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Research Article

Simulation for migration and treatment of groundwater contamination in coal mining subsidence area: A case study of Datong dump, Huainan, China

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Abstract

The liquid that seeps into the earth from landfills and removes garbage is called landfill leachate. Pollutants like organic and inorganic chemicals, xenobiotic substances, etc. are found in landfill leachate which contaminates groundwater. To study the contamination and treatment of landfill leachate to groundwater, Datong landfill was selected as a target zone. Samples of monitoring wells in the landfill site, the eastern collapse pond, and wells in groundwater from the goaf were tested and analyzed for TDS, conductivity, and dissolved oxygen (DO). To simulate all processes, various modules were built under different conditions. It was found that the leachate not only had polluted surface water but also groundwater. The simulation results showed that the pollution plume expanded spatially and temporally, mainly flowing from west to east and spreading to the north-south direction and reverse flow direction due to the low water level between the east and west sides. Anti-seepage walls and pumping-injection methods were used to control the migration and diffusion of pollution from landfill leachate. The simulation results also showed that both methods were effective in reducing the concentration and range of pollution plumes which would provide a theoretical basis for the treatment of pollutants in the Datong landfill site.

Keywords: Leachate in Datong landfill, groundwater pollution of goaf, prevention and control scheme, aquifers, pollution plume

1. Introduction

The average daily household waste generated by cities across China is 0.85 kg per person, with an average annual output of 135 million tons and an annual growth rate of no less than 8%. More than ten years ago, landfill was an important method for dealing with municipal solid waste and domestic waste in most countries, but due to the immaturity of the method of treating landfill leachate at that time, and the construction of some landfills did not meet the relevant standards, the leachate produced by landfills leachate into the aquifer and polluted the groundwater. A lot of garbage is untreated, piled up outdoors for a long time, after fermentation, a series of physical, chemical, and biological reactions occur, and then washed by rainwater, a large number of harmful gases and waste liquid will be produced. Leachate is an aqueous effluent made of dissolved organic matter (DOM), xenobiotic organic compounds, various anions and cations, and heavy metals, and is the result of solid waste undergoing physical, chemical, and biological alteration in landfills [1]. Municipal landfills are a major source of worry because of the potential for pollution caused by the produced leachate to mobilize into surface and groundwater through the unsaturated zone [2,3]. Nevertheless, this process is going on even after landfills have ceased to receive waste [4]. Hence, it is imperative to continue conducting thorough investigations and ongoing surveillance around landfills. To simulate the flow movement of groundwater pollutants, some software such as MODFLOW, GMS, and Feflow are used [5]. The U.S. Geological Survey has released six "core" versions of MODFLOW, the most recent of which is MODFLOW 6. In addition to groundwater flow, the MODFLOW 6 design facilitates the integration of other hydrologic processes and permits interprocess communication [6]. The process can be represented using conceptual models and can be further enhanced and revised by the incorporation of elements such as points, arcs, and polygons. Additionally, it can be employed in the context of solute transport inside construction projects. The advection-dispersion model is used to evaluate the sensitivity of the model parameters to identify the primary elements that influence the solute transport model inside the designated study area [7,8]. Researchers have conducted analytical simulations to investigate the pollution of aquifers resulting from the accumulation of solid waste [9,10]. The leachate produced by the dump is also a highly concentrated wastewater containing various pollutants, which causes serious pollution to the surrounding surface water, and groundwater. So, it is important to clarify the mechanism by which pollutants from leachate generated by landfills migrate and disperse in underground aquifers.

This paper takes the Huainan Datong landfill as the research object and analyzes the pollutant concentration distribution and chemical characteristics by investigating the hydrogeological conditions and collecting samples, and simulates the transport and diffusion of pollutants from the leachate to groundwater in the aquifers of goaf, and predicts the pollution plume within 10 years, deeply discusses the solute transport characteristics of pollutants under such conditions as convective dispersion, aerobic degradation, and microbial action, and puts forward the prevention and control scheme about landfill leachate under coal mining subsidence. The simulation and analysis of the impermeable wall and pumping well conditions were carried out, which provided a theoretical guide for groundwater contamination restoration for two aquifers of the mined goaf.

2. Description of study Area

The Datong District is situated in the eastern region of Huainan City, positioned on the southern bank of the Huaihe River. It is bordered by the Shungeng Mountains to the north. Datong district belongs to a warm temperate semi-humid monsoon climate zone and is characterized by wet summers and cold winters. The average temperature ranges between 15.8 and 40.3 C. Its average rainfall is 942.8 mm. The groundwater level depth varies from 0.5 to 12 m. The simulation area is about 5 km^2 with three main stratums.

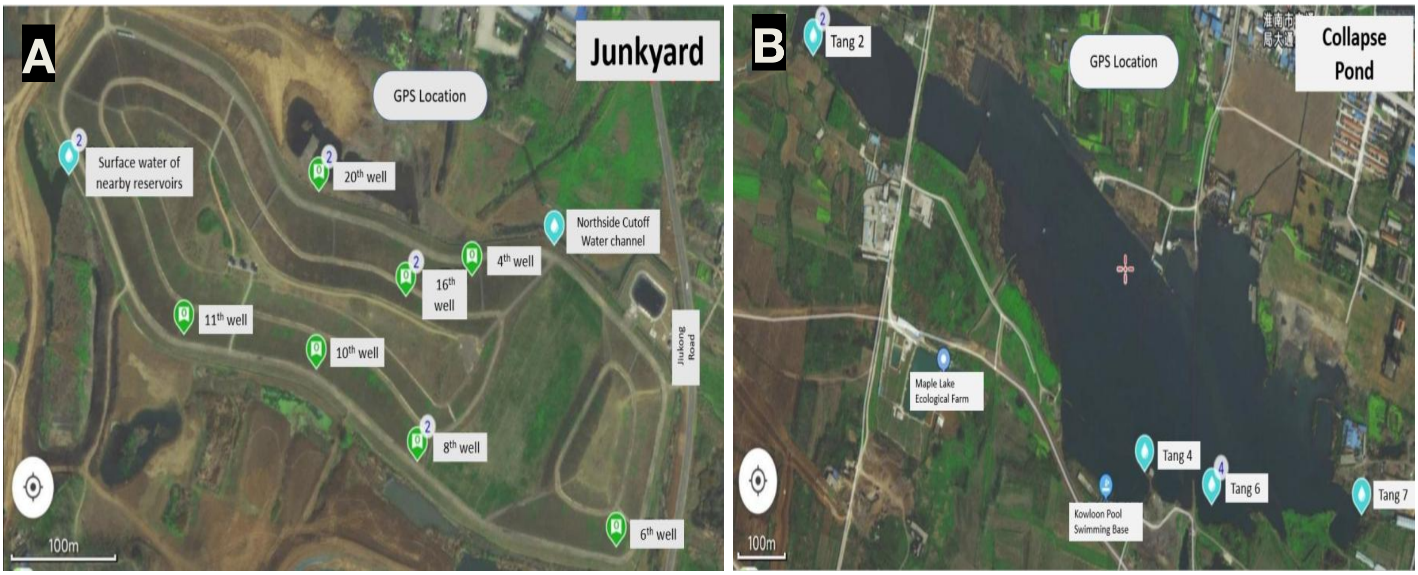

Figure 1. ((A) Datong dump site (sampling positions) and (B) Landfill water surface (sampling positions) using OvitalMap.

The first layer is filled with miscellaneous and domestic garbage and the thickness is about 0~19 m. The second layer is filled with silty clay and the thickness is 0.7~15 m. The third layer is weathered sandstone. At present, the landfill site spreads over an area of about 650×200 m^2. This site has not been designed systematically before being used for the landfill and the base has not been lined. Figure 1(a-b) illustrates the landfill site of Datong district.

In particular, the Huainan Datong dump was closed in 2017 and repaired in situ, but due to the early stacking conditions of the dump, the site did not work for bottom seepage prevention, and at this stage, there is only vertical seepage prevention, and top seepage prevention work, although fresh leachate is not produced at this stage, the leachate leakage generated during the previous stage of operation still produce environmental pollution problems, which has a certain impact on the around groundwater. Until now, the mechanism of migration and diffusion of leachate from the Datong domestic waste landfill in Huainan City in groundwater is unclear.

2.1. Groundwater contamination's

Huainan Datong landfill is located in the mining subsidence area which is not yet a garbage dump, due to the mining of local coal mines, the stress of the rock layer on the goaf is changed, the balance is destroyed, and the environmental geology and hydrogeological conditions of the mining area are changed, resulting in the deformation of the "upper three belts" of the mining area [11], shallow groundwater leaks along the fissures to the deep depth, resulting in a significant drop in the groundwater table, and the replenishment of groundwater to the surface soil water is also reduced. On the other hand, mining also destroys the original soil structure of the unsaturated zone, resulting in the development of vertical fractures which have a certain degree of impact on surface rainfall infiltration and evaporation, groundwater recharge, etc. In addition, mining wastewater and waste residue also pollute the soil and groundwater, making the land a wasteland, seriously damaging the surface ecological environment [12], and gradually forming a garbage dump site after the surface collapse. Due to long-term coal mining and drainage, causing the collapse of mining hollowing, karst collapse has also occurred in the surrounding area due to special geological conditions, forming more than 10 waterlogged puddles.

After geological investigation, limestone was revealed in the southeast corner of the site, and there may be local caves [13]. In the past years, the landfill was conducted in coalmine subsidence areas without the implementation of suitable liners that avert the absorption of leachate into underground aquifers.

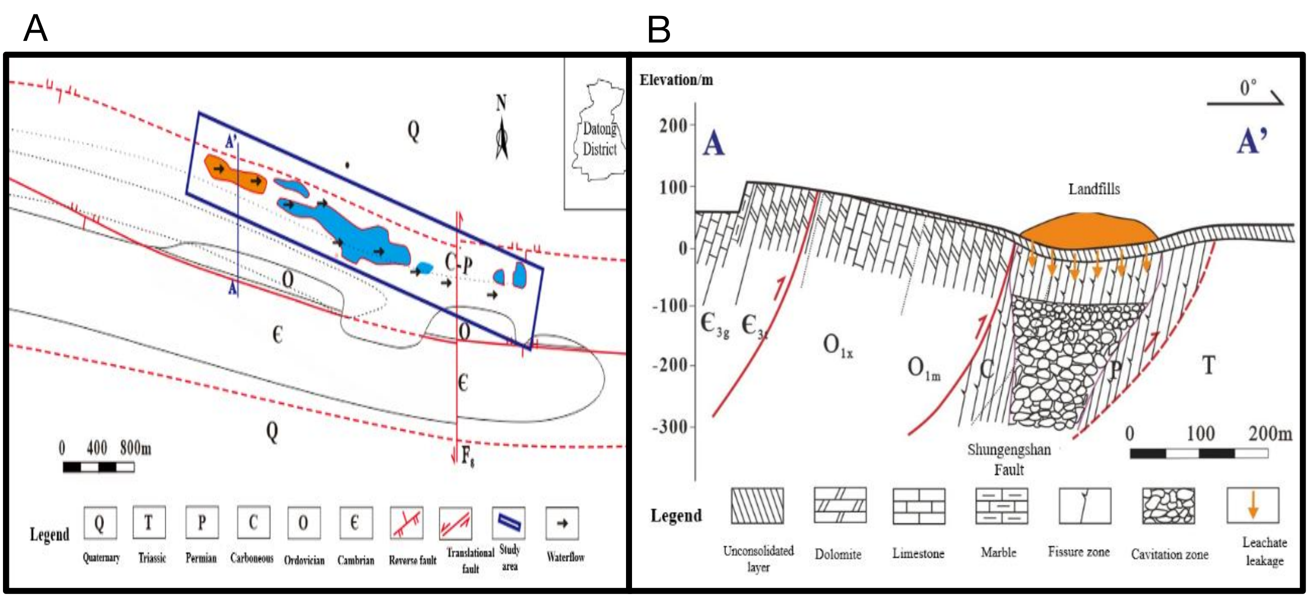

Figure 2. (A Hydrogeological plane map and (B) hydrogeological cross section map.

The leachate that arises from the closing of a landfill for garbage typically exhibits a significant presence of organic pollutants, often in high concentrations. The presence of leachate has the potential to result in widespread contamination of groundwater [14, 15]. Furthermore, it is important to note that the quality of groundwater and the composition of microbial communities undergo substantial changes as a result of the degradation of organic pollutants, the depletion of electron acceptors, and alterations in the redox zone over time and space [16, 17]. The presence of oxygen is a crucial element in aerobic degradation [18]. In the case of a contaminated aquifer, aerobic microorganisms utilize oxygen to metabolize organic contaminants, resulting in the conversion of these contaminants into carbon dioxide and water. Based on the investigation conducted on the characterization of microbial communities in landfill leachate throughout the process of aerobic biodegradation, it was shown that the population of aerobic microorganisms in the leachate experienced a significant rise of two orders of magnitude within the initial few months of air injection [19]. The number of bacteria present in aquifers contaminated with leachate was found to be significantly greater when compared to that observed in uncontaminated aquifers [17].

3. Methodology

3.1. Collection of Samples

Thirteen sampling sites were designed, including 2#, 3#, 4#, 6#, 12#, Tang 1, Tang 2, Tang 3, GW (groundwater)1, GW5, GW8, GW9, AND GW10 (Fig.2 a, b). These sites consist of 5 wells of landfill, five samples were from groundwater, and three samples were located in the eastern region of the collapse pond (Fig. 2). Water samples have been gathered utilizing polyethylene plastic bottles, specifically PET (polyethylene terephthalate) bottles. Before the collection of water samples, rigorous washing procedures are implemented. The plastic bottles undergo a minimum of three washes using on-site water at the location of collection [13].

3.2. Physicochemical Characteristics

Physicochemical characteristics of the leachate depend primarily upon the contaminant composition and water content in total waste. According to the water samples taken, the monitoring data results were obtained according to the field measurement and laboratory calibration, as shown in Table 1. From the measurement results, it can be seen that the total dissolved solids (TDS) and conductivity values of the water samples in the monitoring wells in the dump are higher than those of the water samples in the subsidence pond, while the dissolved oxygen DO is much lower than that in the subsidence pond, indicating that the shallow groundwater in the monitoring wells in the dump may be polluted to varying degrees. [20,21]. According to the water samples taken, the monitoring data results were obtained according to the field measurement and laboratory calibration, as shown in Table 1.

3.3. Prevention of pollution and control seepage

In coal mining, due to the expansion of the goaf area, the collapse of the coal seam roof overburden is caused, thus forming the "upper three belts". When the upper rock layer is bent as a whole, the surface begins to shift horizontally and vertically, and finally, a subsidence zone is formed, within the scope of the slope aeration zone, deformation and cracks will appear, which will cause a series of environmental geological problems and hurt the restoration of the agricultural ecological environment [22].

According to the specific situation of Huainan Datong landfill, a plan for the prevention and control of pollution in the seepage field of the garbage dump was proposed, and the GMS software was used to simulate and analyze the given scheme, to protect and control the groundwater pollution in the study area. According to the data, for the Huainan Datong landfill, which is an informal landfill, groundwater pollution is mainly dealt with through two technical aspects: source control and cutting off pollution pathways. Source control is generally in two ways: source item removal and source item reduction, and given that the old Datong garbage dump has been closed for many years, the pollution source has been greatly reduced. Methods such as impermeable walls or pumping wells are generally used to control the outward spread of pollutants from the site [23].

Table 1. Test index content of sampling sites

Test index	Sampling Positions												
	2#	3#	4#	6#	12#	Tang 1	Tang 2	Tang 3	GW1	GW5	GW8	GW9	GW10
D0 (mg/l)	1.12	1.48	1.35	1.83	2.42	6.34	6.62	5.61	2.91	5.93	4.55	5.09	2.97
BOD_5(mg/l)	12.88	97.15	66.56	8.96	93.28	8.42	13.44	8.06	6.42	7.92	5.04	1.62	5.76
TDS (ppm)	535	539	2760	693	1710	647	642	621	1320	363	384	611	453
Electrical conductivity (μs)	1050	1086	5540	1386	3420	321	321	309	2630	728	766	1226	904
Ammonia nitrogen	8.149	10.517	53.087	3.308	43.736	1.766	1.476	3.136	5.749	2.139	1.057	8.249	1.974
TP (mg/L)	0.099	0.061	0.324	0.102	0.072	0.025	0.025	0.026	0.036	0	0.001	0	0.006
TN (mg/L)	13.038	18.404	93.434	4.797	67.818	3.376	3.763	4.471	8.273	3.478	1.942	13.119	4.037
CODcr (mg/L)	36.8	128	211.2	28	176	24	32	22.4	20	24	14.4	8	196

Note: Dissolved Oxygen (DO), Biological Oxygen Demand after five days (BOD_5), Total Solids Dissolved (TDS), Total Phosphorus (TP), Total Nitrogen (TN), and Chemical Oxygen Demand (CODcr)

This section considers the method of cutting off the source of pollution, simulating the scenario of using anti-seepage walls and pumping wells to prevent the spread of pollutants in the leachate to the surrounding area after landfill leachate leakage.

4. 4. Study on the migration and diffusion of landfill leachate under different conditions

4.1. Hydrogeological conceptual model

The hydrogeological conceptual model is a generalization of the hydraulic characteristics of the groundwater system in the study area, including boundary conditions, aquifer structure, hydrodynamic and hydrochemical characteristics, hydrogeological parameters and their recharge and discharge conditions, etc., to facilitate the simulation of groundwater flow and the migration of pollutants and solutes by using GMS software in the later stage.

4.1.1 Aquifer structure

The lower part of Datong old landfill is a Quaternary loose sediment, according to the combination characteristics of lithology and the water richness of the aquifer, the study area can be generalized into two layers, according to the mining properties and roof collapse, the confined aquifer can be divided into two layers, the upper goaf mainly contains pebbles and coarse ore particles, the permeability coefficient is large, and the lower permeability coefficient is small. In addition, this paper only studies the movement of groundwater flow under the condition of steady flow and treats the groundwater in the study area as a stable flow.

4.1.2 Boundary conditions

The boundary conditions are the conditions under which the boundary of the study area is located, that is, the conditions for the recharge, discharge, and runoff of groundwater at the boundary. According to the previous survey data, the groundwater flow direction in the study area is from west to east, and the shallow groundwater receives the local atmospheric precipitation recharge and the western direction of underground runoff recharge, so a fixed water head recharge boundary is assigned to the eastern and western boundaries, and the boundary water head is 35~32m. Due to the proximity of the south side to the mountain piedmont, there is an infiltration recharge of atmospheric precipitation, which is the boundary of weak recharge flow, and the north side can be turned into a water barrier boundary.

4.1.3 Sources and Sinks

The main source of groundwater recharge is atmospheric precipitation infiltration recharge, and the annual rainfall is 1275.2mm/year. In addition, there is the infiltration of shallow groundwater and the recharge of the east and west recharge boundaries. The exploitation of pumping wells in the eastern part of the study area is the main method of discharge.

4.1.4 Hydrogeological parameters

The hydrogeological parameters mainly include the permeability coefficient K, water supply, porosity, and transverse (longitudinal) dispersion coefficient of each aquifer. Hydrogeological parameters are an important part of the mathematical model, which directly determines the rationality of the simulation results. According to the relevant hydrogeological data for many years, as well as field investigation and experiments, in the process of determining the parameters of groundwater numerical modeling, the permeability coefficient of each layer of the model was assigned. Considering that the groundwater flow direction is east-west and mainly horizontal, the vertical permeability coefficient is small. The specific hydrogeological parameters of the layers are shown in Table 2.

Table 2. Specific Hydrogeological parameters of Layers

Layers	Kxx (m/d)	Kyy (m/d)	Porosity
Layer 1	5	3	0.2
Layer 2	2.5	2	0.3

Note: Kxx (Horizontal permeability coefficient K)

Kyy (Vertical permeability coefficient K)

4.2. Numerical simulation of groundwater flow

4.2.1 Mathematical model

Based on the hydrogeological condition, the three-dimensional flow of groundwater can be generalized as the following mathematical model, without considering the change in water density:

$$\frac{\partial}{\partial x}(k_{xx}\frac{\partial H}{\partial x})+\frac{\partial}{\partial y}(k_{yy}\frac{\partial H}{\partial y})+\frac{\partial}{\partial z}(k_{zz}\frac{\partial H}{\partial z})+w=\mu_s\frac{\partial H}{\partial t}$$

$$\begin{cases} H(x,y,z,t_0)=H_0(x,y,z) & (x,y,z)\in D \\ H(x,y,z,t)|_{t=t_0}=H_1(x,y,z)(t>0) & (x,y,z)\in s_1,s_2 \\ K\frac{\partial H}{\partial n}=q(x,y,z) & (x,y,z)\in s_3 \\ \frac{\partial H}{\partial n}=0 & (x,y,z)\in s_4 \end{cases}$$

… **(Eq.1)**

where *Kxx, Kyy*, and *Kzz*, are the permeability coefficient in the *x, y*, and *z* directions, respectively, and LT^{-1};

H, the water head, *L*;

μs, the specific storage, L^{-1};

t, the time, *T*;

w, is source and sink term LT^{-1};

$H_0\ (x, y, z)$: the initial head value, *L*;

$H_1\ (x, y, z)$: the boundary head value, *L*;

S_1 and S_2 are the given head boundaries on the eastern and western sides;

S_3 is the flow boundary on the southern side;

S_4 is the impervious boundary on the northern side.

4.2.2 Simulation area segmentation

According to the measurement data, the length of the simulation area is 2500 m from east to west, the width from north to south is 500 meters, the cells on the plane are 100x20 (row x columns), and the vertical area is divided into two layers according to the conditions of the aquifer, and the total number of cells is divided into 4000 cells, see Figure 3.

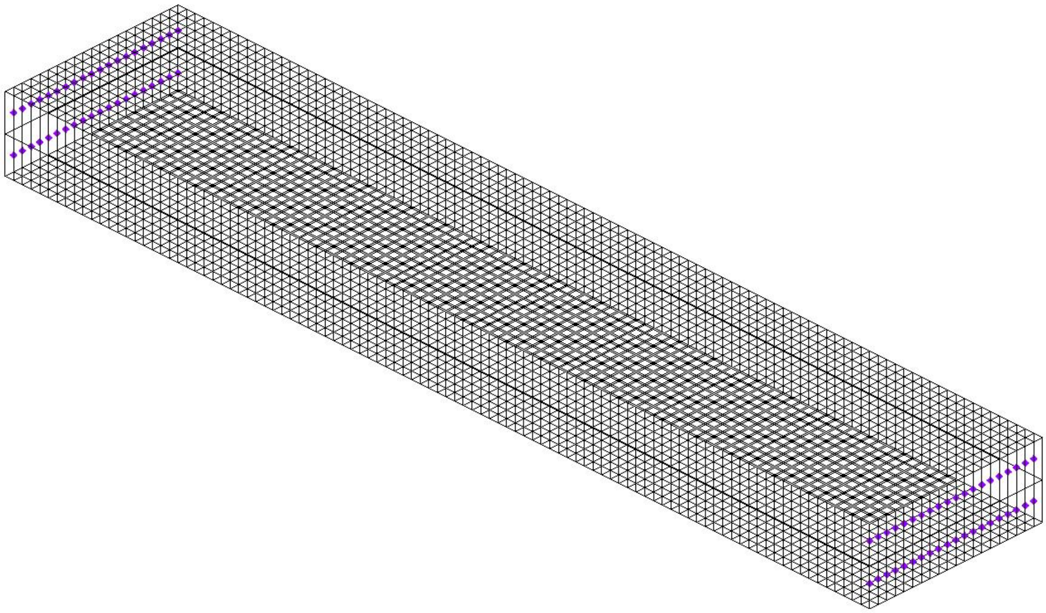

Figure 3. Grid view of the simulation area.

4.2.3 Initial conditions

(1) According to the hydrogeological conditions of the place and borehole data, the elevation of the aquifer roof and floor are set, and the specific values are shown in Table 3.

Table 3: Elevation data of the roof and floor of each aquifer

	Aquifer roof elevation (m)	Aquifer floor elevation (m)
Layer 1	30	-50
Layer 2	-50	-150

(2) The horizontal permeability coefficient, vertical permeability coefficient, and porosity parameters of each layer are from Table 2.

(3) According to the generalized hydrogeological conceptual model, the boundary conditions and initial water heads of each layer are set.

(4) According to the actual situation of the study area, several wells were added to the east side of the simulation area as the discharge of the study area.

4.2.4 Result analysis

Under the condition that no pollution source is added to the simulation area, the above model is run to obtain the distribution of water head, as shown in Figure 4. As shown in Figure 4, we can see that the water head in this area forms a descending funnel around the pumping well, and the water head is the smallest at the pumping well, and the water head increases when the two sides extend outward. Within the confines of the dump, it is consistent with the west-to-east flow of groundwater.

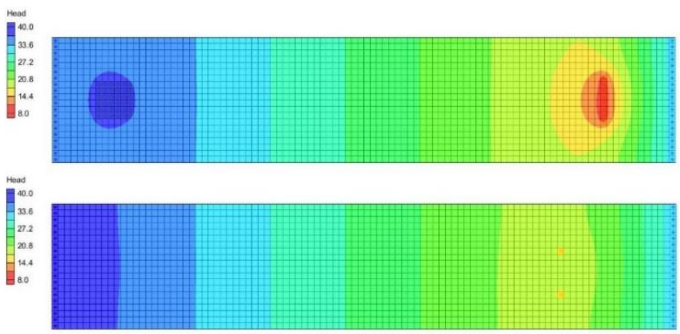

Figure 4. Two aquifers water head distribution of the simulated area

4.3. Simulation of landfill leachate migration under advection-diffusion

After the groundwater seepage field model is established based on the above-mentioned groundwater seepage field model, the pollutants of the garbage dump are added to the model by using the MT3DMS module in the GMS software.

4.3.1 Mathematical model of solute transport

The migration and diffusion of pollutants in leachate in groundwater are very complex processes, and the mathematical model of the three-dimensional advection-diffusion equation of solute transport is as follows, under no other chemical reactions:

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}(D_{xx}\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(D_{yy}\frac{\partial C}{\partial y})+\frac{\partial}{\partial z}(D_{zz}\frac{\partial C}{\partial z})-\frac{\partial(V_xC)}{\partial x}-\frac{\partial(V_yC)}{\partial y}-\frac{\partial(V_zC)}{\partial z}+f\ (R) \quad (1)$$

$$\begin{cases} C(x,y,z,0)=C_0(x,y,z) & (x,y,z)\in D \\ C(x,y,z,t)=\varphi(x,y,z,t) & (x,y,z)\in s_1,s_2 \\ D\cdot\nabla c=0 & (x,y,z)\in s_3,s_4 \end{cases}$$

. **(Eq.2)**

In the formula, C is the concentration of pollutants (ML^{-3}) in the groundwater

T for time work

Dxx, *Dyy*, and *Dzz* for hydrodynamic dispersion coefficient L^2T^{-1}

Vx, *Vy*, *Vz* for the seepage velocity (LT^{-1}) in the direction of x, y, z

f for source or sink, ML^3T^{-1}

R is the reaction term of microbial action.

C_0 for the initial concentration function of the study area

S_1 and S_2 are the boundaries of the given concentration on the eastern and western sides

S_3 and S_4 is the unit mass boundaries on both sides of the northern and southern sides.

4.3.2 Analysis of Pollution sources

According to the analysis of the hydrogeological conditions of the study area, the geographical location of the garbage dump, the stacking characteristics of the garbage before the closure, and the discharge characteristics of the leachate after treatment, because the garbage dump was a large amount of garbage piled up first, and then the garbage treatment began, the garbage dump was an informal landfill, which led to the lack of good protection technology in the early stage of the garbage dump. In 2017, the garbage dump began to be closed, and artificial seepage prevention was carried out in the landfill, using HDPE membrane to intercept seepage at the top of the landfill, vertical seepage prevention in the underground area and a large number of flood interception ditches to carry out rain and sewage diversion to reduce the production of a large amount of leachate. However, due to the early stacking conditions of the garbage dump, the underground in the site is impermeable for the bottom of the construction, and there is still the possibility of landfill leachate leakage. Therefore, by monitoring and analyzing the water samples around the landfill site, the main pollutants in the landfill leachate are COD, ammonia nitrogen, etc. Considering the complexity of the migration and diffusion process of leachate in groundwater, DO was used as the simulation factor to study the solute transport law of pollutants in leachate.

In the model, a new MT3DMS is used and the main parameters required for the model simulation are provided:

1) Pollutant concentration

According to the results of the DO concentration of water chemistry monitoring in the leachate in the garbage dump, to simplify the calculation process of the simulation, it was decided to set the DO concentration to 2mg/L, and generalize it to enter the aquifer in the form of a water injection well, the flow rate of the water injection well is 100m^3/d, and the DO concentration does not change with time.

Table 4. Dispersion of each aquifer

	Longitudinal dispersion (m)	TRPT	TRVT	DMCOEF(m^2/s)
Layer 1	40	1.0	0.08	0.0
Layer 2	20	1.0	0.08	0.0

Note: TRPT = Ratio of horizontal transverse dispersivity to longitudinal dispersivity; TRVT= Ratio of vertical transverse dispersivity to longitudinal dispersivity; DMCOEF =Effective Molecular diffusion coefficient.

2) Dispersion

The relevant dispersion degree is set according to the hydrogeological conditions of the site, and the specific data are shown in Table 4.

When the MT3DMS module in the GMS software was used to simulate the solute transport and diffusion process of pollutants within 10 years, four-time nodes were selected as the phased prediction results.

4.3.3 Result analysis and prediction

According to the results of seepage calculation, the migration and diffusion simulation of DO are carried out, and the migration results are shown in Figures 5-9.

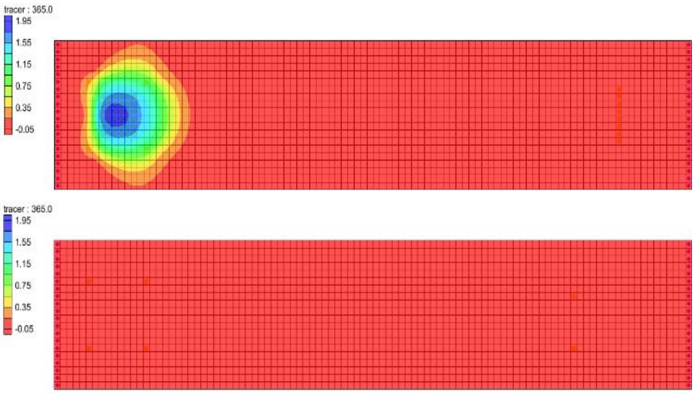

Figure 5. Simulation plan of DO migrating to each aquifer in the simulation area (365 days).

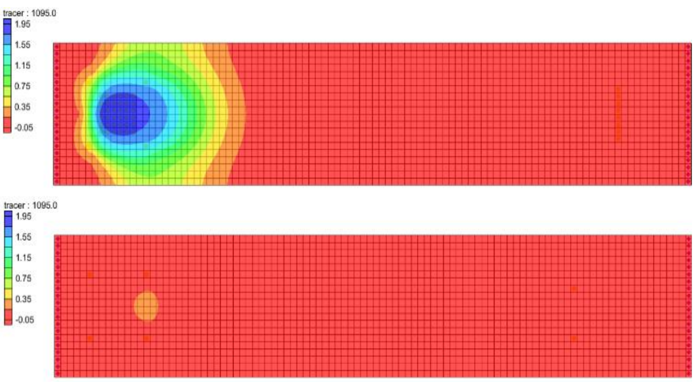

Figure 6. Simulation plan of DO migrating to each aquifer in the simulation area (1095 days).

From the plan and profile plots of the four periods of the migration simulation of DO, it can be seen that the concentration of pollutants is highest in the landfill area located in the direction of groundwater flow, and the longer the period is from the landfill, the lower the concentration of pollutants, and even the dispersion of pollutants does not occur in the middle and eastern parts of the simulation area.

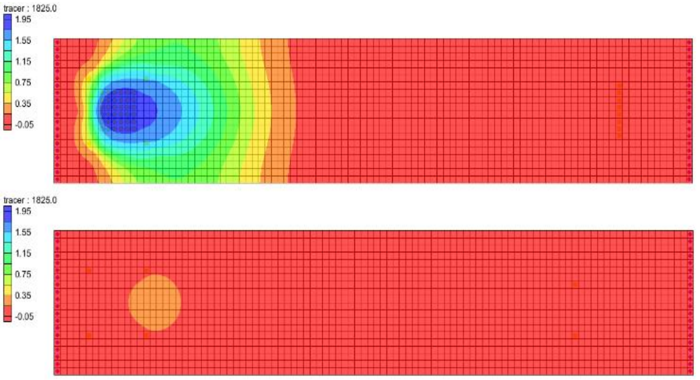

Figure 7. Simulation plan of DO migrating to each aquifer in the simulation area (1825 days)

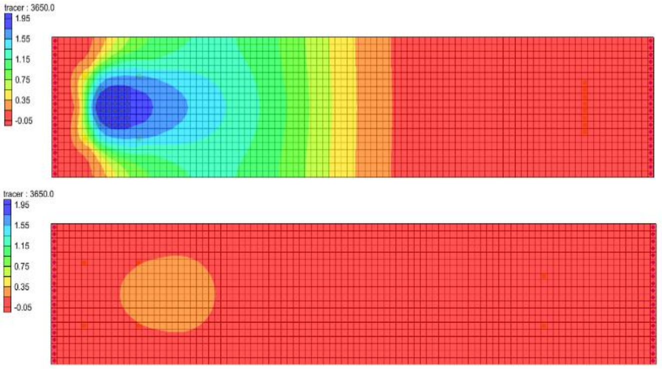

Figure 8. Simulation plan of DO migrating to each aquifer in the simulation area (3650 days).

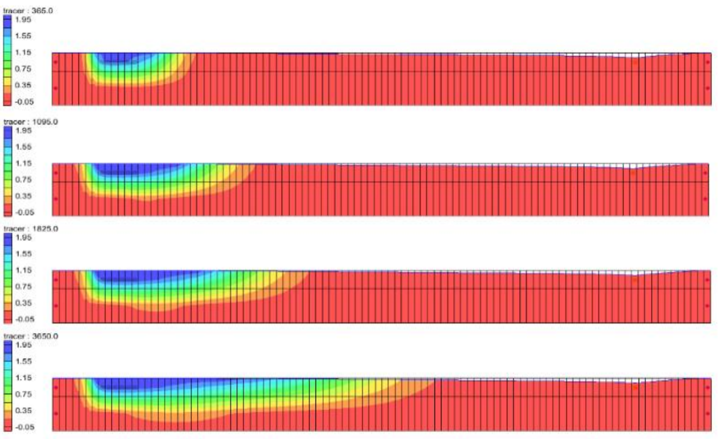

Figure 9. Simulation section of DO migration in four-time nodes

When the leachate leaks and diffuses through the clay layer to the confined aquifer, it will continue to migrate and diffuse along the groundwater flow direction, so the pollutants will gradually migrate and spread from west to east along the water flow direction to form a pollution plume. At the same time, upstream of the groundwater flow direction, due to the convective diffusion of the aquifer and the influence of the hydraulic slope, it will also migrate to a certain extent on the west side of the garbage dump, but the pollutants will mainly migrate and spread along the direction of the water flow to the east.

The prediction time nodes of this simulation are 365 days, 1095 days, 1825 days, and 3650 days, and it can be seen from the results that with time, the range of pollutants in groundwater diffusion gradually increases, and the range of pollution plume along the direction of water flow is quite different from that in the direction of water flow, and the pollution plume along the direction of water flow accounts for the main part. According to the prediction results, the pollution plume increased significantly after 1095 days, basically covering the entire range of the garbage dump, and began to have a certain impact on the quality of the living environment of the residents in the surrounding villages and towns. In the 1825 and 3650-day prediction plans, it can be seen that the diffusion trend of the pollution plume of DO in the first layer remains unchanged, but the diffusion rate slows down significantly, but from the prediction profiles of each period, the pollutants have been diffusing to the depths, and it can be seen from Figures 5-9 that it has spread to the second aquifer floor at 1825 days, and over time, the pollution range of the second layer floor surface has been expanding, but the pollutant concentration is also decreasing with the increase of the pollution distance.

4.4. Simulation of landfill leachate migration under microbial action

Due to the operation mechanism of the landfill and the special environment of the garbage treatment process, which is conducive to the growth and reproduction of microorganisms, this section considers the migration and diffusion law of pollutants in the leachate in the study area under the action of microorganisms.

4.4.1. Mathematical model of solute transport

The degradation of pollutants by microorganisms is carried out through the metabolism of microorganisms. While the microorganisms in the leachate are degrading the pollutants in the leachate, they are also migrating with the pollutants along with the groundwater flow, but the migration and diffusion process of microorganisms in the ground is much more complex than that of ordinary pollutants in the ground [24]. The mathematical model of the dispersion equation for solute transport considering microbial action is the same as Eq.2.

4.4.2 Contaminant simulation

In the groundwater seepage field model, a new SEAM3D module provide such packages as chemical reaction package and biodegradation package the main parameters required for the model simulation are given.

The diffusion of leachate in the area of the dump area is generalized as the water injection well, and the flow rate is set to 100 m^3/d, and the O_2 concentration is set to 3 mg/l, and the Fe (II.) concentration is set to 0.002 mg/l, and the other parameters are kept at the default value of 0.0 mg/l. In addition, the initial concentration of O_2 is 3 mg/l and the initial concentration of Fe (II.) is 0.002 mg/l.

4.4.3 Result analysis and prediction

According to the results of seepage calculation, the migration and diffusion simulation of microorganisms in groundwater is added, and the O_2 migration results are shown in Figures 10-14.

Figure 10. O_2 distribution plan of each aquifer under the action of microorganisms (365 days).

Since the seepage state of groundwater remains unchanged, and the aerobic degradation of pollutants is added to the original convective dispersion state, the law of pollutant transport is the same as that of section 3.3, but there are slight differences in the range and concentration of pollutants.

The temporal and spatial distribution of the content can also show the range and speed of pollutant transport. From the profile of the oxygen distribution over the four times, the oxygen decreases faster directly below the dump, and the oxygen content on the west side is lower than that on the east side, indicating that the oxygen content in the groundwater in the west side decreases due to aerobic degradation and the action of microorganisms.

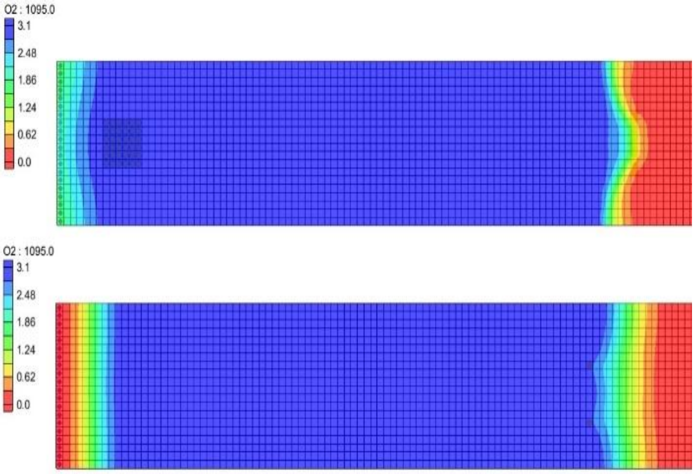

Figure 11. O_2 distribution plan of each aquifer under the action of microorganisms (1095 days).

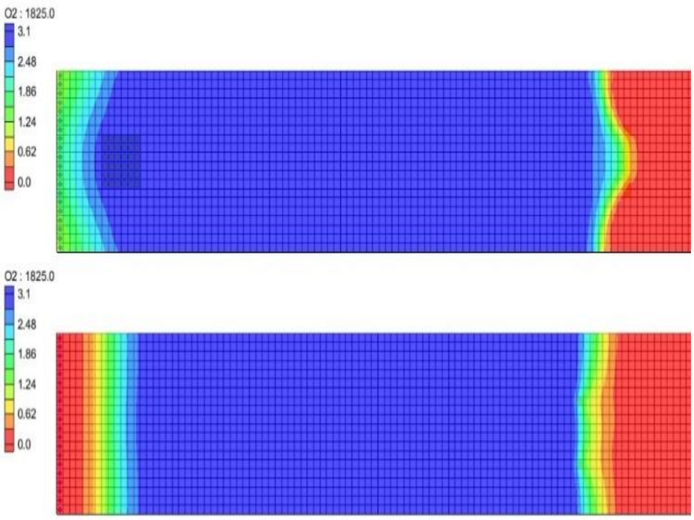

Figure 12. O_2 distribution plan of each aquifer under the action of microorganisms (1825 days).

The oxygen content in most areas of the study area still maintained the initial concentration, indicating that the pollutants did not diffuse to the east of the study area, and the pollutant content gradually decreased under the action of microorganisms.

5. Landfill leachate prevention and control simulation

5.1. Design of anti-seepage walls

The specific location of the anti-seepage wall is set around the garbage dump area and downstream of the garbage dump, running through the entire aquifer, and the entire area is closed

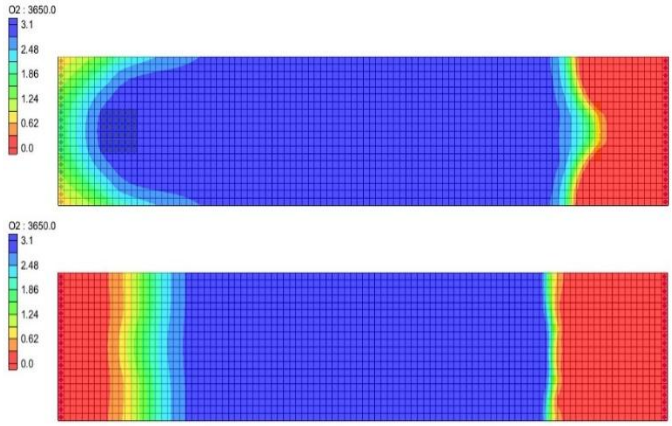

Figure 13. O_2 distribution plan of each aquifer under the action of microorganisms (3650 days).

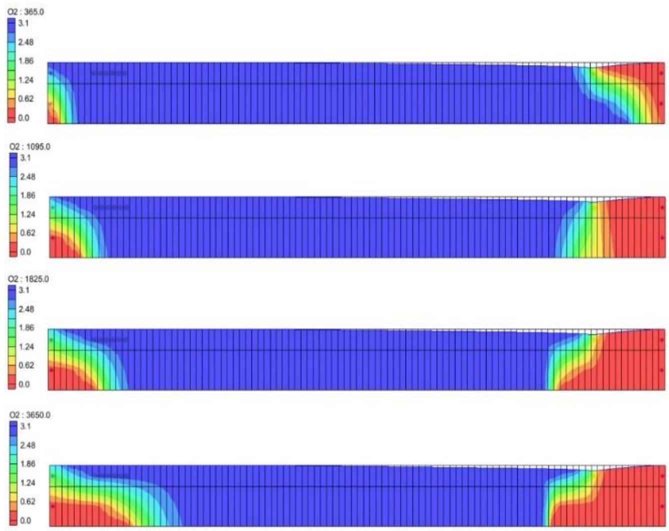

Figure 14. Profile of O_2 distribution in each aquifer under the action of microorganisms.

and vertically impermeable, and permeability coefficient of the anti-seepage wall is set to 8.64×10^{-7}m/d, as shown in Figure 15. After adding the impermeable wall to the simulation area, the head distribution of the groundwater seepage field is shown in Figure 16.

The simulation results are the scenario of 10 years, and after the implementation of the vertical anti-seepage wall scheme, the results are shown in Figures 17 and 18.

Based on the modeling findings presented earlier, the introduction of anti-seepage walls downstream of the two layers of the aquifer leads to an accelerated vertical speed of contaminant migration within a short time.

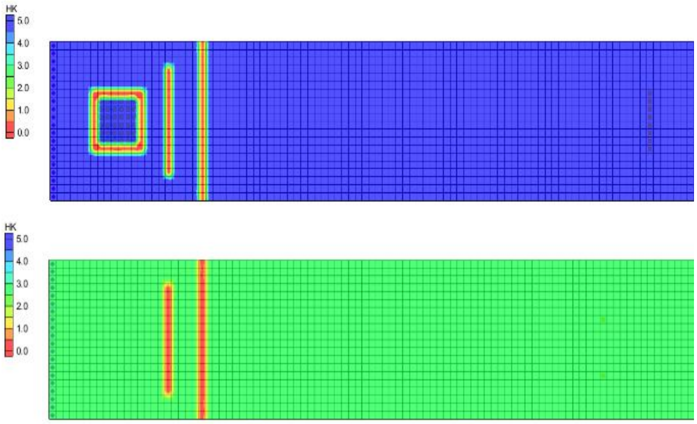

Figure 15. Design for positions of anti-seepage walls.

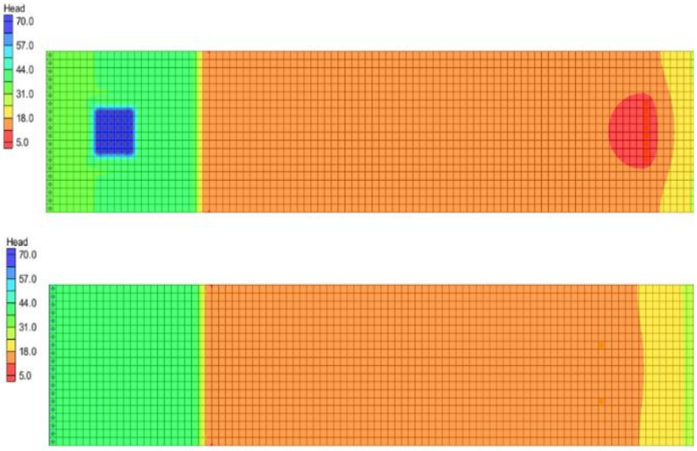

Figure 16. **Distribution** of water head of anti-seepage wall condition.

Additionally, the quantity of contaminants in the second layer experiences a rapid increase. The concentration of contaminants near the boundary of the waste dump is intensified due to the limited penetration of the anti-seepage wall [26]. The dispersion of the polluted plume was not seen to propagate in the downstream direction. The potential for contamination of groundwater in aquifers located downstream is significantly diminished. The findings indicate that the impact of obstacles on the escape and dispersal of pollutants is significant, resulting in a noticeable reduction in the dispersion of a variety of pollutants. This effect is particularly evident in the immediate proximity of the rubbish disposal

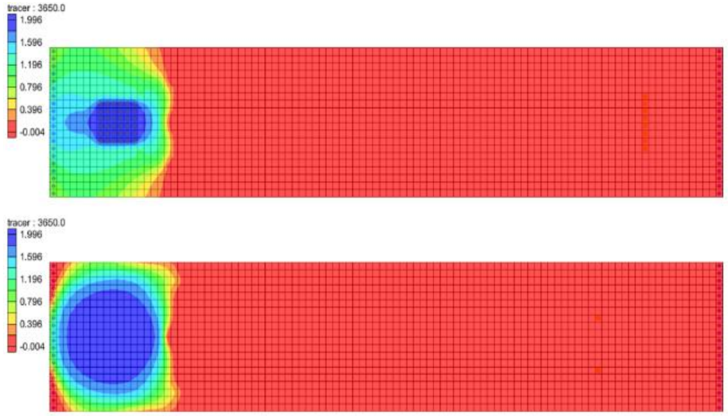

Figure 17. Horizontal map of DO migration in each aquifer under the anti-seepage wall (10years).

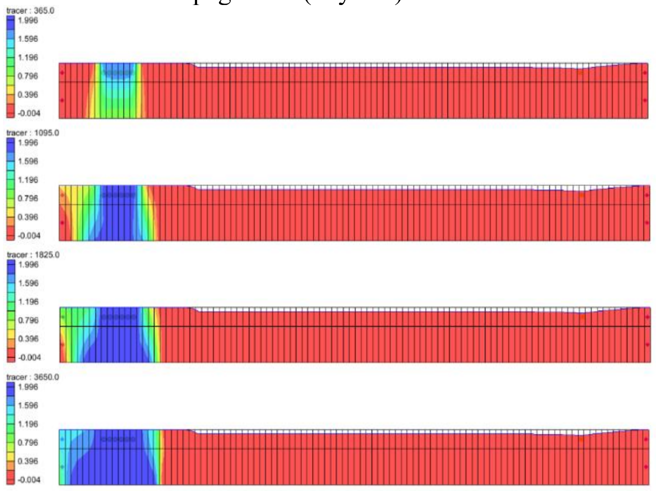

Figure 18: DO migration profile under anti-seepage wall.

5.2. Simulation under pumping and injection wells

The alteration of the hydraulic profile of groundwater through the extraction of contaminated groundwater via a pumping well can have an impact on the flow pattern of the groundwater. This process has the potential to decrease the concentration of pollutants present in the groundwater, as well as impede the movement of the pollution plume. This phenomenon has been documented in previous studies [27]. The implementation of pollution control can be achieved by the regulation of pumping time, rate, and flow rate, as demonstrated by the use of pumping wells [28]. The modeling process involves the placement of transportation and water intake wells at the four edges of the waste disposal facility and downstream of the landfill, respectively. The flow rate for the first layer is 3000 m^3/d, while the water injection well has a flow rate of 300 m^3/d. Additionally, the pumping rate for the second layer is 1500 m^3/d.

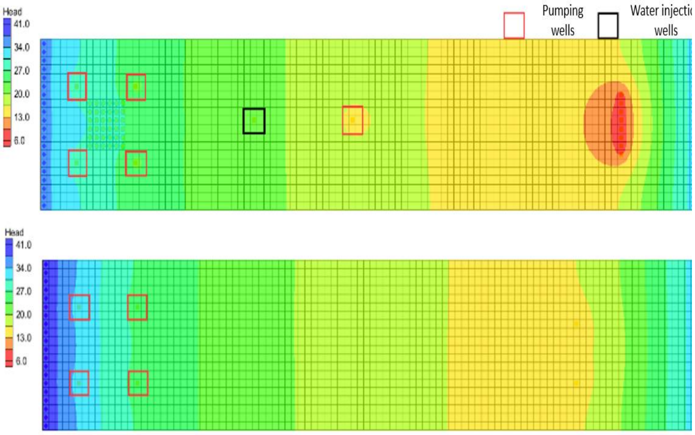

Figure 19. Water head distribution of each aquifer under pumping well condition

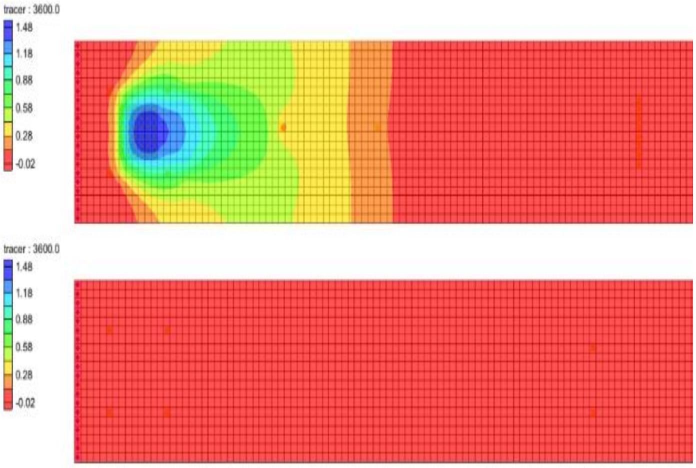

Figure 20. Horizontal map of migration to each aquifer under pumping well conditions (3650 days).

Figure 19 illustrates the geographic arrangement of the groundwater seepage field after the operation of pumping and injection wells.

The simulation results are 3650 days scenarios after the implementation of the pumping well program, and the results are shown in figure 20.

The extent of the pollution plume beyond the boundaries of the anti-seepage wall. The pumping well procedure facilitates the extraction of a significant quantity of pollutants, resulting in a notable reduction in the overall number of pollutants stored within the aquifer.

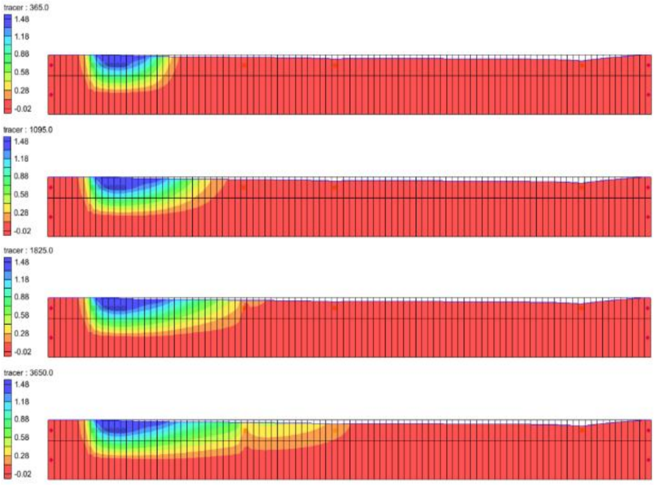

Figure 21. DO transport profile of aquifers under pumping well conditions.

By setting up pumping wells in the two aquifers, it can be seen that the implementation of the pumping well scheme has a good effect on reducing the concentration of pollutants according to the above simulation results. From the DO migration profile, it can be seen that the dispersion rate of the pollutants in the vertical direction is slower and does not spread to the bottom of the second aquifer after 3650 days. Compared with the vertical impermeable wall scheme, the pollutant concentration is greatly reduced [29], and the scope of the pollution plume far exceeds that of the impermeable wall. Under the work of the pumped well, a large number of pollutants is pumped out, which effectively reduces the cumulative concentration of pollutants in the aquifer.

5.3. Simulation on anti-seepage walls and pumping wells together

Based on the simulation outcomes of models, it has been shown that the utilization of anti-seepage measures and pumping wells in isolation has both benefits and drawbacks.

Consequently, a hybrid approach is proposed, integrating both strategies, in order to effectively manage the migration of pollutants towards the groundwater. The impermeable perimeter and the fruit body of the pumping well are strategically positioned around the waste disposal region and downstream to effectively prevent seepage. Simultaneously, a seepage prevention system is implemented across the whole water layer of the containment box, ensuring comprehensive sealing and preventing any genuine seepage. The permeability factor of the anti-seepage wall is determined to be 8.64×10-7m/d. The pumping flow rate for the first layer is 3000 m/d, while the water injection pumping flow rate is also 300 m^3/d. Additionally, the rate of pumps for the second layer is 1500 m^3/d, as illustrated in figure 22. Figure 23 illustrates the head distribution of the groundwater seepage field subsequent to the implementation of a cutoff wall and pumping well inside the simulated zone.

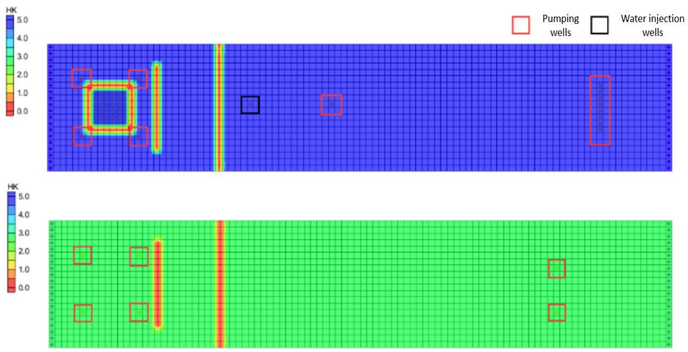

Figure 22. Map of the location of anti-seepage walls and pumped wells

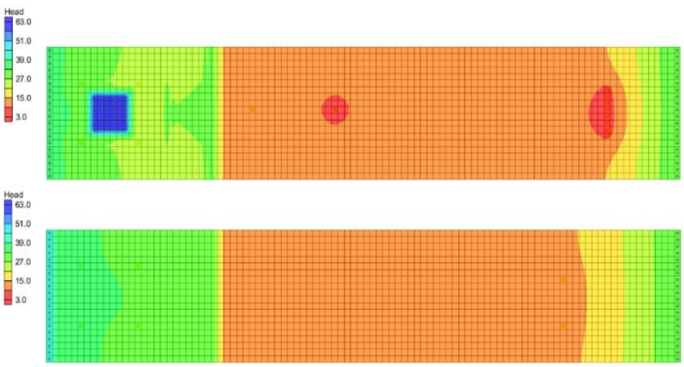

Figure 23. Head distribution of water level about two aquifers under the condition of anti-seepage wall and pumping and injection well

4.3.1. Horizontal and profile characteristics

The simulation results are 3650 days after the implementation of the vertical anti-seepage wall and the pumping and injection well program, and the results are shown in Figures 24 and 25.

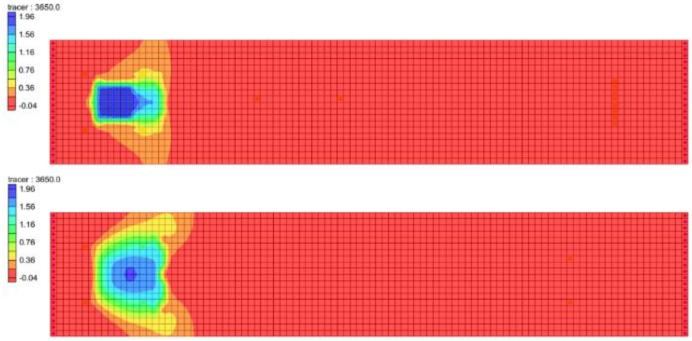

Figure 24. Horizontal map of DO migration in each layer under the anti-seepage wall and pumping well (3650 days)

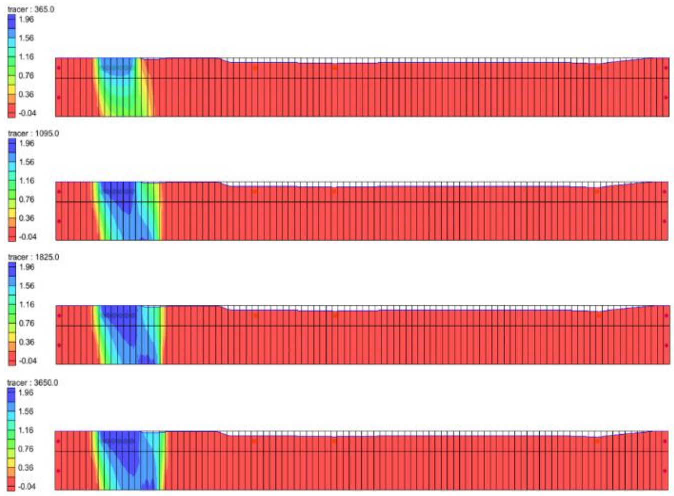

Figure 25. Profile of migrating to anti-seepage walls and pumping wells at different time

After setting anti-seepage wall and pumping well, according to the simulation results, the diffusion range of pollutants is reduced. It is basically controlled near the garbage dump, and the concentration of pollutants is also reduced under the work of pumping wells, which combines the advantages of two kinds of separate work, and has a more comprehensive prevention and control effect on leachate polluted goaf groundwater.

6. Conclusion

The Datong landfill in Huainan City was chosen as the research object. the water samples of the landfill leachate of each internal monitoring well and the collapsed pond on the eastern side were analyzed, and the GMS software was used to simulate and predict the diffusion of pollutants from landfill leachate in the aquifers of goaf under four different conditions and the prevention and control scheme of landfill leachate, and the conclusions were drawn as follows:

(1). Due to the early garbage dumping conditions of Huainan Datong Landfill, there is still a situation in the leachate of the garbage dump that pollutes the groundwater in the lower goaf after the closure of the site.

(2). By constructing the hydrogeological conceptual model of the garbage dump, the head distribution in the underground seepage field in the study area was simulated by using the MODFLOW module of the GMS software, and the simulation results were consistent with the actual water flow state, which was from west to east.

(3). Using the MT3DMS, RT3D, and SEAM3D modules of GMS software, the solute migration law in the leachate under different conditions (convective diffusion, aerobic degradation, microbial action) was discussed: the concentration of pollutants in the landfill leachate injection area was the highest, and the high concentration area also expanded with the increase of time. With the increase of distance and time, the range of pollution plumes gradually expands, and the diffusion rate of pollution plumes slows down when the period is large (10 years), and the range tends to a stable value. The plume is mainly dispersed in the direction of groundwater flow (from west to east), but also to the sides and against the current. Groundwater in the aquifers of Goaf still is facing leachate contamination after the landfill closure.

(4). Based on the law of pollutant migration under different conditions,–the anti-seepage wall and the pumping well are chosen, and the GMS software was used to simulate to predict the diffusion of the pollution plume after the implementation of the control plan. When the pumping well scheme was implemented, the pollutant concentration was significantly reduced, and the effect of the diffusion range of the pollution plume was average. Under the merger and implementation of the two schemes, the diffusion range and concentration of pollutants have a good control effect.

Authors Contribution

Xu Guangquan devised the project, the main conceptual ideas and proof outline. Ayesha Selhaba worked out almost all of the technical details, and performed the numerical calculations for the suggested experiment, wrote the manuscript. Bao Hui helped in sampling from study area and verified the numerical results. Amna Iqbal helped in editing and formatting of manuscript.

Conflicts of Interest

There are no conflicts of interest reported by the writers.

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Data Availability statement

The data presented in this study are available on request from the corresponding author.

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