Study on Rule of Heavy Metal Cu2+ in Small and Medium-Sized Tailings Ponds under Rainfall-Evaporation-Transpiration Coupling

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Abstract. In order to research the heavy metal migration rule of small and medium-sized tailings ponds under the action of climate, vegetation and groundwater, this paper consider the rainfall-evaporation-transpiration and coupling effect of groundwater, establish the model of different dam height, slope ratio, permeability coefficient and migration time impact on the migration of heavy metals of tailings dam, applied to Geostudio software, based on the orthogonal design method of factors significant difference analysis and design method of the comprehensive factors analysis, make up the simulation of the tailings heavy metal pollutants concentration of Cu2+ migration law. The results show that the height of tailing dam is inversely proportional to the average migration velocity of pollutant Cu2+. The effect of slope ratio on migration concentration of Cu2+ pollutant in tailings pond is not significant. The permeability coefficient has a highly significant influence on the migration of heavy metal Cu2+. At the same depth of tailings pond, when Cu2+ migrated for 365 days, the permeability coefficient increased with the increase of pollutant Cu2+ concentration. The concentration of heavy metal increased with the increase of migration time.

Keywords: Tailings ponds; Small and Medium-sized; Rainfall-evaporate-transpiration; Migration of Cu2+; Numerical simulation; Geostudio

1. Introduction
Tailings pond is a major source of pollution and danger in mines [1]. If the tailings pond is not properly managed, it will cause serious safety and environmental problems. Therefore, it is of great practical significance to carry out the study on the law of pollutant migration of tailings pond [2]. At present, many scholars have carried out researches on pollutant migration simulation. Farouk Ben Abdelghani [3] and others used Hydro-Geosphere tool to conduct numerical simulation analysis and evaluation of unsaturated water flow and pollutant migration. B.O.Tsydenov [4] carried out numerical simulation analysis on the spatial distribution of pollutants in a sea area under different wind conditions. F.Wenjuan [5] and others used GMS software to simulate the migration of diesel oil leakage in a strong runoff zone. L.Yuqing [6] and others carried out a simulation study on the transfer and transformation of non-point source pollutants in rice irrigated areas. W.Dandan [7] and others simulated the migration and degradation of NH3-N and NP by using the wetland ecological dynamics model. G.Feng [8] and others used Modflow and MT3DMS groundwater seepage method to simulate and analyze the process of underground water flow and solute transport. W.Yang [9] and others
simulated the migration of pollutants in the coastal waters of irrigation estuaries through a two-dimensional hydrodynamic model and carried out analysis and verification.

The above studies are limited to the convection-dispersion migration of pollutants along groundwater, neither simulation analysis of heavy metal migration in tailings pond under the coupling effect of rainfall-evapotranspiration and groundwater has been carried out, nor influence rule of geometric model, hydrogeological parameters and diffusion time on heavy metal pollutants migration has been studied. In this paper, the effects of tailings dam height, slope ratio, permeability coefficient and migration time on the concentration of heavy metal Cu²⁺ in tailings pond are considered. The simulation study of heavy metal Cu²⁺ migration in small and medium-sized tailings ponds under rainfall-evaporation-transpiration was carried out, and the primary and secondary influences of heavy metal Cu²⁺ in tailings pond were obtained. The law of influence of each factor on the migration of pollutants was analyzed, so as to provide a basis for the analysis, evaluation and prevention of heavy metal pollution in small and medium-sized tailings ponds.

2. Modeling and Boundary Conditions

2.1. Modeling
A third-class tailings pond with the dam height of 80m and the slope ratio of 1:3 is taken as an example to establish a calculation model and grid subdivision. In the model, tailings dam stratum and underlying bedrock are set. Using the Van Genuchten equation to estimate the soil-water characteristic curve in Geostudio, the permeability coefficient function of the soil layer of the tailings dam was estimated according to the soil-water characteristic curve, and three levels were set according to the recommended value of the permeability coefficient of the tailings soil in the Code for design of Tailings Facilities (GB50863-2013). Figure 2 and figure 3 show the soil-water characteristic curve and the permeability coefficient curve of the soil layer at the three levels of the tailing dam.

![Figure 1. Tailings pond model and grid distribution.](image1)

![Figure 2. Soil-water characteristic curve.](image2)

![Figure 3. Permeability coefficient curve.](image3)

2.2. Boundary Conditions
As shown in figure 1, the hydraulic boundary conditions for the steady-state seepage simulation are set as follows: BC is the upstream head, DE is the downstream head, AB is the zero flow boundary, and FG is the drainage boundary. The climate boundary conditions of the transient coupling simulation were selected based on the measured climate data of 365 days in northern China. The curves of
temperature, relative humidity, wind speed and rainfall intensity over time are shown in figure 4. The upstream head and downstream head of transient coupling simulation are the same as the steady-state seepage simulation, AB and CD are the zero flow boundary, AG and GF are the climatic boundary. The pollutant boundary (BC) of initial concentration is set by convection-dispersion simulation.

Figure 4. Curve of temperature, relative humidity, wind speed and rainfall intensity over time.

The transpiration indexes of herbs with high survival rate in natural environment was selected, and the LAI function [10], plant humidity limit function and root depth function were shown in figures 5~7.

Figure 5. LAI function. Figure 6. The limit function of plant humidity. Figure 7. Root depth function.

3. Analysis of Factor Significance Difference Based on Orthogonal Design Method
Orthogonal experimental method was used to study the influence of dam height (A), slope ratio(B), permeability coefficient(C) and migration time (D) on the migration concentration of heavy metals in tailings pond. The experimental scheme was shown in table 1. The orthogonal scheme was designed with the concentration of the vertical section (section 1 as shown in figure 1) as the index. The simulation results were shown in table 2, and the corresponding analysis of variance results were shown in table 3.
Table 1. Orthogonal design scheme.

| Factors            | Dam height/m (A) | Slope ratio (B) | Permeability coefficient/cm·s⁻¹ (C) | Migration time/d (D) |
|--------------------|------------------|-----------------|-------------------------------------|----------------------|
| Level 1            | 80               | 1:3             | 1.5×10⁻³                            | 120                  |
| Level 2            | 45               | 1:4             | 1.3×10⁻³                            | 240                  |
| Level 3            | 15               | 1:5             | 3.75×10⁻⁴                           | 365                  |

Table 2. Orthogonal experimental results.

| Factors | A     | B     | C     | D     | Vertical section concentration (kg/m³) |
|---------|-------|-------|-------|-------|---------------------------------------|
| Experiment 1 | 1    | 1    | 1    | 1    | 0.4312                                 |
| Experiment 2 | 1    | 2    | 2    | 2    | 0.4220                                 |
| Experiment 3 | 1    | 3    | 3    | 3    | 0.1629                                 |
| Experiment 4 | 2    | 1    | 2    | 3    | 0.3839                                 |
| Experiment 5 | 2    | 2    | 3    | 1    | 0.0701                                 |
| Experiment 6 | 2    | 3    | 1    | 2    | 0.3704                                 |
| Experiment 7 | 3    | 1    | 3    | 2    | 0.0745                                 |
| Experiment 8 | 3    | 2    | 1    | 3    | 0.3518                                 |
| Experiment 9 | 3    | 3    | 2    | 1    | 0.3072                                 |
| The sum of level 1 | 1.0161 | 0.8896 | 1.1534 | 0.8085 | —                                  |
| The sum of level 2 | 0.8244 | 0.8439 | 1.1131 | 0.8669 | —                                  |
| The sum of level 3 | 0.7335 | 0.8405 | 0.3075 | 0.8986 | —                                  |
| Mean value 1(K1)    | 0.3387 | 0.2965 | 0.3845 | 0.2695 | —                                  |
| Mean value 2(K2)    | 0.2748 | 0.2813 | 0.3710 | 0.2890 | —                                  |
| Mean value 3(K3)    | 0.2445 | 0.2802 | 0.1025 | 0.0898 | —                                  |
| Range(R)            | 0.0942 | 0.0163 | 0.2820 | 0.1992 | —                                  |

Table 3. Analysis of variance

| Factors | Deviation sum of squares | Degree of freedom | Mean square | F-value | F-critical value | Significance |
|---------|--------------------------|-------------------|-------------|---------|-----------------|--------------|
| A       | 0.0138                   | 2                 | 0.0069      | 184     | 99              | Highly significant |
| B       | 0.0004                   | 2                 | 0.0002      | 5.33    | 9               | Non-significant  |
| C       | 0.1518                   | 2                 | 0.0759      | 2024    | 99              | Highly significant|
| D       | 0.0013                   | 2                 | 0.0007      | 18.67   | 19              | Significant    |
| Error   | 0.0003                   | 8                 | 3.75×10⁻⁵   | —       | —               | —             |

As can be seen from table 3, the significant ranking of the four factors is C>A>D>B. Therefore, the primary and secondary factors influencing the concentration of heavy metal pollutants in the tailings pond are C>A>D>B, namely the permeability coefficient > dam height > migration time > slope ratio.

4. Analysis of Factor Influence Based on Total Design Method

4.1. Modeling Scheme

The initial concentration of heavy metal Cu²⁺ in convection-dispersion and particle tracer model was 0.05 kg/m³, regardless of adsorption and ion interaction. The 27 schemes in table 4 were simulated by Geostudio software to obtain the distribution of heavy metal pollutant concentrations in tailings ponds under different dam heights, permeability coefficients and migration times.
### Table 4. Analysis of overall design.

| Serial number | Dam height/m (A) | Slope ratio (B) | Permeability coefficient/cm·s⁻¹ (C) | Migration time/d (D) |
|---------------|------------------|----------------|-------------------------------------|---------------------|
| 1             | A₁=80            | B=1:3          | C₁=1.5×10⁻³                          | D₁=120              |
| 2             | A₁=80            | B=1:3          | C₁=1.5×10⁻³                          | D₂=240              |
| 3             | A₁=80            | B=1:3          | C₁=1.5×10⁻³                          | D₃=365              |
| 4             | A₁=80            | B=1:3          | C₂=1.3×10⁻³                          | D₁=120              |
| 5             | A₁=80            | B=1:3          | C₂=1.3×10⁻³                          | D₂=240              |
| 6             | A₁=80            | B=1:3          | C₂=1.3×10⁻³                          | D₃=365              |
| 7             | A₁=80            | B=1:3          | C₃=3.75×10⁻⁴                         | D₁=120              |
| 8             | A₁=80            | B=1:3          | C₃=3.75×10⁻⁴                         | D₂=240              |
| 9             | A₁=80            | B=1:3          | C₃=3.75×10⁻⁴                         | D₃=365              |
| 10            | A₂=45            | B=1:3          | C₁=1.5×10⁻³                          | D₁=120              |
| 11            | A₂=45            | B=1:3          | C₁=1.5×10⁻³                          | D₂=240              |
| 12            | A₂=45            | B=1:3          | C₁=1.5×10⁻³                          | D₃=365              |
| 13            | A₂=45            | B=1:3          | C₂=1.3×10⁻³                          | D₁=120              |
| 14            | A₂=45            | B=1:3          | C₂=1.3×10⁻³                          | D₂=240              |
| 15            | A₂=45            | B=1:3          | C₂=1.3×10⁻³                          | D₃=365              |
| 16            | A₂=45            | B=1:3          | C₃=3.75×10⁻⁴                         | D₁=120              |
| 17            | A₂=45            | B=1:3          | C₃=3.75×10⁻⁴                         | D₂=240              |
| 18            | A₂=45            | B=1:3          | C₃=3.75×10⁻⁴                         | D₃=365              |
| 19            | A₃=15            | B=1:3          | C₁=1.5×10⁻³                          | D₁=120              |
| 20            | A₃=15            | B=1:3          | C₁=1.5×10⁻³                          | D₂=240              |
| 21            | A₃=15            | B=1:3          | C₁=1.5×10⁻³                          | D₃=365              |
| 22            | A₃=15            | B=1:3          | C₂=1.3×10⁻³                          | D₁=120              |
| 23            | A₃=15            | B=1:3          | C₂=1.3×10⁻³                          | D₂=240              |
| 24            | A₃=15            | B=1:3          | C₂=1.3×10⁻³                          | D₃=365              |
| 25            | A₃=15            | B=1:3          | C₃=3.75×10⁻⁴                         | D₁=120              |
| 26            | A₃=15            | B=1:3          | C₃=3.75×10⁻⁴                         | D₂=240              |
| 27            | A₃=15            | B=1:3          | C₃=3.75×10⁻⁴                         | D₃=365              |

4.2. Influence of Dam Height on Pollutant Concentration

Figure 8 shows the variation curve of pollutant concentration in different dam height with tailings pond depth at 120 d of pollutant migration. The higher the height of tailing dam is, the higher the concentration of heavy metal Cu²⁺ in its section is, and the faster the average migration rate of heavy metal Cu²⁺ in tailing dam is. The smaller the tailings dam height is, the smaller the tailings pond model is, so that the pollutants can diffuse to the foot of the dam in a short time, and the concentration value of the whole tailings pond model changes relatively greatly. According to the particle tracer simulation results, the average migration velocity of five particles for 120 days was obtained. Taking C₁=1.5×10⁻³ cm/s as an example, the average migration velocity corresponding to A₁=80 m, A₂=45 m and A₃=15 m is respectively 0.3756 m/d, 0.4047 m/d and 0.5052 m/d.

![Figure 8](image_url)
depth at 120 days of pollutant migration

4.3. Influence of Osmotic Coefficient on Pollutant Concentration

It can be seen from figure 9 that, at a certain dam height, pollutant concentration increases with the increase of tailings pond depth in 365 days of pollutant migration, and the pollutant concentration in the surface soil of the tailings pond is smaller than that in the deep soil. The permeability coefficient has a significant influence on the transport of heavy metal. At the same depth of the tailings pond, the higher the permeability coefficient, the higher the pollutant concentration were at 365 days of pollutant migration. Take figure 9 (a) for example, when the elevation is 40 m, the corresponding concentrations of C1=1.5×10^-3 cm/s, C2=1.3×10^-3 cm/s and C3=3.75×10^-4 cm/s are 0.0488 kg/m^3, 0.0468 kg/m^3 and 0.0004 kg/m^3 respectively.

![Figure 9](image_url)

Figure 9. The variation curve of pollutant concentration with tailings pond depth at 365 days of pollutant migration under different permeability coefficients

4.4. Influence of Migration Time on Pollutant Concentration

It can be seen from figure 10 that under the condition of a certain dam height, the concentration of heavy metal Cu^{2+} in the same section increases with the passage of time. With the passage of time, the pollutant concentration in the surface soil of tailings pond gradually increases. Take figure 10(a) for example, when the elevation is 40 m, the corresponding concentrations are 0.0108 kg/m^3, 0.0251 kg/m^3 and 0.0376 kg/m^3 respectively when D1=120 d, D2=240 d and D3=365 d.

![Figure 10](image_url)

Figure 10. The variation curve of pollutant concentration with tailings pond depth at different time of pollutant migration

5. Conclusion

Considering the coupling effect of rainfall-evaporation-transpiration and groundwater, this paper studies the influences of dam height, slope ratio, permeability coefficient and migration time on the heavy metal migration concentration of tailings pond, and draws the following conclusions:

(1) Small and medium-sized tailings ponds play a dominant role in China's tailings ponds. In addition to moving with groundwater, pollutants are also easily affected by external factors such as climate and vegetation. Considering the coupling effect of rainfall-evaporaton-transpiration and groundwater, the simulation accuracy of heavy metal migration in tailings ponds can be improved, so that the calculation results are more in line with the reality, and the scientific basis can be provided for
the analysis, evaluation and prevention of heavy metal pollution in small and medium-sized tailings ponds.

(2) By using orthogonal design method, numerical calculation models are established to study the influence of dam height (A), slope ratio (B), permeability coefficient (C) and migration time (D) on the heavy metal migration concentration of tailings pond. It is concluded that the primary and secondary factors influencing pollutant concentration of tailings pond are C>A>D>B, that is, permeability coefficient > dam height > migration time > slope ratio. The analysis results show that factor B (slope ratio) has a non-significant influence on the index.

(3) Through the comprehensive simulation test of three factors on the heavy metal migration in tailings ponds, the variation rules of the influence of dam height, permeability coefficient and migration time on the heavy metal concentration in tailings ponds are obtained. The smaller the tailings dam height is, the higher the pollutant concentration in the profile is, and the faster the average migration speed of heavy metal pollutants in tailings pond is. The permeability coefficient has a significant influence on pollutant migration. The higher the permeability coefficient is, the higher the pollutant concentration in the same depth of tailings pond is. At a certain dam height, the pollutant concentration in the same section increases with time.

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