Journal of Environmental Sciences Vol.15, No.6, pp.827—835, 2003

ISSN 1001—0742
CN11—2629/X

Article ID: 1001-0742(2003)06-0827-09 **CLC number**: X703; X705 **Document code**: A

A simulation analysis of the migration and transformation of pollutants contained in landfill leachate

WANG Hong-qi[1 *], TIAN Kai-ming[2], QI Yong-qiang[1], CHEN Jia-jun[1], WANG Ya-nan[1]

(1 Institute of Environmental Sciences, State Key Laboratory of Environmental Simulation and Pollution Control, Beijing Normal University, Beijing 100875, China. E-mail: whongqi @ public. bta. net. cn; 2 Department of Water Resources and Environmental Science, China University of Geoscience, Beijing 100873, China)

Abstract: A dynamic composite model for a soil-water system that can be used to simulate the movement of leachate from a landfill. The composite model includes nine sub-models that trace water movement and the migration and transformation of five pollutants(organic N, NH_4^+, NO_3^-, NO_2^-, and Cl^-) in saturated and unsaturated soil. The model to simulate the movement of leachate from a landfill in Laogang Town, Shanghai City was used. In this application, the values for the model parameters were obtained by performing a laboratory simulation experiment of water movement and pollutant migration and transformation in soil columns. Soil and leachate obtained from the landfill site and its vicinity were used in the laboratory experiments. The model was then used to simulate leachate movement and pollutant activity during the ten-year period when the landfill was in operation and in the twenty-year period following its closure. The simulation results revealed that the leachate migrated into the groundwater at the rate of 90—100 meters per year. This model can be applied in the design of future landfills in China for the purpose of assessing and forecasting leachate plumes.

Keywords: simulation; leachate; landfill; pollutant migration; pollutant transformation; mathematical model

Introduction

In recent years, the rapid growth in urban populations and industrial facilities has had an enormous impact on the natural environment. A prominent part of this human influence on the environment is the generation and disposal of large quantities of industrial and domestic wastes. Assessing the impact of these wastes on the environment and finding appropriate forms of waste disposal is an important focus of urban environmental research. When industrial, domestic, and other types of wastes are deposited in large, intensive landfills, pollutants originating from these waste sites may contaminate nearby soil and water resources. This is serious problem in China. As a specific example, nitrogenous compounds leaching from landfills may pollute surface waters and groundwater. Analytical tools that simulate and predict the migration and transformation of pollutants through soil-water systems are needed so that future landfills can be designed in a manner that will minimize environmental impacts.

In this article, we develop and apply a composite mathematical model that simulates the processes of nitrogen mineralization, nitrification, denitrification, nitrogen diffusion, and water movement in soil and groundwater systems. Our main purpose is to build on former research work in which partial aspects of such processes have been considered and take a more holistic approach in assessing and developing an understanding of the movement and transformation of pollutants from landfills. The Nanhui Landfill in Laogang Town, Shanghai City, in China is used as an example to verify the applicability of the model.

Many researchers have studied and developed models of the nitrogen cycle and the leaching of nitrates (Groot, 1991; Lafolie, 1991; Wang, 1992; Nye, 1977). Also, in order to understand the movement and uptake of nitrogen in soil, Barber (Barber, 1984) studied the soil nutrient bioavailability and the relationship between water influx, plant growth, and nutrients. Others have analyzed the transformation of organic nitrogen, ammonium, and nitrate in the soil (Bezdicek, 1974; Ardakani, 1974; Starr; 1974); simulated nitrate transport in a regional groundwater system in South Australia(Forth, 1981); and modeled the contamination in unsaturated zones by heavy metals originating in a landfill(Bear, 1991). Burton (Burton, 1998) inspected the production of ammonia in landfills and Sear *et al*. (Sear, 2000) investigated nitrification and denitrification of leachate in landfills. Previous studies, however, cover only part of the nitrogen transport and transformation process in saturated and unsaturated systems.

1 Soil-water environment of the Nanhui Landfill in Shanghai City

Foundation item: The National Natural Science Foundation of China(No. 29777001); * Corresponding author

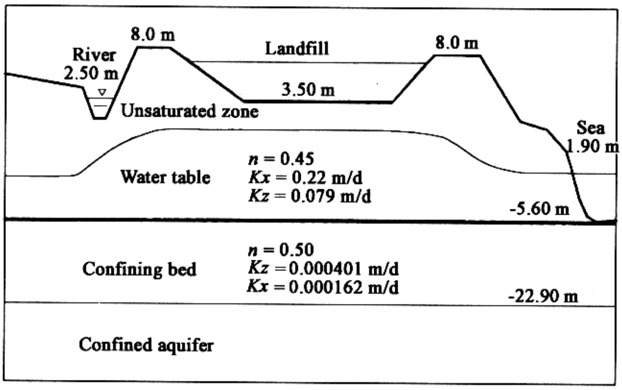

Fig.1 Sketch map of soil-water environment in Laogang landfill area

The Nanhui landfill in Laogang Town, Shanghai City, the facility used as the case study for our modeling project, is one of the largest in China. Located at 31° N, 120°52′ E, the landfill was designed as two parts, one part for construction waste and the other for domestic refuse. The areal dimensions for the domestic refuse part, which is the focus of our modeling project, were 2000 m × 500 m. The deposition depth was about 4.5 m yielding a volumetric capacity of approximately 4940000 m^3. The maximum input during the period when the landfill was in operation was 1500 t per day. The landfill was designed for a nine years' usage. This study started when the landfill had been in use for five years and ended two years later, after the landfill had been in use for seven years. The landfill was equipped with a closing levee, river channel, shipping dock, planting zone(consisting primarily of trees to reduce noise pollution and obscure an unpleasant view) and bridge, road, and distribution station.

The landfill lies near the East China Sea. The surrounding soil-water environment is complex. According to the water storage capacity and hydrodynamic features, the zone from the surface to 30 m below the surface can be divided into one unsaturated zone, two aquifers, and one confining bed. These structural features are shown in Fig.1. Based on the analysis of an aerial photograph of the landfill site and information from other data sources, a map of the landfill site and a coordinate framework for the construction of a quasi-two dimensional model of the unsaturated and saturated zones are sketched as shown in Fig.2. It is noteworthy that the river near the landfill is artificial. It has a good lining-up and a thick silt layer. The hydraulic connection between this river and the ground water is weak.

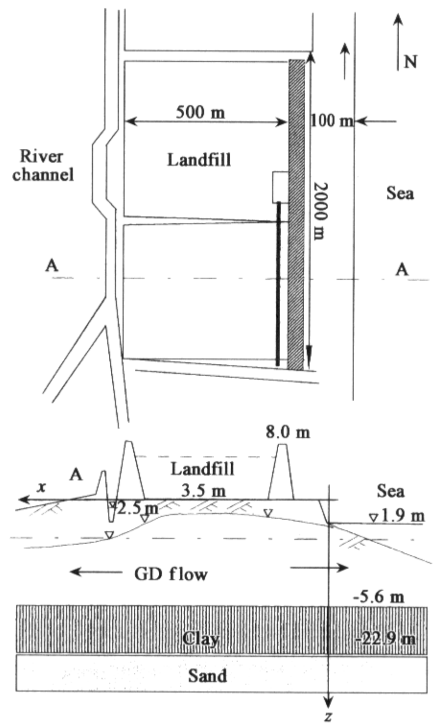

Fig.2 Sketch map of Laogang landfill site and model orientation

2 Model of pollutant migration and transformation

In 1987 and 1988 the Shanghai Municipal Environmental Protection Bureau and the Shanghai Municipal Environmental Sanitation Bureau monitored the surface water, groundwater, and leachate coming from the landfill in Laogang. The results showed that the drainage from the construction waste part of the landfill met the national emission standards, while the leachate, surface water, and groundwater around the domestic refuse part were heavily polluted(Wang, 1992; 1998). The main pollutants were organic wastes, N, and Cl^-. Because of the high rate of dispersion and the fact that Cl^- tends to migrate over a long distance, remediation of these pollutants is difficult(Peter, 1988; Smith, 1990). In addition, the several forms of nitrogen compounds contained in the soil-water environment surrounding the landfill can be easily transformed into NO_3^-. For these reasons, organic N, NH_4^-, NO_2^-, NO_3^-, and Cl^- have been identified as the main pollutants to be incorporated in our simulation model. Based on chemical kinetics for the transformation of pollutants and the hydrodynamics of dispersion in the unsaturated and saturated zones, a composite model was established in order to simulate the extent to which landfills influence the surrounding soil and water environments.

2.1 The composite models of saturated and unsaturated zones

Water movement is the dominant factor in the processes leading to leachate pollution of the soil-water environment. Consequently, accurately describing and predicting the water flow in the unsaturated and saturated zones is the key to an accurate simulation(Bear, 1991).

Based on the structure of the soil-water environment and the sketch model of the region, a generalized composite model was constructed to simulate the water movement from the landfill in Laogang. The composite model includes a vertical one-dimensional model in the unsaturated zone and a horizontal one-dimensional model in the saturated zone. The resulting composite model, called Model 1, is listed below. In this model the capillary potential and water head are dependent variables.

$$\begin{cases}\begin{cases}C(\phi_m)\dfrac{\partial \phi_m}{\partial t} = \dfrac{\partial}{\partial z}\left(k(\phi_m)\dfrac{\partial \phi_m}{\partial z}\right) - \dfrac{\partial k(\phi_m)}{\partial z} & \\ \left[-k(\phi_m)\dfrac{\partial \phi_m}{\partial z} + k(\phi_m)\right]_{z=0} = R(t) & t>0 \\ \phi_m = \phi_m^0(z) \quad t=0 & z\geqslant 0 \\ \phi_m = 0 \quad z = z_{\mathrm{DEP}} - h(x_d, t) & t>0\end{cases} \\ \left[-k(\phi_m)\dfrac{\partial \phi_m}{\partial z} + k(\phi_m)\right] = W(t) \quad t>0 \quad z = z_{\mathrm{DEP}} - h(x_d,t) \\ \begin{cases}\mu\dfrac{\partial h}{\partial t} = \dfrac{\partial}{\partial x}\left(kh\dfrac{\partial h}{\partial x}\right) + W(t) \\ h = h^0(x) \quad t=0 \quad x\geqslant 0 \\ h = h(0) \quad t>0 \quad x = 0 \\ h = h_0 \quad t\geqslant 0 \quad x_0 \to \infty\end{cases}\end{cases} \qquad \textbf{(Model 1)}$$

Variables: t is the time(d); x is the horizontal distance(m); z is the vertical distance(m): h is the saturated thickness(m); φ_m is the capillary potential in soil(Pa); C is the concentration of pollutants (mg/L);

Parameters: k is the conductivity in groundwater(cm/d); μ is the specific yield; $R(t)$ is the landfill leachate rate(cm/d); $W(t)$ is the pollutant flux out of the unsaturated zone (cm/d); $K(\varphi_m)$ is the vertical unsaturated conductivity(cm/d); z_{DEP} is the datum level of saturated zone's water head(m); x_d is the horizontal distance of the point sources(m).

2.2 The composite model of pollutant migration and transformation

The dispersion theories of fluid dynamics in porous media were used as a basis for analyzing and discussing the features of the solute convection-equation. A composite equation that involved chemical transformation, sorption, and sources was then established. The basic pattern of the equation in the vertical dimension of the unsaturated zone is:

$$\theta\frac{\partial C}{\partial t} + \rho\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left(D_{\mathrm{sh}}(\theta)\frac{\partial C}{\partial z}\right) - q\frac{\partial C}{\partial z} + \phi(C), \tag{1}$$

where C is the concentration of the pollutant in the soil(mg/L); $D_{\mathrm{sh}}(\theta)$ is the coefficient of dispersion in the unsaturated zone(cm^2/d); ρ is the bulk density of the soil(g/cm^3); S is the amount of adsorption; and the other parameters are the same as the corresponding ones above.

The basic pattern of the equation for the horizontal dimension in the saturated zone is:

$$n\frac{\partial C}{\partial t} + \rho\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left(D_{\mathrm{sh}}(u)\frac{\partial C}{\partial z}\right) - q\frac{\partial C}{\partial z} + W_i(t) + \phi(C), \tag{2}$$

where C is the concentration of the pollutant in the groundwater(mg/L); $D_{\mathrm{sh}}(u)$ is the coefficient of dispersion in the saturated zone(cm^2/d); ρ is the bulk density in the unsaturated zone(g/cm^3); S is the equilibrium sorption coefficient in the water table(mg/kg); $W_i(t)$ is the flux of pollutant i, where each value of i = 1, 2, 3, 4, 5, denotes one of the five pollutants(organic N, NH_4^-, NO_2^-, NO_3^-, and Cl^-, in that order); and the other parameters are the same as above.

Based on these equations and their initial boundary conditions, we simulated the point-source pollution of the leachate and established a dynamic, composite model for the soil-water system surrounding the landfill. The composite model includes nine main models of water movement and the transport and transformation of five types of pollutants (N, NH_4^- , NO_2^- , NO_3^- , and Cl^-) in the unsaturated and saturated zones. The resulting set of equations, called Model 2 (Nitrogen) and Model 3 (Chlorine), is listed blow.

1 - 1
$$\begin{cases} \theta \dfrac{\partial C_1}{\partial t} + 10 \cdot \rho \cdot \dfrac{\partial S_1}{\partial t} = \dfrac{\partial}{\partial z}\left(D_{sh}(\theta) \dfrac{\partial C_1}{\partial z}\right) - q \dfrac{\partial C_1}{\partial z} - K_2(\theta C_1 + 10 \cdot \rho \cdot S_1) + K_1 \theta C_N \\ \dfrac{\partial S_1}{\partial C_1} = \dfrac{b}{\sqrt{C_1}}(S_{1m} - S_1) \\ S_1 = 0 \quad C_1 = 0 \\ - D_{sh}(\theta) \dfrac{\partial C_1}{\partial z} + qC_1 = R(t) C_{1R}(t) & z = 0 \quad t \geqslant 0 \\ C_1 = C_1^0(z) & t = 0 \quad z \geqslant 0 \\ C_1 = C_{1D}(x_d) & t > 0 \quad z = z_{DEP} - h(x_d, t) \end{cases}$$

1 - 2
$$\begin{cases} \theta \dfrac{\partial C_2}{\partial t} = \dfrac{\partial}{\partial z}\left(D_{sh}(\theta) \dfrac{\partial C_2}{\partial z}\right) - q \dfrac{\partial C_2}{\partial z} + K_2(\theta C_2 + 10 \cdot \rho \cdot S_1) + K_3 \theta C_2 \\ - D_{sh}(\theta) \dfrac{\partial C_2}{\partial z} + qC_2 = R(t) C_{2R}(t) & z = 0 \quad t \geqslant 0 \\ C_2 = C_2^0(z) & t = 0 \quad z \geqslant 0 \\ C_2 = C_{2D}(x_d) & t > 0 \quad z = z_{DEP} - h(x_d, t) \end{cases}$$

1 - 3
$$\begin{cases} \theta \dfrac{\partial C_3}{\partial t} = \dfrac{\partial}{\partial z}\left(D_{sh}(\theta) \dfrac{\partial C_3}{\partial z}\right) - q \dfrac{\partial C_3}{\partial z} + K_3 \theta C_2 \dfrac{62}{46} - K_4 \theta C_3 \\ - D_{sh}(\theta) \dfrac{\partial C_3}{\partial z} + qC_3 = R(t) C_{3R}(t) & z = 0 \quad t \geqslant 0 \\ C_3 = C_3^0(z) & t = 0 \quad z \geqslant 0 \\ C_3 = C_{3D}(x_d) & t > 0 \quad z = z_{DEP} - h(x_d, t) \end{cases}$$

2
$$\left\{ \begin{matrix} W_1(t) = q_D C_{1D} \\ W_2(t) = q_D C_{2D} \\ W_3(t) = q_D C_{3D} \end{matrix} \right\} \quad t \geqslant 0 \quad z = z_{DEP} - h(x_d, t)$$

3 - 1
$$\begin{cases} \theta \dfrac{\partial C_1}{\partial t} + 10 \cdot \rho \cdot \dfrac{\partial S_1}{\partial t} = \dfrac{\partial}{\partial x}\left(D_{sh}(u) \dfrac{\partial C_1}{\partial x}\right) - q \dfrac{\partial C_1}{\partial x} - K_2(\theta C_1 + 10 \cdot \rho \cdot S_1) + K_1 \theta C_N + W_1(t) \\ \dfrac{\partial S_1}{\partial C_1} = \dfrac{b}{\sqrt{C_1}}(S_{1m} - S_1) \\ S_1 = 0 \quad C_1 = 0 \\ C_1 = C_1^0(x) & t = 0 \quad x \geqslant 0 \\ - D_{sh}(u) \dfrac{\partial C_1}{\partial x} + qC_1 = q_0 C_{1h_0} & x = 0 \quad t > 0 \\ C_1 = C_1^0 & t \geqslant 0 \quad x \to \infty \end{cases}$$

3 - 2
$$\begin{cases} n \dfrac{\partial C_2}{\partial t} = \dfrac{\partial}{\partial x}\left(D_{sh}(u) \dfrac{\partial C_2}{\partial x}\right) - q \dfrac{\partial C_2}{\partial x} + K_2(\theta C_1 + 10 \cdot \rho \cdot S_1) \dfrac{46}{18} - K_3 \theta C_2 + W_2(t) \\ - D_{sh}(u) \dfrac{\partial C_2}{\partial x} + qC_2 = q_0 C_{2h_0} & x = 0 \quad t \geqslant 0 \\ C_2 = C_2^0(x) & t = 0 \quad x \geqslant 0 \\ C_2 = C_2^0 & t > 0 \quad x \to \infty \end{cases}$$

$$
3-3\begin{cases} n\dfrac{\partial C_3}{\partial t} = \dfrac{\partial}{\partial x}\left(D_{sh}(u)\dfrac{\partial C_3}{\partial x}\right) - q\dfrac{\partial C_3}{\partial x} + K_3(\theta C_2\dfrac{62}{46} - K_4\theta C_3 + W_3(t) & \\ -D_{sh}(u)\dfrac{\partial C_3}{\partial x} + qC_3 = q_0 C_{3h_0} & x=0 \quad t\geqslant 0 \\ C_3 = C_3^0(x) & t=0 \quad x\geqslant 0 \\ C_3 = C_3^0 & t>0 \quad x\to\infty \end{cases} \qquad \text{(Model 2)}
$$

$$
\begin{cases} \begin{cases} \theta\dfrac{\partial C_4}{\partial t} = \dfrac{\partial}{\partial z}\left(D_{sh}(\theta)\dfrac{\partial C_4}{\partial z}\right) - q\dfrac{\partial C_4}{\partial z} & \\ -D_{sh}(\theta)\dfrac{\partial C_4}{\partial z} + qC_4 = R(t)C_{4R}(t) & z=0 \quad t\geqslant 0 \\ C_4 = C_4^0(z) & t=0 \quad z\geqslant 0 \\ C_4 = C_{4D}(x_d) & t>0 \quad z = z_{DEP} - h(x_d,t) \end{cases} \\ W_4(t) = q_D C_{4D} \qquad t\geqslant 0 \\ \begin{cases} n\dfrac{\partial C_4}{\partial t} = \dfrac{\partial}{\partial x}\left(D_{sh}(u)\dfrac{\partial C_4}{\partial x}\right) - q\dfrac{\partial C_4}{\partial x} + W_4(t) & \\ -D_{sh}(u)\dfrac{\partial C_4}{\partial x} + qC_4 = q_0 C_{4h_0} & x=0 \quad t\geqslant 0 \\ C_4 = C_4^0(x) & t=0 \quad x\geqslant 0 \\ C_4 = C_4^0 & t>0 \quad x\to\infty \end{cases} \end{cases} \qquad \text{(Model 3)}
$$

Variables: t is the time(d); x is the horizontal distance(m); z is the vertical distance(m); h is the saturated thickness(m); C_1 is the concentration of ammonium in soil and groundwater(mg/L); C_2 is the concentration of nitrite in soil and groundwater(mg/L); C_3 is the concentration of nitrate in soil and groundwater(mg/L); C_N is the concentration of organic nitrogen in soil and groundwater (mg/L); C_4 is the concentration of Cl^- in soil and groundwater(mg/L); S_1 is the adsorption amount of ammonium (mg/100g soil).

Parameters: K_1 is the mineralization rate constant(1/d); K_2 is the $NH_4^+ \rightarrow NO_2^-$ rate(1/d); K_3 is the $NO_2^- \rightarrow NO_3^-$ rate(1/d); K_4 is the denitrification rate(1/d); u is the flow velocity of groundwater; θ is the water content in soil; $W_1(t)$ is the ammonium flux out of the unsaturated zone(cm/d); $W_2(t)$ is the nitrite flux out of the unsaturated zone(cm/d); $W_3(t)$ is the nitrate flux out of the unsaturated zone (cm/d); $W_4(t)$ is the Cl^- flux out of the unsaturated zone(cm/d); $D_{sh}(\theta)$ is the coefficient of dispersion in unsaturated zone(cm^2/d); $D_{sh}(u)$ is the coefficient of dispersion in saturated zone (cm^2/d); S_{1m} is the maximum equilibrium sorption capacity of ammonium(mg/100g soil); $R(t)$ is the landfill leachate rate(cm/d); n is the soil porosity; ρ is the dry bulk density(g/cm^3); q is the water flux between the unsaturated and saturated zones(cm/d); z_{DEP} is the datum level of saturated zone's water head(m); x_d is the horizontal distance of the point sources(m).

2.3 Laboratory simulation experiments and the determination of model parameters

Laboratory experiments were conducted in the State Key Laboratory of Environmental Simulation and Pollution Control at Beijing Normal University to determine values for several important parameters in the model. The experimental apparatus was 300 cm high, 400 cm long, and 120 cm wide and was composed of two parts. One part, a cylindrical soil column with a height of 200 cm and a diameter of 120 cm, was used to simulate nitrogen movement and transformation in the unsaturated zone. The second part, placed under the cylindrical column, had a 400 cm × 120 cm surface and a depth of 100 cm; it was used to simulate the movement and transformation of pollutants in groundwater. A sketch of the laboratory apparatus is shown in Fig.3. The device was filled with a mixture of gray sub-clay and light sub-clay soils from the landfill site. The density of the clays was 1.4 g/cm^3.

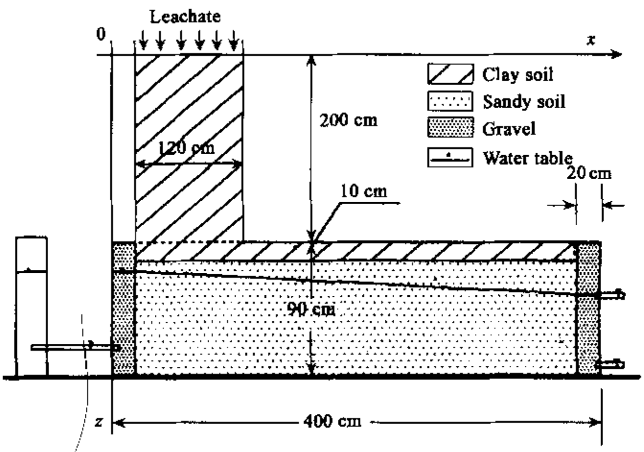

Fig.3 Schematic diagram of laboratory simulation experiment

Soil from the landfill surroundings and leachate from the landfill were used in the laboratory experiments. Monitoring information concerning soil capillary potential, water content in the soil, water table, and the concentrations of ammonium, nitrite, and nitrate in the saturated and unsaturated zones was taken into account when designing the experiments. In addition, the experiments included a series of tests on the chemical kinetics of nitrogen and hydrodynamics. Tests dealing with the reaction kinetics of mineralization, nitrification, and denitrification were also performed.

The percolation water containing NH_4^+ and Cl^- at concentrations of 250 mg/L and 1200 mg/L, respectively, was prepared from landfill leachate, solid NH_4Cl, and supplied water. The liquid was applied to the surface of the laboratory device with a given water head. Two days were required to supply 135.2 mm of water. With a zero-flux boundary, the capillary potential of the soil was monitored with a tensiometer, and the water content and the concentrations of the pollutants were monitored periodically. Then, the conductivity of the unsaturated soil, $K(\theta)$, the diffusivity of the unsaturated soil, $D(\theta)$, and the dispersion coefficient of the unsaturated zone, $D_{sh}(\theta)$ were calculated based on data from the test.

Other experiments were also conducted, including tests on the sorption of ammonium on colloids, the transformations of $NH_4^+ \rightarrow NO_2^-$ and $NO_2^- \rightarrow NO_3^-$, and the denitrification of NO_3^-. Based on the data from these experiments, the authors determined that a coefficient needed in the adsorption equation was 0.0238, the constant rate of nitrification in the first stage, k_2, was 0.0531/d, the constant rate of nitrification in the second stage, k_3, was 0.4061/d, and the constant rate of denitrification was 0.00215/d. Moreover, the parameters associated with the saturated zone were chosen according to investigations at the landfill site, and the sea and river level values used in the composite model were average elevations above sea level taken over 40 years. The leachate generation, the pollutant concentrations, and the decomposition factor were determined according to conditions in the area of the landfill. The values for other parameters and several relationships involving key variables used in the model are listed in Table 1.

Table 1 Equations and parameters for the composite model

Parameters	Variable	Value or formula	Unit	Data source
Water supply rate	u	0.1526		Report of investigation*
Saturated hydraulic conductivity	K_s	0.22	m/d	Assess report of landfill**
Unsaturated perpendicular hydraulic conductivity	$K(\theta)$	$K(\theta) = 0.0010248e^{22.359\theta}$	cm/d	Laboratory test
Bulk density	ρ	Unsaturated zone 1.401 Saturated zone 1.390	g/cm^3	Assess report of landfill
Unsaturated diffusivity	$D(\theta)$	$D(\theta) = 4.682775e^{20.528\theta}$	cm^2/d	Laboratory test
Unsaturated dispersion coefficient	$D_{sh}(\theta)$	$D_{sh}(\theta) = 6.88946\theta^{0.18}$	cm^2/d	Laboratory test
Saturated dispersion coefficient	$D_{sh}(u)$	$D_{sh}(u) = 6.88 + 8.142u$	cm^2/d	Empirical equation
Speed constant of mineralization	K_1	0.0051	1/d	Zhu, 1992
Speed constant in the first stage of nitrification	K_2	0.0531	1/d	Laboratory test
Speed constant in the second stage of nitrification	K_3	0.4061	1/d	Laboratory test
Speed constant in denitrification	K_4	0.00215	1/d	Laboratory test
Adsorption amount	S	$S = S_m(1 - e^{-2\times0.0238\times sqrt(c)})$	mg/100g soil	Laboratory test
The maximum sorption capacity	S_m	71.4	mg/100g soil	Laboratory test

* Report on the geologic condition of Laogang landfill, Shanghai City, 321 Group, Chinese Ministry of Geology and Minerals

** Environmental impact assessment of Laogang landfill, Shanghai Institute of Environmental Science

3 Simulation analysis of the environmental impact from landfill leachate

The simulation analysis was based on two distinct periods: the landfill operation period and the 20-year period following the cessation of landfill operations.

3.1 The landfill operation period

The landfill was designed to operate for a period of nine years; hence, for simulation purposes, it was assumed that the duration of the dumping period was 10 years. Using the values for the parameters as described in the previous section, the resulting partial differential equations were solved numerically. The results obtained from the calculations revealed that the total discharge of leachate to the ocean over the 10-year period was estimated at 900700 m^3, while the amount to the Suitang River over the same period was estimated to be 683000 m^3. The distance over which the leachate would be dispersed in the saturated zone over the 10-year period is 1100 m. That is, the average rate of dispersion of the polluted leachate through the saturated zone was estimated to be 110 m annually. Table 2 lists the wastewater discharges to different components of the soil-water environment.

Table 2 Wastewater discharge during Laogang landfill operation

Year	Residual water in unsaturated zone, m^3/a	Discharge to aquifer, m^3/a	Recharge to phreatic water, m^3/a	Discharge to East Sea, m^3/a
1	116810.00	275390.00	233700.00	18465.31
2	87195.00	305005.00	219586.11	42253.04
3	86994.00	305206.00	188853.00	61316.80
4	86825.00	305375.00	164473.68	77117.58
5	87202.00	304998.00	144378.86	90279.62
6	87226.00	304974.00	123069.41	104091.37
7	86868.00	305332.00	109623.13	113514.77
8	87064.00	305136.00	95676.03	122837.53
9	87043.00	305157.00	84688.65	130987.79
10	86841.00	305359.00	73057.48	139909.84
Total	900068.00	3021932.00	1438106.41	900773.65

From the results of the simulation, it was determined that most of the original pollutants in the leachate do not directly pollute the groundwater. Secondary pollutants cause the pollution of the groundwater. For example, ammonium as a pollutant exists only within a layer extending only 80 cm below the surface. After its transformation into nitrate, it begins to pollute the groundwater because nitrate is easily transported in the soil.

The amounts of the main pollutants discharged to the various environmental components are listed in Table 3. From this table we can see that organic N was transformed into ammonium and nitrate, which caused groundwater pollution. Fig.4 displays the distribution profile of NH_4^+ in the unsaturated zone at different times. From this figure it can be seen that most of the NH_4^+ stayed in positions at a depth of less than one meter and, therefore, as noted above it polluted the groundwater when it was transformed into NO_3^-. Furthermore, NO_3^- heavily polluted the groundwater and its migration speed was faster than any other ions except Cl^-. From Fig.5, it is obvious that the NO_3^- and Cl^- concentrations near the landfill increase over time. Obviously, therefore, depositing refuse in the landfill brings about a serious environmental impact. The key problem is to find ways to keep the pollution at the minimum extent possible. Monitoring BOD and COD alone cannot determine whether groundwater is polluted because some organic compounds can change into more dangerous compounds. For example, NO_2^- is far more poisonous than NH_4^+ or organic N. Accordingly, to effectively prevent

Table 3 Discharge of pollutants during Laogang landfill operation stage

Pollutants	Quantity in leachate, ton	Discharge to ground water, ton	Discharge to East-Sea, ton	Residue in phreatic water, ton
Organic N	961.243	58.565	8.3210	8.5710
NH_4^+	1201.583	4.291	0.0162	1.4732
NO_2^-	15.688	8.461	0.4504	0.7191
NO_3^-	120.710	423.079	90.0776	302.0023
Cl^-	8985.302	5348.820	1801.547	2659.3050

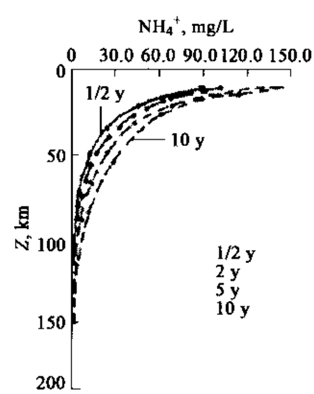

Fig.4 Distribution profile of NH_4^+ concentration in the unsaturated zone

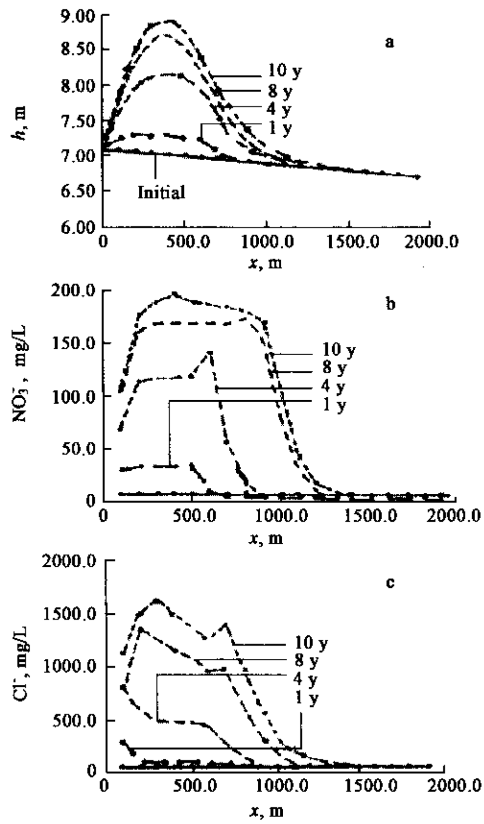

Fig.5 Distribution profile of water table and NO_3^- and Cl^- concentrations

groundwater pollution, not only the quantity, but also the inter-transformation between pollutants must be taken into account.

3.2 The period following landfill closure

Although the concentrations of pollutants in leachate are reduced exponentially after the landfill is closed, the environmental impacts continue to be severe and last a long time. To analyze the continuing impacts on groundwater, we conducted a simulation of the 20-year period following the landfill closure. From Table 4 and Fig.6 it can be observed that during this 20-year period the scale and degree of pollution of groundwater becomes larger and more severe, even though the input quantities of pollutants decrease gradually. As a result, when assessing pollution caused by solid waste deposited in landfills, consideration should not be given exclusively to the operational period.

The chemical transformations are expected to be active for a long time after the landfill operational period ceases. For example, most organic compounds will be transformed into inorganic compounds that are more likely to migrate and cause further pollution to the environment. Our simulation study shows that most of the organic compounds degrade in the unsaturated zone. However, since the thin unsaturated zone at the Laogang landfill site was exposed to pollutants over a long period of time, its self-cleaning capacity almost reached its upper limit. As a result, some of the organic pollutants entered the groundwater directly, were transformed there, and then were dispersed in the aquifers by following groundwater flows. From Fig.6, it is clear that NH_4^+ pollutes the groundwater more and more heavily as time goes on; a similar observation holds for NO_3^- and Cl^-. The plumes containing these pollutants increase their distance by 90 to 100 meters each year. This enlargement will extend to a distance of approximately 2800 meters from the landfill during the 30-year period following the inception of the landfill operation. In short, the concentrations of pollutants are expected to increase rather than decrease after the landfill closure, and the impact of the pollutants on the surrounding soil-water environment will last for a long time.

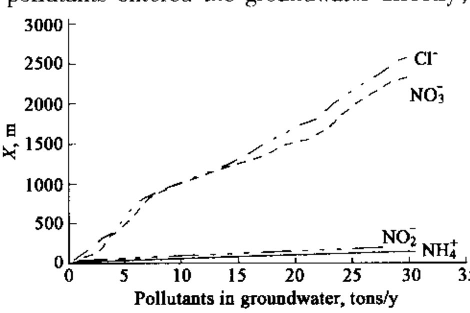

Fig.6 Process curves of pollutant transport in the water table(X denotes the horizontal distance from landfill)

Table 4 Discharge of pollutants during the 20-year period following Laogang landfill closure

Pollutants	Quantity in leachate, ton	Discharge to ground water, ton	Discharge to East Sea, ton	Resident in phreatic water, ton
Quantity of water	7844000.00	6099960.00	3394694.475	795241.84
Organic N	498.172	48.767	12.1125	13.8735
NH_4^+	884.097	62.8296	2.0368	12.8829
NO_2^-	31.376	42.0897	10.1841	26.4338
NO_3^-	88.402	884.4942	577.0981	3320.9299
Cl^-	9381.5	12017.984	2478.1270	4688.3948

4 Conclusions

In order to analyze the migration and transformation of pollutants in saturated and unsaturated zones surrounding a landfill, and to understand the types of landfill designs that are needed to minimize groundwater pollution, a laboratory experiment was conducted on leachate and a dynamic model for a soil-water system constructed and described. The composite model includes nine sub-models of water movement and analyzes the migration and transformation of five types of pollutants (organic N, NH_4^+, NO_2^-, NO_3^-, and Cl^-) in saturated and unsaturated zones. Geochemical kinetics, soil-water dynamics, salt dynamics, ion adsorption theory, reaction kinetics, and diffusion theory were used to set up the partial differential equations describing reversible ion exchange, nitrogen ionic adsorption and irreversible microbiological transformation and migration by mass flow and diffusion.

An application of the composite model to simulate the movement and transformation of pollutants from a landfill in Laogang Town, Shanghai City, demonstrated that the model is efficacious. The modeling results provided important and significant information about the nature and intensity of the pollutants and the distance of pollutant migration during both the 10-year period when the landfill was in operation and the 20-year period following its closure. The model results revealed that the landfill wastewater intruded into the groundwater at a rate of about 90 to 100 meters per year.

An important purpose in developing the model was to design a tool that can be used to study leachate migration and transformation problems associated with future landfills in China. With the aid of this model, environmental management issues related to landfill design and operation can be addressed and facilitated. For example, "build or no build" decisions, selection of appropriate sites, scheduling of landfill operation plans, and the selection of pollution prevention measures can all be informed by simulation results derived from this model. In China, it is important to give more careful attention to environmental management issues associated with landfills because soil and water pollution problems are very serious throughout the country. Our study shows that insights regarding chemical transformations and hydrodynamic processes are very important in understanding the causes and effects of groundwater pollution.

Acknowledgements: The authors are deeply grateful for the help of Professor Robert B. Wenger from the University of Wisconsin-Green Bay. He made many valuable suggestions and provided several modifications leading to significant improvements in the manuscript.

References:

Ardakani M S, 1974. A kinetic study of ammonium and nitrite oxidation in a soil field plot[J]. Soil Science Society of America Proceedings, 38: 237—277.

Barber S A, 1984. Soil nutrient bioavailability—a mechanistic approach[M]. New York, US: John Wiley & Sons.

Bear J, 1991. Modeling the contamination of the unsaturated zone by heavy metals originating in a landfill[C]. In: Proceedings of the international conference on modeling groundwater flow and pollution, Nanjing, China. 229—310.

Bezdicek D F, 1974. Influence of organic nitrogen on soil nitrogen, nodulation, nitrogen fixation and yield of soybeans[J]. Soil Science Society of America Proceedings, 38: 268—272.

Burton S A, 1998. Ammonia and nitrogen fluxes in landfill sites: Applicability to sustainable landfilling[J]. Waste Management and Research, 16(1): 41—53.

Forth J R, 1981. Modeling nitrate transport in a regional groundwater system in South Australia[C]. In: Proceedings of the groundwater pollution conference. Australian Government Publishing Service. 101—118.

Groot J J R, Willigen, Verberne E L J, 1991. Nitrogen turnover in the soil-crop system[M]. The Netherlands: Kluver Academic Publishers.

Lafolie F, Bruckler L, Tardieu F, 1991. Modeling root water potential and soil-root water transport[J]. Soil Science Society of America Journal, 55: 1203—1219.

Nye P H, Tinker P B, 1977. Solute movement in the soil-root system[M]. Oxford: Blackwell Scientific Publications.

Peter J, 1988. Combined ion exchange/biological denitrification for nitrate removal from groundwater[J]. Water Science Technology, 22(6): 679—684.

Sear L, Coleman M, Brown M, 2000. Nitrification and denitrification of leachate at Tiscott Wood Landfill Site, Cornwall[J]. Waste Management, March: 31—33.

Starr J L, 1974. Nitrogen transformation during continuous leaching[J]. Soil Science Society of America Proceedings, 38: 283—289.

Smith E H, 1990. Comparative assessment of the chemical and adsorptive characteristics of leachates from a municipal and industrial landfill [J]. Water Air and Soil Pollution, 53 (3—4): 321—327.

Wang H Q, 1992. Modeling nitrogen transport and transformation in the unsaturated zone[C]. In: Proceedings of the international workshop on groundwater and environment. Beijing: Seismological Press.

Wang H Q, 1998. Modeling analysis of geological environment influenced by a landfill[J]. Acta Geoscienta Sinica, 19(3): 315—324.

Zhu Z, 1992. Nitrogen in soil of China[M]. Nanjing: Jiangsu Science and Technology Press.

(Received for review August 19, 2002. Accepted October 12, 2002)