading edge to contaminant source (m)
		100	500	1000	1300		
nitrate acid salt	46	278.29	98.24		47.61	1300	234
	92	303.83	121.28	72.63		1000	281

5. Conclusion

(1) Through the flow model, it is found that the groundwater hydraulic slope of the landfill site in Zhenjiang New District is small, which leads to the trend of the pollution plume extending upstream without cutting off the pollution source. Through the solute transport model, it is found that the waste seepage causes a large area of pollution under the condition of a large flow, which has a certain impact on the groundwater flow field.

(2) By summarizing the simulation and prediction results under the two scenarios, it is found that after the nitrate leachate is cut off, the residual pollutants in the landfill gradually expand the scope of pollution plume with the extension of migration time, and then gradually shrink until it disappears after reaching the maximum area.

(3) This simulation is only carried out near the landfill site, and only considers the migration of pollutants in the aquifer vertically, without involving confined water. The adsorption

of soil, chemical reaction and biodegradation in groundwater are not considered in the calculation, and the values of all parameters are conservative when the model is established, so the actual migration rate of pollutants in the aquifer is relatively fast. The area of the pollution plume is also slightly larger than that of the model simulation.

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