

# Application of Visual MODFLOW to assess the Sewage Plant accident pool leakage impact on groundwater in the Guanting Reservoir area of Beijing

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**Abstract** In this paper, Visual MODFLOW is used to simulate groundwater flow and transport within the study area based on a certain scenario, assessing the leakage impact of a Sewage Plant accidental pool on groundwater using  $\text{NH}_3\text{-N}$  as the assessment factor. In the model constructed, soil absorption and degradation was taken into account; the adsorption process of  $\text{NH}_3\text{-N}$  adopted the Langmuir equation and the degradation was simplified as a first-order dynamic reaction. The leakage process was defined as a recharge with contaminants in the case that where there are two accidents happening to the Sewage Plant within a one month interval. The result of the model indicated that the  $\text{NH}_3\text{-N}$  concentration of groundwater increased sharply when the Sewage Plant was malfunctioning. The peak of  $\text{NH}_3\text{-N}$  concentration under the accident pool was about  $8.0 \times 10^{-5}$  mg/L at the first accident. When the second accident happened, the  $\text{NH}_3\text{-N}$  concentration increased to a maximum of about  $1.1 \times 10^{-4}$  mg/L. At a location of about 20 m from the accident pool, the concentration declined to about one sixth of the center, which demonstrated that the  $\text{NH}_3\text{-N}$  concentration increase caused by leakage of the accident pool was little, and the spatial influence also was small. The paper provides a method of dealing with the transport of physically and chemically reactive substances in groundwater with Visual MODFLOW and assessing the Sewage Plant accident pool leakage impact on groundwater quantitatively.

**Keywords** groundwater, leakage, Visual MODFLOW, adsorption, dynamic reaction

## 1 Introduction

The Guanting Reservoir is a water source for Beijing city. According to the Law of the People's Republic of China on the Prevention and Control of Water Pollution and the Beijing Municipality approach to implementing "The People's Republic of China Water Pollution Prevention Law", projects involving any water pollution discharge are forbidden within a 5 km buffer zone around the Guanting Reservoir. A construction project at the location about 3 km away from the top level of the Guanting Reservoir will be built, so a Sewage Plant is needed to treat the waste water generated by the project, and the treated water should be reused in the project. However, if the Sewage Plant malfunctions, the waste water would discharge directly to the ground, which would result in pollution of the groundwater. Because the groundwater has a very close hydraulic connection with the water of the Guanting Reservoir, which accepts directly the recharge of the groundwater, the water of the Guanting Reservoir will also be polluted. Therefore, it is essential to build an accident pool to store the waste water for when the Sewage Plant malfunctions.

After the accident pool is built, the ground water can be kept unpolluted from most of the Water Pollutant in the waste water; however, leaking from the accident pool is another potential pollution pathway. Usually, the impact of this type of contaminant is neglected or only qualitative assessment is made in most cases. Since the distance of the accident pool from the Guanting Reservoir is short, it is necessary to consider the impact of the accident pool leakage on groundwater and assess it quantitatively.

In this study, we analyze the impacts of the leakage of the accident pool in terms of both quality and quantity. Achieving this entails using numerical groundwater flow

model. MODFLOW is programmed under FORTRAN 77 (American National Standards Institute, 1978) language environment with the finite-difference method to describe the movement of groundwater flow. It was developed by McDonald and Harbaugh (1984) of the US Geological Survey in 1984 and had been updated for three times including MODFLOW-88 (McDonald and Harbaugh, 1988), MODFLOW-96 (McDonald and Harbaugh, 1996) and MODFLOW-2000 (Harbaugh et al., 2000). The newest version of MODFLOW-2000 can be compiled by the FORTRAN language of the Visual Studio program and general C language could be used here. At the same time many new packages have been added into the code which can simulate the hydrogeological problems much better than ever. For example, Reservoir Package (RES1) (Fenske et al., 1996) can simulate leakage from reservoirs; Evapotranspiration with a segmented function (ETS1) (Banta, 2000) package allows simulation of evapotranspiration with a user-defined relation between evapotranspiration rate and hydraulic head; Drain Return (DRT1) (Banta, 2000) Package can be used to simulate the return flow of water discharged from a drain back into the ground-water system. As a modular three-dimensional finite difference groundwater flow model (McDonald and Harbaugh, 1988), MODFLOW can be used to simulate transient/steady groundwater flow in complex hydraulic conditions with various natural hydrological processes and/or artificial activities and can be used for large areal extent and for multi-aquifer modeling. Hydrogeological layers can be simulated as confined, unconfined or a

combination of the two. Boundary conditions include specific head, specific flux and head-dependent flux.

Visual MODFLOW integrating the MODFLOW for simulating the flow and MT3D for simulating the transport and combined with GIS technology provided a good visualization interface for users and played a significant role in the groundwater evaluation. In this paper, it will be used to simulate the flow and contaminant transport under a certain scenario and estimate the increased contaminant concentration in groundwater and assess the impact.

## 2 Study area

The study area is located in the northwest part of Beijing in China between latitude  $40^{\circ}24'20.00''$  to  $40^{\circ}29'4.18''$  N and longitude  $115^{\circ}44'39.97''$  to  $115^{\circ}55'17.51''$  E, covering an area of about  $40 \text{ km}^2$  (Fig. 1). Southeast of the area is the Guanting Reservoir and in the northwest of the area is a mountainous region. The altitude varies from 470 to 720 m above mean sea level, and the altitude of the location of the Sewage Plant is about 505 m (Fig. 2). The groundwater flows from northwest to southeast and flows into the Guanting Reservoir ultimately.

## 3 Methods

The waste water discharged by the project was typical of Domestic Wastewater containing  $\text{COD}_{\text{Cr}}$ ,  $\text{BOD}_5$ ,  $\text{NH}_3\text{-N}$ ,

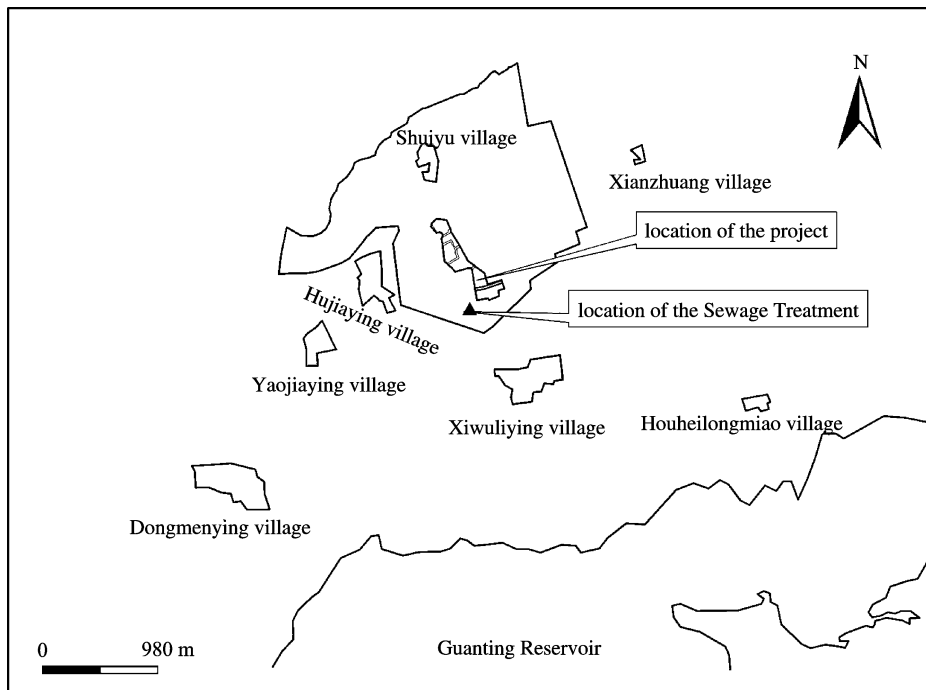


Fig. 1 Map of the study area

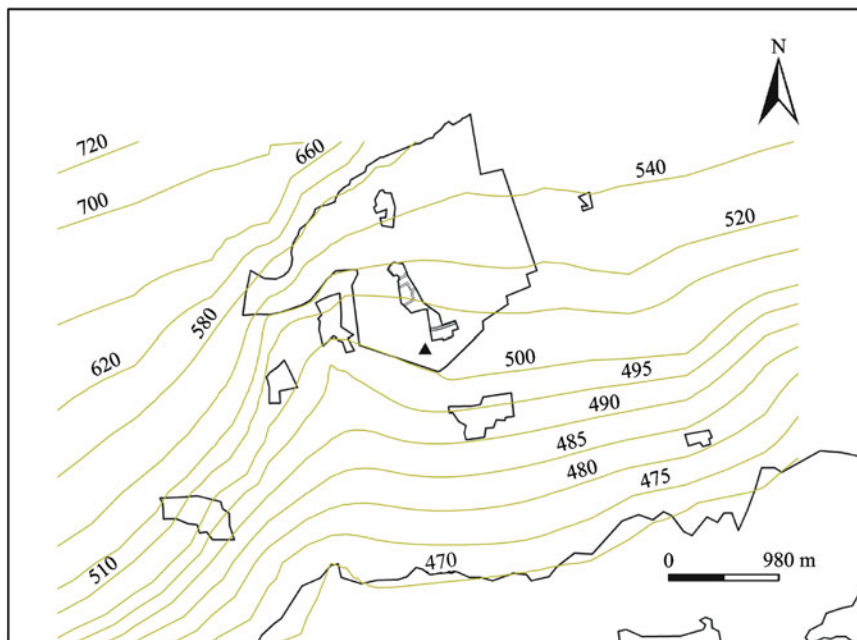


Fig. 2 Elevation of the study area

etc. In this paper,  $\text{NH}_3\text{-N}$  is chosen as the assessment factor. The leakage volume of the waste water from the accident pool is calculated by

$$Q_{\text{leakage}} = AK_s \frac{d + h_{\text{max}}}{d}, \quad (1)$$

where  $d$  is the thickness of the base of the accident pool,  $K_s$  is the permeability coefficient of the base of the accident pool,  $A$  is the area of the bottom of the accident pool,  $h_{\text{max}}$  is maximum depth of waste water in the accident pool. For the accident pool,  $h_{\text{max}} \gg d$ , Eq. (1) can be expressed as

$$Q_{\text{leakage}} \approx AK_s \frac{h_{\text{max}}}{d} = K_s \frac{Ah_{\text{max}}}{d} = K_s \frac{V_{\text{max}}}{d}, \quad (2)$$

where  $V_{\text{max}}$  is maximum volume of waste water in the accident pool.

As for the model of Visual MODFLOW, three-dimensional partial finite differential equation for a constant density transient groundwater flow and that of transport in a heterogeneous and anisotropic medium (provided the principal axes of hydraulic conductivity are aligned with the coordinate directions), for a confined or unconfined aquifer, is expressed as (Bear, 1979; Freeze and Cherry, 1979; Charles, 2002; Todd and Larry, 2005).

$$\begin{aligned} & \frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) \\ & + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) + N(x, y, z, t) \\ & = S_s \frac{\partial h}{\partial t}, \end{aligned} \quad (3)$$

where  $K_{xx}$ ,  $K_{yy}$ , and  $K_{zz}$  are the hydraulic conductivities along the  $x$ ,  $y$ , and  $z$  coordinate axes parallel to the major axes of hydraulic conductivities ( $L/T$ ),  $h$  is the hydraulic head ( $L$ ),  $S_s$  is the specific storage of the porous medium,  $N$  is the volumetric flux per unit volume representing sources and/or sinks of water; and  $t$  is time. While the general three-dimensional equation for solute transport assuming constant porosity and macro-dispersiveness in time and space is given by

$$\begin{aligned} & \frac{\partial}{\partial x} \left( D_{xx} \frac{\partial c}{\partial x} + D_{xy} \frac{\partial c}{\partial y} + D_{xz} \frac{\partial c}{\partial z} \right) \\ & + \frac{\partial}{\partial y} \left( D_{yx} \frac{\partial c}{\partial x} + D_{yy} \frac{\partial c}{\partial y} + D_{yz} \frac{\partial c}{\partial z} \right) \\ & + \frac{\partial}{\partial z} \left( D_{zx} \frac{\partial c}{\partial x} + D_{zy} \frac{\partial c}{\partial y} + D_{zz} \frac{\partial c}{\partial z} \right) \\ & - \left[ \frac{\partial}{\partial x} (V_x c) + \frac{\partial}{\partial y} (V_y c) + \frac{\partial}{\partial z} (V_z c) \right] + \sum R_n \\ & = \frac{\partial c}{\partial t}, \end{aligned} \quad (4)$$

where,  $x$ ,  $y$ , and  $z$  are Cartesian coordinates aligned along the major axes of hydrodynamic dispersion coefficients  $D_{xx}$ ,  $D_{yy}$ ,  $D_{zz}$  ( $L^2/T$ );  $c$  is the concentration of contaminants dissolved in groundwater ( $M/L^3$ );  $V_x$ ,  $V_y$ , and  $V_z$  are the seepage velocities in  $x$ ,  $y$ , and  $z$  directions ( $L/T$ ),  $\sum R_n$  is physical and chemical reaction items.

Adsorption on soil and degradation occurs when  $\text{NH}_3\text{-N}$  transfers and transforms in soil and groundwater, of which the adsorption process on soil is in accordance with the Langmuir equation (Jiang, 2004).

$$S = \frac{kS_m c}{1 + kc} \quad (5)$$

where  $S$  is adsorption,  $S_m$  is the maximum adsorption capacity,  $k$  is adsorption equilibrium constant, and  $c$  is adsorbate concentration in solution. Analogy Analysis of Soil Properties of the study area, through calculation of the value of  $k$  in Eq. (5) is 0.898 L/mg, the value of  $S_m$  is 628.9 mg/kg. The biochemical reaction of  $\text{NH}_3\text{-N}$  in soil and groundwater is extremely complex, the reaction dynamics equation simplified as first-order dynamic reaction is expressed as

$$\frac{\partial c}{\partial t} = -Kc, \quad (6)$$

where  $c$  is substance concentration in reaction process,  $K$  is first-order reaction rate constant,  $t$  is Reaction Time. Through Analogy Analysis (Li and Yang, 2006), the value of  $K$  of the study area in Eq. (6) is  $0.04 \text{ d}^{-1}$ .

Establishing the Numeric model by using software Visual MODFLOW version 4.2, the study area was discretized into 144 rows and 177 columns, the cell size in the location of the accident pool was  $10 \text{ m} \times 10 \text{ m}$ , outward was  $20 \text{ m} \times 20 \text{ m}$ ,  $50 \text{ m} \times 50 \text{ m}$ ,  $100 \text{ m} \times 100 \text{ m}$  in succession. The entire model structure was a matrix of  $144 \text{ rows} \times 147 \text{ columns} \times 2 \text{ layers}$ . Hydraulic conductivity value is  $2.6 \times 10^{-4} \text{ m/s}$  of the first layer, and  $1.0 \times 10^{-10} \text{ m/s}$  of the second layer. The north and the west of the study area receive the recharge of the mountainous region, so it was defined as the second flow boundary; the Guanting Reservoir was defined as the constant head boundary and the head is 470 m.

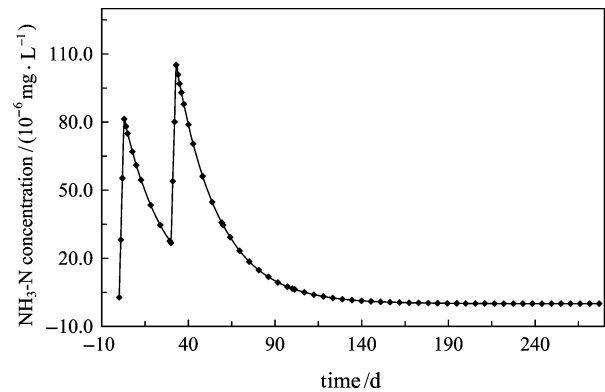
A certain scenario is that there are two accidents happening in the Sewage Plant within a one month interval. The maintenance period of the Sewage Plant is 3 d; the capacity of the accident pool must be 3 times the daily capacity ( $277.3 \text{ m}^3$ ) of the Sewage Plant. The leakage volume is calculated by Eq. (2) and the leakage process is defined as a recharge with contaminants as shown in Table 1. Soil adsorption and degradation of  $\text{NH}_3\text{-N}$  was taken into account in the model with MT3D in Visual MODFLOW, adopting the absorption and degradation model and the parameters as above.

**Table 1** Definition of the leakage

time/d	recharge/( $\text{mm} \cdot \text{d}^{-1}$ )	recharge concentration/( $\text{mg} \cdot \text{L}^{-1}$ )
0–3	23.96	35
3–30	0.00	0
30–33	23.96	35
33–	0.00	0

## 4 Results and discussion

After running the model, the observed  $\text{NH}_3\text{-N}$  concentration of the first layer under the accident pool varied with time as shown in Fig. 3 (the background of the groundwater was set at  $0 \text{ mg/L}$ ). The  $\text{NH}_3\text{-N}$  concentration increased sharply to about  $8.0 \times 10^{-5} \text{ mg/L}$  (on the third day) after the first accident, and declined quickly to about  $2.5 \times 10^{-5} \text{ mg/L}$  (on the thirtieth day) because of dilution of groundwater, adsorption by soil and degradation. When the second accident occurred, the concentration increased sharply once again and reached the maximum ( $1.1 \times 10^{-4} \text{ mg/L}$ ) on the thirty-third day, then it started to decline, and became stable after 200 d.



**Fig. 3**  $\text{NH}_3\text{-N}$  concentration varying with time observed under the accident pool

The  $\text{NH}_3\text{-N}$  concentration declined gradually with the distance increasing from the accident pool (Fig. 4). At a location of about 20 m from the accident pool, the concentration declined to about one sixth of that in the center. Indicated by Fig. 4, the concentration contour retracted in the period from the third day to the thirtieth day, while spreading in the period from the thirtieth day to the thirty-third day, then retracted once again, which is consistent with Fig. 3. In general, the  $\text{NH}_3\text{-N}$  concentration increase caused by leakage of the accident pool was little, and the spatial influence also was small.

However, only two accidents in the Sewage Plant were considered in the scenario. In fact, a Sewage Plant will malfunction many times, but it would be once a month more frequent than usual. From Fig. 3, it can be seen that at the interval of more than 100 d, the concentration of the groundwater declined to the level before the initial accident happened. Therefore, the concentration would not be too high in the actual situations.

## 5 Conclusions

To construct the groundwater flow model using the Visual MODFLOW software, based on a certain scenario,

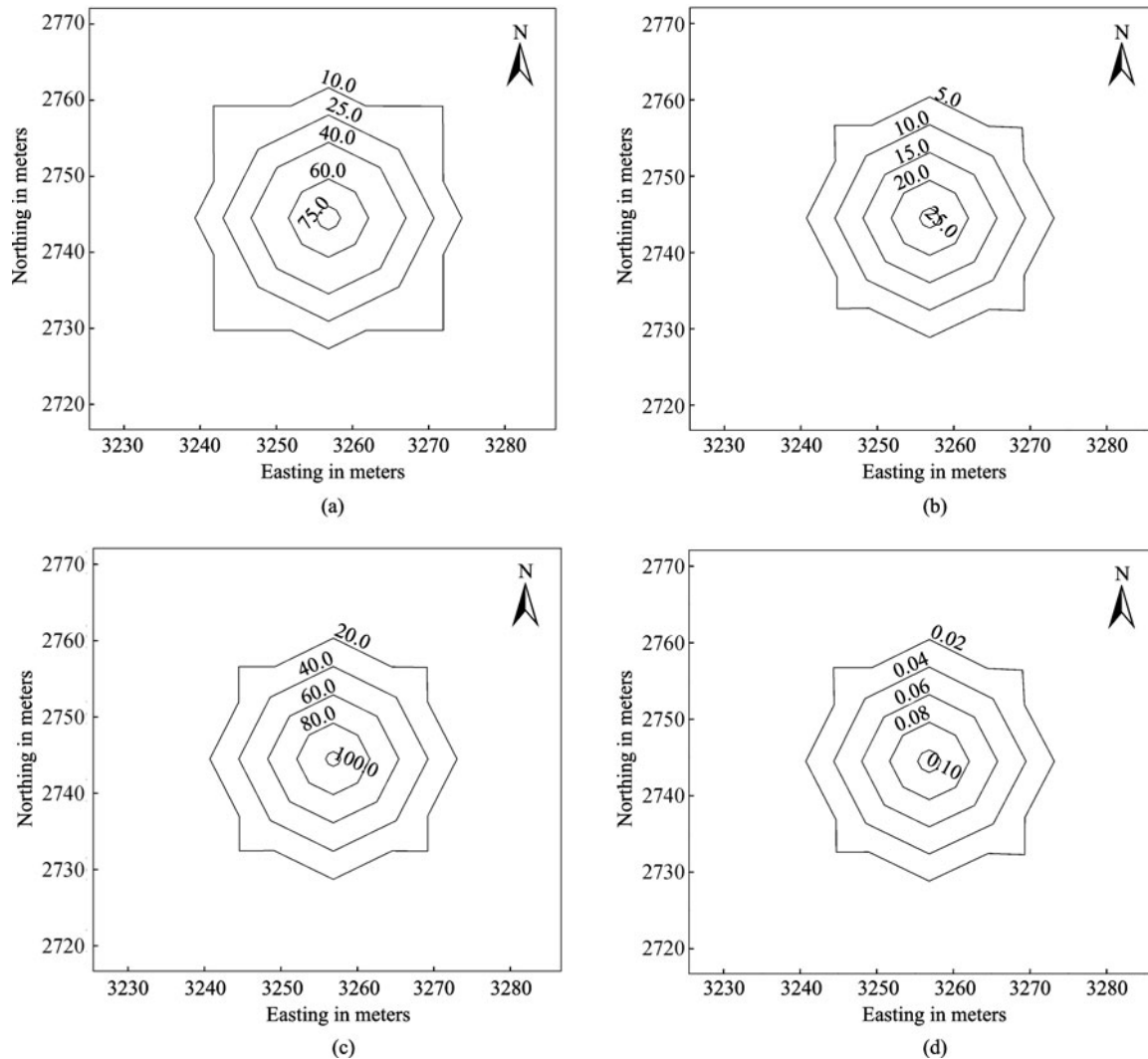


Fig. 4  $\text{NH}_3\text{-N}$  concentration contour at different simulation time (unit:  $10^{-6} \text{ mg} \cdot \text{L}^{-1}$ ). (a) 3 d; (b) 30 d; (c) 33 d; (d) 200 d

simulating and assessing the impact on groundwater of a leakage of the Sewage Plant accident pool using  $\text{NH}_3\text{-N}$  as the assessment factor, defining the leakage process as a recharge with contaminants, the result obtained from running the model demonstrated that the  $\text{NH}_3\text{-N}$  concentration increase was little and the impact on the environment was small, which was the effect of dilution of groundwater, adsorption by soil and degradation.

In the paper, taking soil absorption and degradation into account in the model, the adsorption process of  $\text{NH}_3\text{-N}$  adopted the Langmuir equation and the degradation was simplified as a first-order dynamic reaction. This indicated that the transport of the physical and chemical reactive substance of ground can be simulated well in Visual MODFLOW through proper simplification.

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