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SIMULATION OF THE MIGRATION PATH OF THE MAXIMUM POLLUTANTS' CONCENTRATION. CASE STUDY OF THE TAILING POND, SOUTHWEST CHINA

Following China's economic development, lots of tailing deposits have become potential pollution sources, and their leaching would release the trace elements into the natural environment. The leakage rate model and the solute transport models of groundwater are coupled to investigate the effects of the tailing ponds on groundwater. It indicates that the anti-seepage layer is a necessary and important component of the tailing ponds, which could protect the soil or groundwater to be polluted by wastewater. Under three scenarios (scenario A – ideal conditions, scenario B – the worst conditions, and scenario C), the proportions of maximum concentration to source concentration are 1.2, 94.6, and 19.1%, respectively. Under the worst states of anti-seepage layers, the pollution areas after 730, 1800, 3807 and 7300 days were 130 500, 313 200, 523 800, and 729 000 m^2, respectively. Compared with Scenario B, the pollution areas of Scenario C after 1800, 3807, and 7300 days were cut by 52.97, 74.55, and 81.73, respectively. Given important anti-seepage layers, the tracking monitor system is necessary and important to discover whether the groundwater was contaminated in time.

1. INTRODUCTION

Lead and zinc as the common nonferrous metals have been widely used in the electrical, metallurgical, pharmaceutical, and mechanical industries. China is one of the world's largest lead and zinc mining countries, which produced 2.40 million tons of lead concentrate and 5.10 million tons of zinc concentrate in 2017 [1]. Meanwhile, lots of tailings that would release toxic elements are potential soil or groundwater pollution sources [2]. The mine water from the lead-zinc mine is usually acidic, and the dissolved metals would contaminate soil and water by the seepage or run-off [3].

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The investigations indicated the potential environmental risks in the soil, rivers, and plants around the mining areas [4, 5]. The groundwater nearby the mines would not meet the drinking water criteria established by the World Health Organization, e.g., leakage from the Bayan Obo tailing pond in northwest China probably caused the elevated concentration of NO_2^-, B, Mn, NH_4^+, F, and SO_4^{2-} in groundwater [6]. The microorganisms and enzymes in soils of lead-zinc tailing ponds are significantly negatively correlated with concentrations of heavy metals, which indicates that the soil could be polluted by tailing ponds [7]. The effects of heavy metals from tailing ponds on soil or groundwater are codetermined by pH, vegetation coverage, and soil types [8].

Thus, it is significant to investigate the effects of the tailing ponds on soil or groundwater. As a lack of routine monitoring and few complete hydro-geochemical data, it is difficult to accurately assess the influence of the tailing ponds on groundwater. The research usually focused on the behavior and fate of leachate released from the unlined tailing ponds or tailing ponds with artificial impermeable layers, the impacts of leachate on the groundwater have rarely been well reported.

Normally, the anti-seepage measure of the tailing ponds could prevent the leachate to infiltrate the soil or groundwater. The anti-seepage material of the tailing pond from bottom to top is usually as follows clay (20 cm), geotextiles (600 g/m^2), HDPE (2 mm), and geotextiles (600 g/m^2), and its vertical permeability coefficient would be not higher than 8.64×10^{-5} m/d [9]. In theory, the infiltration condition of these tailing ponds is poor, the leachate could be prevented to seep into the soil or groundwater system. The anti-seepage material of HDPE usually exists some flaws during the installation and construction procedures, its performance of seepage could not reach the effect of theory. These defective anti-seepage materials would form the preferential and primary pathway of leachate [10, 11], which could significantly impact the groundwater quality [12]. The research indicated the hydraulic conductivity and thickness of the compacted clay liner, leachate depth on the HDPE, hole density in the HDPE, and the contact conditions between HDPE and the compacted clay liner would codetermine the leakage rate of leachate [13, 14].

The accurate leakage rate of leachate is the precondition to assessing the influence of the tailing ponds on groundwater or soil. Predicting the pollutants diffusion and understanding its laws play an important role in effectively protecting the groundwater and soil resources. The leakage rate model and the solute models of groundwater were coupled together to influence the tailing ponds on groundwater in different scenarios. The remainder of the article is organized as follows: In Section 2, the geomorphology, conceptual model of hydrogeology, and three scenarios were described; in Section 3, the steady flow model and solute transport models and their parameters were shown. Then, the maximum concentration and pollution areas, and the path of maximum concentration were discussed in Section 4. Lastly, some conclusions were drawn.

2. STUDY AREA

2.1. GEOMORPHOLOGY

The study area is located in the northern valley in the middle of the Lhasa River. There are the high mountains, river valley plain, and pluvial fan. The elevation of the tailing pond ranges from 3887 to 4305 m. The mountain slope is commonly the straight lines, with a terrain slope of 35°. The surfaces of High Mountain are mainly the talus material and residual deposit, with thickness between 1 and 6 m. The river valley plain which is formed by the bed and first terrace of the Lhasa River locates at the southern of the tailing pond. The river valley plain is flat land and dips to the southeastern.

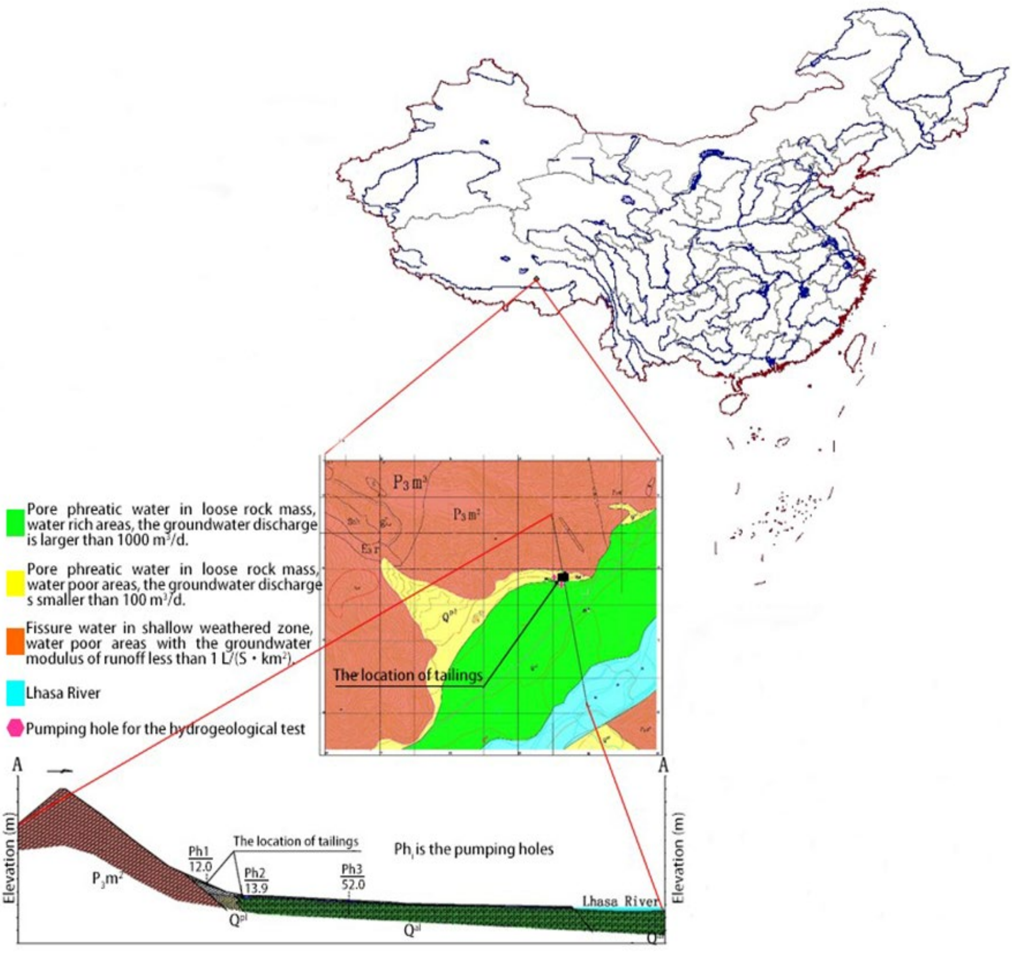

Fig. 1. Hydrogeological map at the location of tailings

The first terrace of the Lhasa River is the agricultural land, while its bed is piled with pebbles and boulders. The pluvial fan locates in a narrow and long belt between the High Mountain and the Lhasa River. The diffuser angle of the pluvial fan ranges from 60° to 90°, with the axial length between 670 and 2400 m. The pluvial fans contact the first terrace of the Lhasa River with gentle slopes. The components of the pluvial fan are mainly the rubble and gravel soil, with a depth between 5 and 10 m. The strata from old to young are the upper Permian series of the Neogene system (P_3), Eocene series of the Eogene system (E), and Quaternary system (Q) (Fig. 1). The upper Permian series of the Neogene system includes two groups (P_3m^2 and P_3m^3). P_3m^2 is the 2nd Mong La group, which is affiliated with the upper Permian series of the Neogene system. Its upper part is made up of middle-thin-bedded fine feldspathic sandstone, while the bottom part is made up of a brown blanket. The local area is the thin argillaceous siltstone with alternating layers of sericite phyllite. Its thickness is larger than 858 m. P_3m^3 is the 3rd Mong La group, which is also affiliated with the upper Permian series of the Neogene system. Its bottom part is made up of middle-thin-bedded feldspathic quartz sandstone, sandwiching a layer of gravel-bearing slate and gravel-bearing sandstone. Its thickness is larger than 1682 m.

E_3r is the Ri Gong La group, which is affiliated with the Eocene series of the Eogene system. It consists of a coarse-fine conglomerate and gravel-bearing debris sandstone. The conglomerate is mainly sandstone and quartzite, with its size between 3 and 5 cm. Its thickness is between 299 and 398 m.

The Quaternary system includes the quaternary alluvium and diluvia. Q^{al} is alluvial sediment of the quaternary system, which is mainly distributed on both sides of the Lhasa River. The top of Q^{al} is light yellow sandy silt and gravel-bearing silt clay, which is rich in plant roots. And its bottom consists of pebbles filled with sand or gravel, of the size between 5 and 30 cm. The thickness ranges from 0.3 to 1.5 m. Q^{pl} is diluvial sediment of the quaternary system, which is mainly distributed at the Mizuguchi of branch gully. It mainly consists of rubble, breccia, and silty sand, and the local area covered with gravel-bearing debris silty sand. The main constituents of the rubble are andesite, andesite tuff, sandstone, and mudstone. Its thickness ranged from 1 to 20 m.

2.2. CONCEPTUAL MODEL OF HYDROGEOLOGY

The tailing pond is located at the end of the first terrace of the Lhasa Rivers, the foothills of the high mountains. The ridge to the north of the tailings pond is an impermeable boundary that the groundwater could not flow past. Thus, the ridge would have seemed as the impermeable boundary. On the northeastern, the Zhi Kong reservoir which connects with the Lhasa River is the source of surface water. The Lhasa River is located on the southeast side of the tailing ponds, and across the study area from northeast to southwest. As the water level of the Lhasa River changed little, thus, it would have seemed to the constant head boundary. Similarly, there is a gulley on the southwestern of the tailing pond. The gulley goes through the study area from northwest to southeast. The gulley has water flowing all the year-round, so it also is seemed to a constant head boundary. The ridge on the north, the Lhasa River on the east, and the gulley on the southwestern formed a complete hydrogeological system.

2.3. SCENARIOS

Scenario A. Scenario A is the normal situation that which the tailing pond is anti-seepage treatment by the technical specifications. The anti-seepage of the tailing pond from bottom to top is clay (20 cm), geotextiles (600 g/m^2), HDPE (2 mm), and geotextiles (600 g/m^2). Under ideal conditions, the vertical permeability coefficient of the tailing pond is not higher than 8.64×10^{-5} m/d.

Scenario B. Many factors such as the hydraulic conductivity and thickness of the compacted clay liner, the water depth on the HDPE, the contact condition between the HDEP and the compacted clay liner, and the hole density in HDPE would significantly influence the leakage rate [12, 15]. Although the anti-seepage layer of the tailing pond is usually constructed by the technical specification, the seepage prevention effect would not be so good. Giroud and Bonaparte [12, 16] proposed an empirical model to estimate the leakage rate of the tailing pond

$$q = 10^{-4}\beta_C\left(1+0.1\left(\frac{h_w}{L_s}\right)^{0.95}\right)\alpha^{0.1}h_w^{0.9}k_s^{0.74}N \tag{1}$$

where, q is the leakage rate of landfill leachate (m/d), α is the area of the defects in the HDPE (m^2), K_s and L_s are the hydraulic conductivity (m/s) and thickness (m) of the compacted clay liner, respectively, h_w is the leachate depth on the HDPE (m), N is the hole density in the HDPE (holes/ha), β_c is the coefficient which is determined by the contact between HDPE and the compacted clay liner.

The parameters of β_c and N significantly affect the leakage rate. For the good and poor contact between HDPE and the compacted clay liner, the β_c is 0.21 and 1.15, respectively [15]. The hole density of HDPE is usually between 2.5 holes/ha and 40 holes/ha [2]. The leakage rate in the worst cases would be 87.6 times more than that in the best cases. The vertical permeability coefficients of the tailing pond in the best and the worst cases are 8.64×10^{-5} m/d, and 7.57×10^{-3} m/d, respectively. The tailing pond is in the worst cases all the time.

Scenario C. The tailing pond is used for one year under Scenario B, the concentration of pollutants in groundwater exceeds that of the background level. According to the technical specification, the remedial measure is adopted to repair the anti-seepage of the tailing pond. Thus, the vertical permeability coefficient is 7.57×10^{-3} m/d in first two years. Two years later, the vertical permeability coefficient is 8.64×10^{-5} m/d.

3. METHODS AND PARAMETERS

3.1. SIMULATION MODEL OF THE STEADY FLOW

The tailings pond is assumed as a steady-state seepage field, and the inflow of each unit equals its outflow. Thus, the steady flow models in a two-dimension plane are employed to manage the groundwater movement [16]:

$$\begin{cases} k_x \dfrac{\partial}{\partial x}\left(\dfrac{\partial h}{\partial x}\right) + k_y \dfrac{\partial}{\partial y}\left(\dfrac{\partial h}{\partial y}\right) = S\dfrac{dh}{\partial t} + w \quad (x, y) \in \varOmega,\ t \ge 0 \\ h(x, y, t)_{|\varGamma_1} = h_0(x, y, t) \quad (x, y) \in \varGamma_1,\ t \ge 0 \\ h(x, y, t)_{|\varGamma_2} = 0 \quad (x, y) \in \varGamma_2,\ t \ge 0 \end{cases} \tag{2}$$

where k_x and k_y are the permeability coefficients (m/d), w is the groundwater recharge (m/d), $\varOmega$ is the study area, S is water storage efficiency, $\varGamma_1$ is the constant head boundary, $h_0(x, y, t)$ is the water head at the point x, y. $\varGamma_2$ is the impermeable boundary. The successive over-relaxation method was employed to solve equation (2) [17].

3.2. SOLUTE TRANSPORT MODEL

The two-dimensional flow and diffusion model are employed to govern the solutes transported in the phreatic aquifer. The groundwater flow is the vector that would be decomposed in x and y directions. The two-dimensional flow model would simulate the solutes transporting which is determined by the groundwater flow. While the two-dimensional diffusion model would simulate the Fickian diffusive process which is determined by the concentration differences of solutes [18]. The control equation is:

$$\theta\frac{\partial C}{\partial t} = \theta\left(D_x\frac{\partial^2 C}{\partial x^2} + D_y\frac{\partial^2 C}{\partial y^2}\right) - \mu_x\frac{\partial C}{\partial x} - \mu_y\frac{\partial C}{\partial y} \tag{3}$$

where C is the concentration of pollutants in groundwater (mg/dm^3), θ is the porosity of groundwater storing medium which is dimensionless, D_x and D_y are principal terms of dispersion coefficient (m^2/d), μ_x and μ_y are velocity components in x and y directions (m/d).

3.3. INPUT PARAMETERS

Horizontal permeability. The horizontal permeability coefficient of the study area was obtained by the site pumping experiment. The depth, radius, and initial water level of the pumping well are 4.5, 0.15, and 2.5 m, respectively. After pumping for 45 min, the groundwater level is stable. Meanwhile, the groundwater level and the quantity of pumping water are 3.82 m and 21.36 m^3/d, respectively. According to the experimental relationship [19], the horizontal permeability would be calculated by the following equations,

$$\begin{cases} K = \dfrac{0.366(\lg R - \lg r)}{HS} \\ R = 2S\sqrt{HK} \end{cases} \tag{4}$$

where K is the horizontal permeability (m/d), Q is the quantity of pumping water under stable conditions (m^3/d), R and r are reference radius and pumping well radius (m), S is the decreased depth of groundwater table under stable conditions, which equals the stable groundwater table minus initial groundwater table (m), H is the depth of exposed aquifer which equals to the depth of pumping well minus initial groundwater table (m).

Vertical permeability, *Scenario A*. The tailing pond would be anti-seepage treatment by the technical specifications, and the vertical permeability is not higher than 8.64×10^{-5} m/d. Thus, the vertical permeability coefficient of the tailing pond is 8.64×10^{-5} m/d.

Scenario B. The anti-seepage of the tailing pond is constructed according to the technical specification, but its seepage prevention effect would not be so good. According to the empirical model proposed by Giroud and Bonaparte [13], the vertical permeability is 7.57×10^{-3} m/d.

Scenario C. The tailing pond is used for one year under Scenario B and the concentration of pollutants in groundwater exceeds that of the background level. Then, the anti-seepage layer of the tailing pond is improved according to the technical specification. Thus, the vertical permeability coefficient is 7.57×10^{-3} m/d in the first two years. Two years later, the vertical permeability coefficient is 8.64×10^{-5} m/d.

Pollutants concentration. The water leaching of the tailing is introduced to confirm the pollutants of the tailing pond. The experimental results are shown in Table 1. The indexes of Cr^{6+}, As, CN, and F are not detected. The concentrations of Cu, Ni, and Be are lower than those of groundwater quality standards. The concentrations of Pb, Zn, Cd, and Hg are 0.076, 3.2, 0.1, and 0.013 mg/dm^3, respectively, and all are higher than those of the groundwater quality standards. Especially, the concentrations of Cd and Hg are over 20 and 13 times higher than the corresponding limit concentrations given in the groundwater quality standards.

Table 1

Concentration of pollutants (*C*) in the tailing pond [mg/dm^3]

Index	Cu	Pb	Zn	Ni	Be	Cr	Cr^{6+}	As	Cd	CN	Hg	F
C	0.035	0.076	3.2	0.015	0.032	0.002	ND	ND	0.1	ND	0.013	ND
Standard	1.0	0.01	1.0	0.02	0.70	ND	0.05	0.01	0.005	0.05	0.001	1.0
EQ	0.035	7.6	3.2	0.75	0.046	–	–	–	20	–	13	–

ND is not detected. *EQ* (equivalent pollution load) is the ratio of pollutants concentration (*C*) to corresponding standards of groundwater.

4. RESULTS AND DISCUSSION

4.1. CONTAMINANT SOLUTE TRANSPORT

The maximum concentrations of Cd under different scenarios are shown in Fig. 2. The maximum concentration of Cd under the Scenario A has a similar trend with that under Scenario B. In the beginning 500 days, the maximum concentration of Cd exponentially increased. Then, the maximum concentration of Cd was at equilibrium during the period 500 days and 1800 days. The equilibrium concentration of Cd under Scenarios A and B were 0.00026 and 0.02 mg/dm^3, respectively. 1800 days later, the maximum concentration of Cd increased linearly. At the 7300 days, the maximum concentration of Cd under Scenario A and B were respectively 0.0012 and 0.095 mg/dm^3.

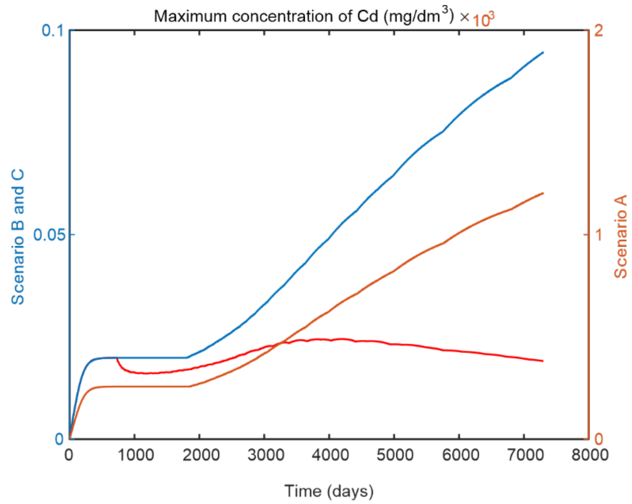

Fig. 2. Maximum concentration of Cd under different scenarios

The maximum concentration of Cd under Scenario C was the same as that under Scenario B at the beginning 730 days. Then, the maximum concentration of Cd decreased from 0.02 mg/dm^3 (on 730 days) to 0.016 mg/dm^3 (on 1286 days) as the vertical permeability coefficient of the anti-seepage layer returned to the ideal state. Then, the maximum concentration of Cd slowly reached the peak value (0.024 mg/dm^3) on 3807 days and declined all the time. On 7300 days, the maximum concentration of Cd is 0.019 mg/dm^3.

The order of magnitude of the maximum concentration under Scenario B and Scenario C is the same. The trend of maximum concentration of Cd under Scenario A is similar to that under Scenario B. According to the Darcy law, the infiltration of pollutants is linear with the vertical permeability coefficient [17]. Generally, the groundwater flow field determines the spreading direction of pollutants, while the groundwater velocity determines the speed of diffusion [20, 21]. Thus, the difference in vertical permeability coefficient leads to a different order of magnitude between scenarios, while the groundwater flow field determines a similar trend between Scenario A and Scenario B. Excluding the vertical permeability coefficients, other parameters are the same for the three hypothetical scenarios. Thus, the maximum concentration of Cd in different scenarios is determined by the vertical permeability coefficients.

According to the maximum concentration of Cd under different scenarios, the anti-seepage of the tailing pond under ideal conditions (Scenario A) could effectively prevent wastewater infiltrate into soil or groundwater. Its proportion of maximum concentration to source concentration is 1.2%, while it is up to 94.6% under worst conditions (Scenario B). Repairing the damaged anti-seepage of the tailing pond (Scenario C), the proportion of maximum concentration to source concentration is 19.1%. Meanwhile, the research indicated that the retention efficiencies of the 0.2 m engineered barrier against the heavy metal contaminant for 15 and 30 years would be respectively 45.4% and 57.2%. Moreover, it would be exceeded 87% if the engineered barrier thickness increased to 0.5 m [16]. Thus, the anti-seepage layer is a necessary and important component of the tailing ponds, which could protect the soil or groundwater to be polluted by wastewater.

4.2. THE MAXIMUM CONCENTRATION AND POLLUTION AREAS

The maximum concentration of Cd and pollution areas upon a time are shown in Table 2. The tailing pond under Scenario A could not cause the groundwater quality to exceed the third group of groundwater quality standards. The maximum concentration of Cd on 730, 1800, 3807 days, 7300 days are 0.0003, 0.0003, 0.0006, and 0.0012 mg/dm^3, respectively. Under Scenario B, the corresponding values are 0.0199, 0.0199, 0.0463, and 0.0946 mg/dm^3. The areas in which the concentration of Cd exceeds the third group of groundwater quality standards are 130 500, 313 200, 523 800, and 729 000 m^2, respectively. For scenario C, the maximum concentrations of Cd on 730, 1800, 3807 and 7300 days are 0.0199, 0.0170, 0.0244, and 0.0191 mg/dm^3, respectively. The areas in which the concentration of Cd exceeds the third group of groundwater quality standards are 130 500 m^2, 131 400 m^2, 123 300 m^2, and 133 200 m^2.

According to the simulation results, the ideal states of the anti-seepage layer would effectively prevent the wastewater in the tailing pond to be infiltrated into the soil or groundwater system. Under the worst states of anti-seepage layers, the pollution areas increased all the time. Compared with Scenario B, the pollution areas of Scenario C on 1800, 3807, and 7300 days were respectively cut by 52.97%, 74.55%, and 81.73%. Because of the importance of anti-seepage layers, the tracking monitor system is necessary and important to discover whether the groundwater was contaminated in time.

Table 2

The pollution areas and maximum concentration of Cd

Scenario	Maximum concentration [mg/dm^3]				Pollution area [m^2]			
	Number of days							
	730	1800	3807	7300	730	1800	3807	7300
A	0.0003	0.0003	0.0006	0.0012	0	0	0	0
B	0.0199	0.0199	0.0463	0.0946	130 500	313 200	523 800	729 000
C	0.0199	0.0170	0.0244	0.0191	130 500	131 400	123 300	133 200

Scenario A is the ideal state of an anti-seepage layer of the tailing pond, and the performance of its anti-seepage materials could match that of 1.5 m thick clay bed (permeability coefficient is no higher than 8.64×10^{-5} m/d). It indicates that the leachate could be effectively prevented from entering the groundwater under the ideal state [22]. The high cost of the horizontal anti-seepage has limited the spread of the anti-seepage type, the enterprises reluctantly agree to lay geomembrane anti-seepage lining to pass environmental protection acceptance to maintain production [9]. Thus, ideal states of Scenario A what the regulations required would be almost non-existent in reality.

Scenario B is the worst case with the anti-seepage material and its permeability coefficient is 87.6 times higher than that in Scenario A. The anti-seepage layer is often arranged at the bottom of the tailing pond, thus it is difficult to discover the flaws and holes, e.g., some tailing ponds carried out the anti-seepage treatment according to the regulations required, but the groundwater nearby the tailing pond also showed varying degrees of pollution [23, 24]. Although the anti-seepage layer of the tailing pond could prevent most pollutants seep into groundwater, the groundwater nearby the tailing pond would be seriously polluted by the driving force of convection-dispersion [25, 26]. More specifically, the Pleistocene Holocene muddy clays which show strong anti-seepage capacity in the laboratory would not completely prevent pollutants seep into groundwater, e.g., the Bayan Obo tailing pond in northwest China owns a thick impermeable unit of Pleistocene Holocene muddy clays as the anti-seepage material, but its leakage had caused serious groundwater pollution [6]. Generally, the permeability coefficient of the anti-seepage layer is between that of Scenario A and Scenario B.

Scenario C is a common scenario that which remedial measures of anti-seepage were immediately taken when the pollutants' concentration of groundwater increased.

For the high-risk tailings pond, the resistivity, the very low-frequency electromagnetic method, and radiometric measurement are often introduced to investigate the delineation of subsurface structures, which would reflect its hydrogeological characteristic. These geophysical measurements which would not destroy the structure of the tailing pond were never mentioned by the environmental regulations, in China. The tracking monitor system is the common supervision method, which the groundwater pollution could be found in time. As the high economic cost and time cost, it is difficult to take effective anti-seepage control of the tailing pond. The tracking monitor system of the tailing pond is often a form of groundwater protection. Thus, geophysical measurements become very important to protect against groundwater pollution.

4.3. THE PATH OF MAXIMUM CONCENTRATION

By contaminant solute transporting, the path and characteristics of maximum pollutants concentrations under Scenarios A, B, and C are similar, which is shown in Fig. 3.

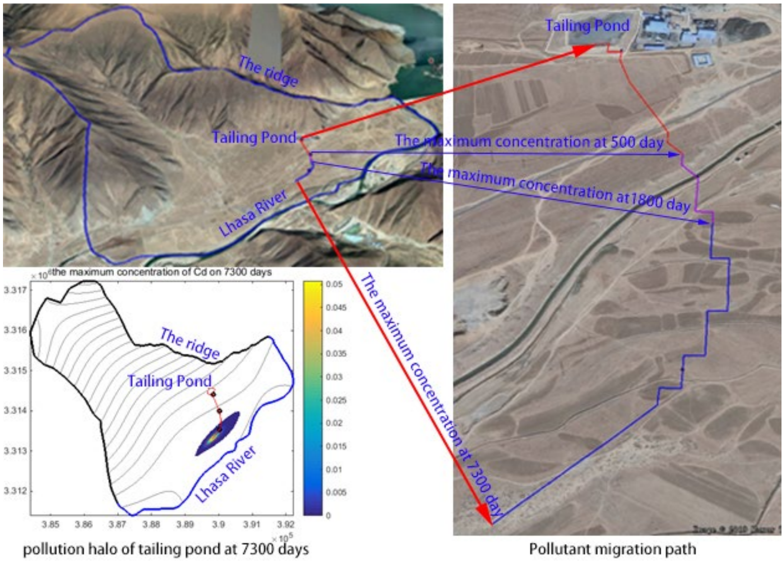

Fig. 3. Migration path of maximum concentration of Cd

The path of maximum pollutants concentration is perpendicular to the groundwater contour. Generally, the pollutants almost migrate to the Lhasa River along the low-lying gulley. Before 500 days, the pollutants are mainly concentrated on the first terrace of the Lhasa River, as the hydraulic gradient is small. The pollutants leaking into groundwater would diffuse through the first terrace of the Lhasa River. The small hydraulic gradient and short distances caused the maximum concentration of pollutants to increase exponentially. Then, from 500 days to 1800 days, the pollutants diffuse through the areas between the first terrace of the Lhasa River and its flood land. The terrain is relatively steep, which would be conducive to the spread of pollutants. Thus, the maximum concentration of Cd was closed to balance. 1800 days later, the pollutants migrated to the flat flood land. The small hydraulic gradient is not conducive to the spread of pollutants. Thus, the maximum concentration of Cd increased in a straight line.

Both the low permeability and small hydraulic gradient are not conducive to the spread of pollutants. The low permeability barriers would change the local hydraulic gradient, which would make the pollutants concentrated inside the low permeability barriers [27]. The interior and exterior extraction wells would help maximize containment inside the barrier and capture leakage outside the barrier. In the case study, the first terrace and flood Land of the Lhasa River would be the same as the low permeability barriers as their small hydraulic gradients. Without the extraction wells, the pollutants would be concentrated in the areas with the maximum concentration growth rapidly. Otherwise, the groundwater flow in flood land of the Lhasa River is seriously influenced by the water level of the Lhasa River. In the rainy season, the water of the Lhasa River would recharge the groundwater in the flooded land of the Lhasa River and vice versa. Thus, the path of maximum concentration of Cd would fluctuate on either side. Once the tailing pond is seepage, not only groundwater but also the Lhasa River would be polluted. Future more, the tracking monitor wells would not find the abnormalities of pollutants.

5. CONCLUSIONS

- The anti-seepage layer is a necessary and important component of the tailing ponds, which could protect the soil or groundwater to be polluted by wastewater. Under Scenario A (the ideal conditions), Scenario B (the worst conditions), and Scenario C, the proportion of maximum concentration to source concentration are respectively 1.2, 94.6, and 19.1%. The maximum concentration of Cd would exceed the third group of the groundwater quality standard under Scenarios B and C.
- As the small hydraulic gradients, the first terrace and flood land of the Lhasa River are not conducive to the spread of pollutants. The pollutants would be concentrated at the areas with the maximum concentration growth rapidly. Under the worst states of anti-seepage layers, the pollution areas on 730, 1800, 3807, and 7300 days were 130, 500, 313 200, 523 800, and 729 000 m^2, respectively. Compared with Scenario B, the pollution areas of Scenario C on 1800, 3807, and 7300 days were cut by 52.97, 74.55, and 81.73%, respectively. Because of the importance of anti-seepage layers, the tracking monitor system is necessary and important to discover whether the groundwater was contaminated in time.
- The trend of the maximum concentration of typical pollutants is similar when the anti-seepage system of the tailing pond is out of artificial control. The diffusion of pol-

lutants is mainly controlled by hydraulic conditions. The anti-seepage layer is an effective measure to prevent pollutants infiltrate into the groundwater system. A suitable tracking monitor system could discover whether the groundwater was contaminated in time, and the repairing measure could lessen the degree of groundwater pollution.

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