ORIGINAL ARTICLE

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Experimental and numerical study of pollution process in an aquifer in relation to a garbage dump field

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Abstract The water quality of shallow aquifers that have direct relationship to human heath and ecological safety has been seriously threatened by widespread dumping of industrial solid waste, urban and rural garbage. A garbage dump field with hydrogeological, environ-geological characteristics typical of the Beijing plain was selected for investigation. A hydrogeological model was constructed and the equations used to describe pollutant transport in one-dimensional (1D) steady, uniform groundwater flow to investigate the transport/diffusion processes. In addition to the coefficients for calculation, diffusion coefficient and other coefficients of the aquifer were obtained by conducting in situ diffusion experiments and sample tests. Velocity and scope of pollutant transport/diffusion process were cal-culated. Accordingly, the real pollution situation in the aquifer was evaluated through in situ drilling and sample testing. Transport/diffusion processes of pollutants within the aquifer abide by the solute equation applicable to 1D steady flow. The transport and diffusion dominate in the direction of groundwater flowing at a speed of about 120 m per year. Comparably, the lateral diffusive width is much smaller. Pollution degree decreases by the law of $Y = 1.08 \exp(33.533/X)$, where Y is the distance from the garbage dump field and X is the overall pollution index.

Keywords Pollution process · Aquifer · Garbage dump field

Introduction

More than 440 of 668 cities in China have "garbage mountains," as of the end of the year 2002. In addition, 300-million-tons of garbage is produced each year in rural areas (State Environmental Protection Bureau, China 2002). The garbage is dumped everywhere. The rural garbage may contain fertilizer, battery, and medicine etc., which could cause more serious pollution to aquifers than urban garbage. Widespread dumping of solid waste has not only covered a large area of land and polluted soil, surface water, but has also polluted groundwater, particularly, shallow aquifers. Such aquifers supply water to plants, crops, animals, microbes and people living in suburb areas. Though often neglected as usable water sources, they have intimate relationship and exert huge influence upon human beings. Figure 1 shows the relationship between contaminants in garbage and human health parameters.

One isolated garbage dump field may appear as a local source of pollutants, but it can affect a much larger area due to transport and diffusion once pollutants enter an aquifer. What are the scope and velocity of transport/diffusion, the degree of pollution and the dynamic process within the aquifer? The answers to these questions are helpful for pollution assessment from garbage

dumps. A dump field with characteristic hydrogeological and environ-geological conditions of the Beijing plain was chosen as an experimental study site. Transport/diffusion process and scope of garbage pollutants within the aquifer were calculated, and groundwater pollution degree and scope assessed.

Regional hydrogeology and geo-environmental setting

Regional hydrogeology (Sun 1984)

The dump field is located in the Qingheying village in the northern suburb of Beijing city. The regional hydrogeology is mainly controlled by the fluviopluvial fan of the Chaobai River with apparent horizontal zonation. From northwest to southeast, lithostratigraphy changes from coarser sediments to finer ones. Aquifers evolve from single phreatic aquifer to multi-aquifers, including a phreatic aquifer and a phreatic confined aquifer where the garbage dump field lies. The uppermost phreatic aquifer is the focus of this study. Three other deeper aquifers are also present at the site.

The lithostratigraphy of the phreatic aquifer mainly consists of medium-fine sand with a thickness varying from 1.2 m to 6 m. Although the aquifer cannot be used as a large-scale water-supply due to its small water storage, it is of great importance to the local eco-system. The aquifer underlies much of the Beijing plain. It is covered with a 0–8 m thick layer of clay silt and sandy clay or clay. The aquifer is used for cultivation of corn, rice, vegetable, wheat, and other crops, as well as flowers, grass, and trees. The aquifer is the zone in which water circulates most intensely. Supply sources, runoff and drainage conditions are as follows:

The supply sources include rainfall, surface water (rivers, ditches, etc.) and flow of excess surface water from irrigation. Rainfall and river water are the dominant supply sources with an infiltration coefficient of normally over 0.4. Regional groundwater flow is from the northwest to the southeast. Drainage routes include soil evaporation, plant evaporation and discharge into lakes, ponds and man-made canals. Long-distance drainage rarely occurs.

Geo-environmental setting and the generalized hydrogeological model of the aquifer

Geo-environmental setting

The dump field is 4 years old and is a huge rectangular former sand-excavation pit with an area of about 45,000 m². It is mainly used for dumping urban garbage.

Fig. 1 The route of garbage pollutants to cause diseases of human beings
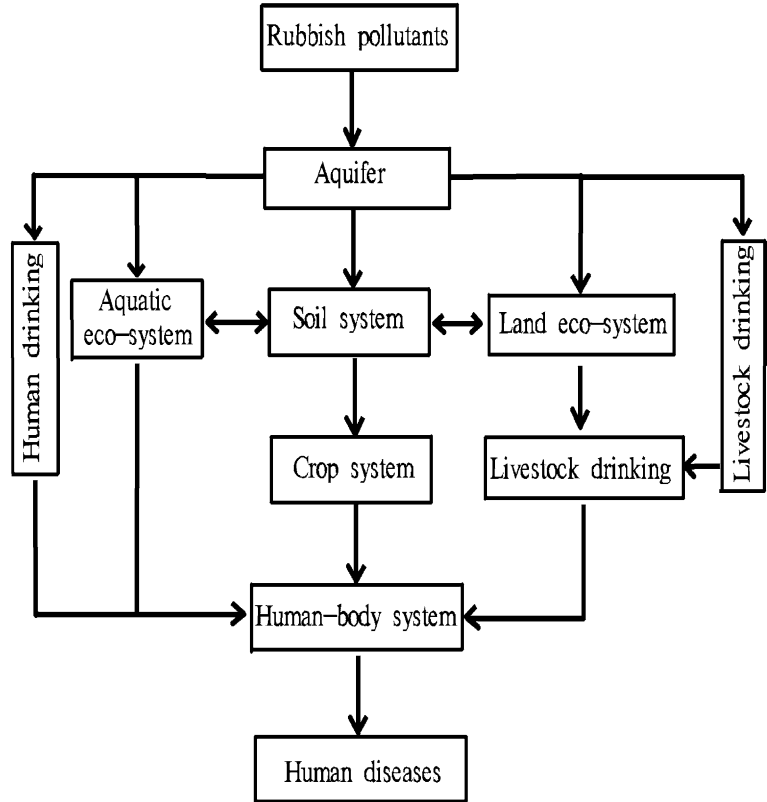
Its top horizon is higher than the water level by about 1–2 m. Dark black water within the pit is directly connected with the aquifer. There are no anti-infiltration measures implemented in the pit. This has caused groundwater pollution. To the north of the field is an artificial river less than 3 m deep, the Qinghe. Cultivated land surrounds other three sides.

Generalized hydrogeological model

To develop the hydrogeological model which serves as the basis for this study, a large data set of geological site investigation was analyzed and necessary hydrogeological drilling investigation was performed. The aquifer is 2.2 m thick, consisting of fine-medium sand. Seasonal groundwater levels vary between 0.9 m and 2.0 m. Overlying the aquifer are one 0.95-m-thick layer of clay silt and another 0.80-m-thick layer of sandy clay. It is a clayey aquifuge (Sun 1984) with 8.0 m–15.5 m of clay underlying the aquifer. The resulting model is shown in Fig. 2.

Experimental study and numerical calculation of the transport/diffusion process of pollutants in the aquifer

Calculation method and parameters

Calculation method

The aquifer is only 2.2 m thick but it extends horizontally up to several hundred square kilometers. Regional groundwater flows horizontally (Sun 1984) with a hydraulic slope of 1.143‰. The solute transport equation applicable to one-dimensional (1D) steady, uniform flow was used for calculation. The regional hydrogeological conditions are basically in agreement with the following assumptions (Javandel et al. 1984; Liu et al. 1989):

1. The aquifer is composed of uniform fine–medium sand.
2. The phreatic bed extends horizontally to infinite with constant thickness, the water flows in the direction of positive x-axis at a constant infiltration velocity v.
3. The sewage into the phreatic bed is negligible in comparison with the regional groundwater discharge.
4. The pollutant concentration of the whole aquifer is zero before the pollutants enter it.
5. Supposing that the seepage fluids originating from rainfalls are continuous, they run down through the whole aquifer and mix fast vertically.
6. Compared with the scale of the phreatic aquifer, the dump field can be considered as a spot pollution source. It continuously inputs water that has a pollutant concentration C_0 into the aquifer at a velocity Q. If the start-to-dump site of the dump field is taken as the origin and the infinite horizontal plane as the xoy plane and the groundwater flowing direction as the x-axis, the above-mentioned assumptions can be described by the following mathematical model (Javandel et al. 1984; Liu et al. 1989)

$$D_{\mathrm{L}} \frac{\partial^2 C}{\partial x^2} + D_{\mathrm{T}} \frac{\partial^2 C}{\partial y^2} - v \frac{\partial C}{\partial x} - \lambda R_{\mathrm{d}} C + \frac{m}{n} = R_{\mathrm{d}} \frac{\partial C}{\partial t} \quad (1)$$
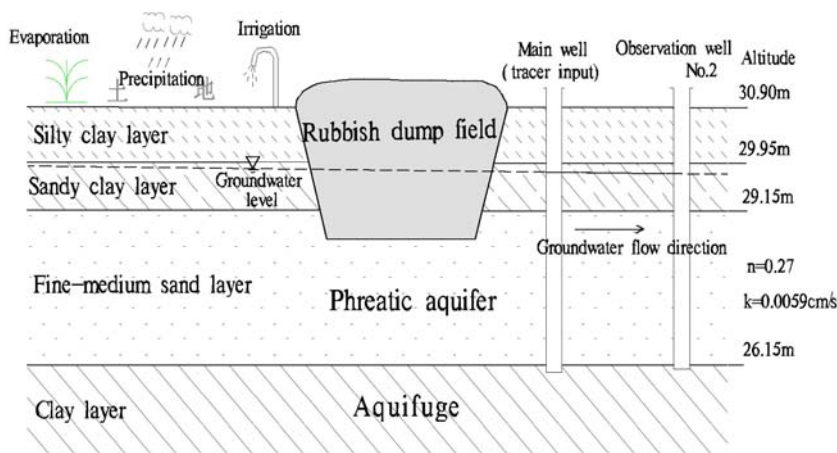
$$C(x, y, 0) = 0 \quad (2)$$

$$m(x, y, t) = Q C_0 \delta(x, y) \quad (3)$$

$$C(\pm\infty, \pm\infty, t) = 0 \quad (4)$$

$$C(x, y, t) = \frac{C_0 Q \exp\left(\frac{x}{B}\right)}{4\pi\eta_{\mathrm{e}}\sqrt{D_{\mathrm{L}} D_{\mathrm{T}}}} w(u, r/B) \quad (5)$$

where C is the pollutant concentration in the groundwater, M/L^3; D_{L} and D_{T} is the longitudinal diffusion

Fig. 2 Illustration of the generalized hydrogeological model of the aquifer

coefficient and the transverse coefficient, respectively, L^2/T; v is the real velocity of groundwater flow, L/T; λ is the attenuation coefficient of pollutants, T^{-1}; R_d is a non-dimensional inactive factor; m is the inputting velocity of pollutant mass into per volume of phreatic aquifer, M/L^3T; n is the non-dimensional effective porosity; Q is the velocity of fluid volume flowing into per thickness of phreatic aquifer, L^3/TL; C_0 is the pollutant concentration of garbage diffuses entering the aquifer, M/L^3 and $\delta(x,y)$ is the Darac variable increment function.

The analytic solution was given by Wilson and Miller (1978), that is, the $W(u, r/B)$ in (5) is a Hankel leakage well function. It was hard to find the needed values in the available Hankel leakage well in this situation. The following approximate equation has been used to calculate this function:

$$W(u, r/B) \cong \sqrt{\frac{\pi B}{2r}} \exp\left(\frac{r}{B}\right) \text{erfc}\left(-\frac{r/B - 2u}{2\sqrt{u}}\right) \quad (6)$$

where

$$B = \frac{2D_L}{v} \quad (7)$$

$$r = \sqrt{\left(x^2 + \frac{D_L}{D_T}y^2\right)\left(1 + \frac{2B\lambda R_d}{v}\right)} \quad (8)$$

$$u = \frac{r^2 R_d}{4D_L t\left(1 + \frac{2B\lambda R_d}{v}\right)} \quad (9)$$

when $0 \leq y \leq 3$, the complementary error function is

$$\text{erfc}(y) = \frac{1}{(1 + a_1 y + a_2 y^2 + \cdots + a_6 y^6)^{16}} + \varepsilon(y) \quad (10)$$

$$erfc(y) = \frac{1}{\sqrt{\pi}}/(y + 0.5/(y + 1.5/(y + 2/(y + 2.5/(y + 1))))) \quad (11)$$

where $a_1, a_2,\ldots,a_6$ are constants.

When $y > 3$ and $y < 0$, the relation equation of (10) and (11) is used for calculation:

$$\text{erfc}(y) = 1 + \text{erfc}(-y) \quad (12)$$

In Eqs. 1 and 7, the real groundwater flow velocity, v can be obtained according to the

$$v = 0.78 \frac{d}{n\alpha} \frac{1}{\Delta t} \ln\frac{c_1 - c_0}{c_2 - c_0} \quad (13)$$

concentration-attenuating values in the tracer input well: where d is the diameter of input well (m), n is effective porosity, α is the comprehensive effect factor,

generally 0.5–2.0, Δt is the time elapsed since tracer input (days), C_0 is the bench value of the concentration (mg/l), C_1 is the concentration in the input well after the tracer is input (mg/l) and C_2 is the concentration in the input well after Δt (mg/l).According to the mathematical model of instantaneous input of tracer:

$$\begin{cases} \frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} + D_T \frac{\partial^2 c}{\partial y^2} - v\frac{\partial c}{\partial x} \\ \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} nc\, dx\, dy = m \\ \lim_{x \to \pm\infty} c(x, y, t) = 0 \\ \lim_{y \to \pm\infty} c(x, y, t) = 0 \\ c(x, y, t)|_{t=0} = 0 \end{cases} \quad (14)$$

where c is the value of groundwater concentration change caused by tracer (mg/l), v is the real groundwater flow velocity (m/days), n is the effective porosity of aquifer (dimensionless function), m is the mass of tracer and D_L, D_T is the longitudinal, transverse diffusion coefficient (m^2/days), respectively.

$$c(x, y, t) = \frac{m/n}{4\pi vt\sqrt{\alpha_L \alpha_T}} \exp\left\{-\frac{(x - vt)^2}{4vt\alpha_L} - \frac{4y^2}{4vt\alpha_T}\right\} \quad (15)$$

Neglecting the molecular dispersion and supposing $D_L = a_L v$, $D_T = a_T v$, the solution of Eq. 14 is: Supposing

$$c_R = c/c_{max} \quad (16)$$

$$t_R = v_t/a_L \quad (17)$$

$$a = (x^2/a_L^2 + y^2/a_L a_T)^{1/2} \quad (18)$$

$$C_R(a, t_R) = Kt_R^{-1}exp\left\{-\left[\frac{a^2 + t_R^2}{4t_R}\right]\right\} \quad (19)$$

in (19):

$$K = t_{R\,max}\exp\left\{\frac{(a^2 + t_{R\,max}^2)}{4t_{Rmax}}\right\} \quad (20)$$

$$t_{R\,max} = (a^2 + 4)^{1/2} - 2 \quad (21)$$

where a_L, a_T is the longitudinal diffusion degree and transverse diffusion degree, respectively, c_{max} is the maximum of trace concentration.

The values of c_R varying with t_R for different values of a can be calculated by Eqs. 19, 20 and 21. This leads to the drawing of c_R-t_R curves, i.e., the standard curves.

By transforming Eq. 18, Eq. 22 is obtained:

$$a_T = y_i^2/a_L(a_i^2 - x_i^2/a_L^2) \quad (22)$$

To sum up, if at least one of the two observation wells are not in the groundwater flowing direction, the cor-

responding a values can be obtained by comparing the measured curve with the standard curve. Furthermore, a_T and a_L can be calculated using Eq. 22.

Calculation parameters

Various hydrogeological parameters are needed to calculate the transport/diffusion velocity, degree and range of pollutants in groundwater. Some of these parameters are taken from previous work (Sun 1984). Others are acquired through geotechnical tests and water-drawing experiments or experiential equations. But the diffusion parameter is obtained through in situ diffusion experimentation (Table 1).

In Table 1, garbage diffusion quantity q, and the velocity of fluid volume flowing into per thickness of phreatic aquifer, Q is calculated according to Eqs. 23 and 24, respectively

$$Q = C \times I \times A \times 10^{-3} \qquad (23)$$

In this equation, I is rainfall intensity (mm), A is precipitation area of the garbage dump field (m^2) and C is the seepage-out coefficient of 0.5. A is presumed to increase with time at the constant velocity of 41 m^2/days. I is taken as the multi-year mean rainfall intensity (The Beijing Company of Hydrogeology and Engineering Geology 1982).

$$Q = (C \times A \times G)/(T \times H) \qquad (24)$$

where A and C are defined the same as in Eq. 23, G is the cumulative rainfall intensity from the beginning to the end of calculation time, T is the calculation time (days), H is the thickness of the aquifer (m). Table 2 shows the calculated Q values.

In situ diffusion experiment and acquisition of diffusion coefficient

Important coefficients such as the longitudinal diffusion coefficient D_L, transverse diffusion coefficient D_T, the longitudinal diffusion degree a_L and the transverse diffusion coefficient a_T are acquired through diffusion experiments and subsequent calculation using Eqs. 13, 14, 15, 16, 17, 18, 19, 20, 21 and 22.

Experimental method

Allocation of main observation well (for tracer input) and observation wells

The site of the diffusion experiment is about 50 m south of the garbage field. The main observation well is 4.1 m deep. Each of the observation wells: No. 1, No. 2 and No. 3, are 4.0 m deep and located at a distance of 2.81 m, 3.66 m and 3.00 m from the main observation well, respectively (Fig. 3). Groundwater flow is to the southeast 105° (Fig. 3).

Selection and input of tracer

Since Cl$^-$ is subject to less physical absorption, chemical and biological reactions, NaCl is used as the tracer for the diffusion experiment. The experiment started on October 2, 2001 and was completed on November 11, 2001. During this period, there was no irrigation of the adjacent farmland, nor was there rainfall. When the tracer was input, water level in the main observation well was 1.04 m, and water level in the three observation wells No. 1, No. 2 and No. 3 was1.08 m, 1.16 m and 1.043 m, respectively.

In situ testing was done at fixed times for samples from fixed depth of the input well and observation wells.

Table 1 Calculation parameters

Parameter	Definition	Value	Method
D_L	Longitudinal diffusion coefficient	0.0001391	Diffusion
D_T	Transverse diffusion coefficient	0.01812	Diffusion experiment and calculation
V	Actually seepage velocity of groundwater (m/days)	0.305	Calculated
I	Precipitation (mm)	Shown in Table 2	Multi-year mean value
A	Precipitation area (m^2)	Shown in Table 2	At the speed of 41 m^2/days
C	Seepage out coefficient of leachating liquid	0.5	Measured
K	Infiltrate coefficient	0.146	Measured
D	Test well diameter (m)	0.30	Measured
C_0	*Concentration* of leachating liquid (mg/l)	174.9	Measured
N	Available aperture degree	0.27	Measured
Q	Leachating liquid volume	Shown in Table 2	Calculated using (23)
λ	Attenuation coefficient of pollutants	0	Cl$^-$ not attenuated
R_d		1	
M	Pollutants infiltrating velocity (M/L^{3}T)		Calculated using (3)
Q	Liquid infiltrating velocity (m^2/days)	Shown in Table 2	Calculated using (24)
a_L	Longitudinal diffusion degree	0.0594	Diffusion experiment and calculation
a_T	Transverse diffusion degree	0.000456	Diffusion experiment and calculation

Table 2 The quantity of diffusion into the aquifer (Q)

Time T (days)	Garbage area A (m^2)	Accumulative rainfall intensity G (mm)	Diffusate quantity Q (m^2/days)
90	3,690	16.7	0.03424
181	7,421	135	0.27675
212	8,692	318.9	0.65375
243	9,963	505.1	1.03525
273	11,193	549.3	1.126
310	12,484	572.7	1.174
334	13,694	578.8	1.186
365	14,965	581.5	1.192
730	22,930	1,160	2.384
1,095	44,895	1744.5	3.576
1,460	59,860	2,326	4.728

Accurate data from No. 2 and No. 3 wells were acquired and processed. The resulting curves for the diffusion experiment are shown in Fig. 4.

Acquisition of diffusion coefficients

The diffusion coefficients acquired from the in situ diffusion experiments mainly include D_L, D_T and v. After calculation using relevant equations, the a_L (longitudinal diffusion degree) and a_T (transverse diffusion degree) for the Qingheying experimental site is 0.0594 and 0.000456, respectively.

Calculation result of the transport/diffusion of pollutants in groundwater

Using the coefficients from the above-described calculations (Table 1) and Eq. 5, 2D Cl$^-$ transport/diffusion scope in groundwater during 1-, 2-, 3- and 4-year period of time were calculated (Fig. 5). The ratios of the diffusive zone to the convective zone in the groundwater flow direction are presented in Table 3.

The real pollution degree and scope of the aquifer by the dump field

Table 3 and Fig. 5 show transport velocity of Cl$^-$ ion in the groundwater. Cl$^-$ is the pollutant that transports and spreads fastest in groundwater, whereas the other pollutants considered move a shorter distance at a slower speed. Values were established through field investigation.

Evaluation method

Since the major pollutants in the garbage diffusion in the Beijing area are Cl$^-$, TDS, COD$_{er}$, NO$_3^-$, NO$_2^-$ and NH$_4^+$, these were chosen as the evaluation factors. Because it is
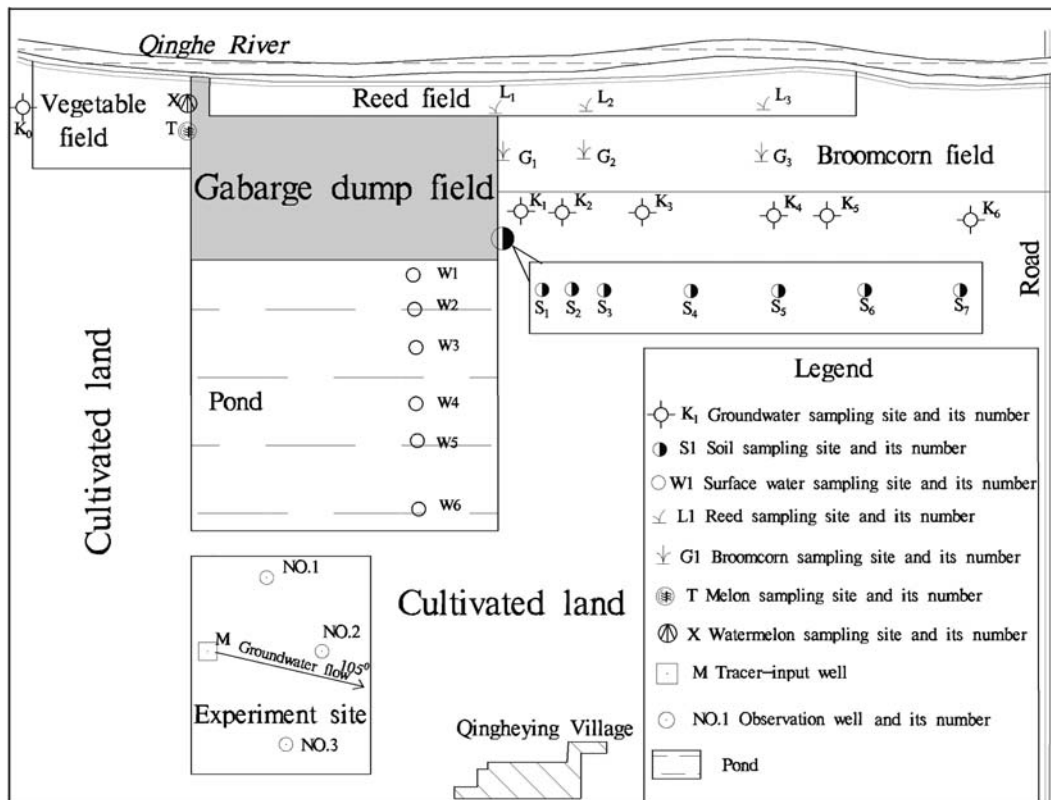

Fig. 3 Map showing the diffusion experiment site and sampling places
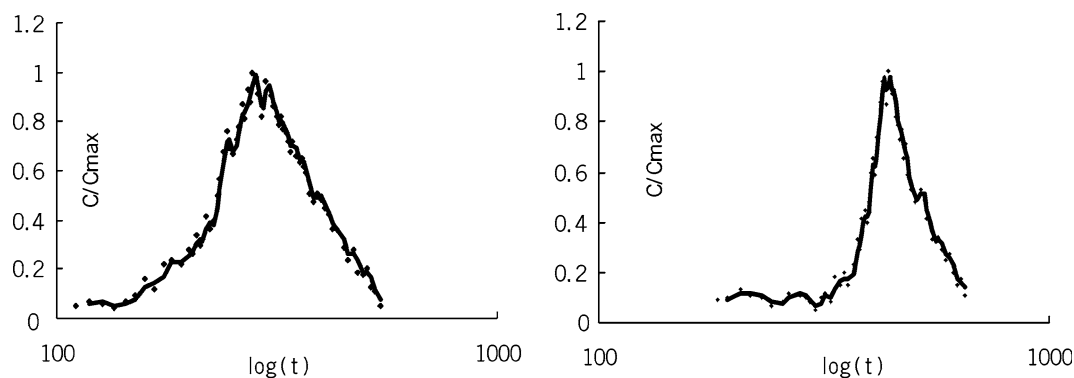
Fig. 4 Fitting curves resulting from the diffusion experiment

difficult to obtain background values, concentration values (reference values) in the upper-reach groundwater down-gradient the dump field were used as evaluation standards. Single-factor pollution index and multi-factor overall index (Liu et al. 1989) were used for calculations.

The pollution degree and affected area of the aquifer by the garbage dump field

Upper-reach groundwater samples 120 m up-gradient from the garbage dump field were used as reference samples. Lower-reach groundwater samples were taken from sampling sites 15, 50, 120, 250, 300 and 420 m distant from the dump field. Pollutants in each sample were tested six times by means of the techniques and methods prescribed by the *State Water Quality Standard*. The results were then averaged as the values for evaluation (Table 4). The single-factor pollution index for each pollutant is shown in Table 5.

Interpretation of results obtained through numerical calculations and field investigations

Interpretation of calculated result

Figure 5 and Table 3 show that the pollution halo mainly distributes along the groundwater flow and exists only as diffusive zones in the direction perpendicular to the groundwater flow. In the groundwater flow direction, pollutants could transport and spread up to 123.96 m, 200.92 m, 338.67 m and 479.86 m from the dump during the first, second, third and fourth year, respectively. In contrast, the diffusive zones are 3.78 m, 4.11 m, 4.14 m and 4.22 m during the respective time period (Fig. 5). If further away from the pollution source, the ratio of the transverse diffusive zone to the convective zone that parallels to groundwater flow becomes smaller and smaller (Table 3). This ratio is 3.05% in the first year and only 0.85% in the fourth year. As time increases, the width of the diffusive zone becomes negligible. The transport distance of pollutants in the groundwater flow direction could be estimated by distance transported purely by the convective flow.

Maximum pollution ranges

Experiment and calculation results show that the maximum longitudinal transport distance of pollutants in the aquifer was 479.86 m at the end of the fourth year. The maximum transverse diffusive width was only 4.22 m.

Attenuation of pollutant concentrations in the aquifer with distance

As seen from Table 4, Cl⁻, TDS, COD, NO_3^-, NO_2^- and NH_4^+ within the first 50−m from the pollution source, all
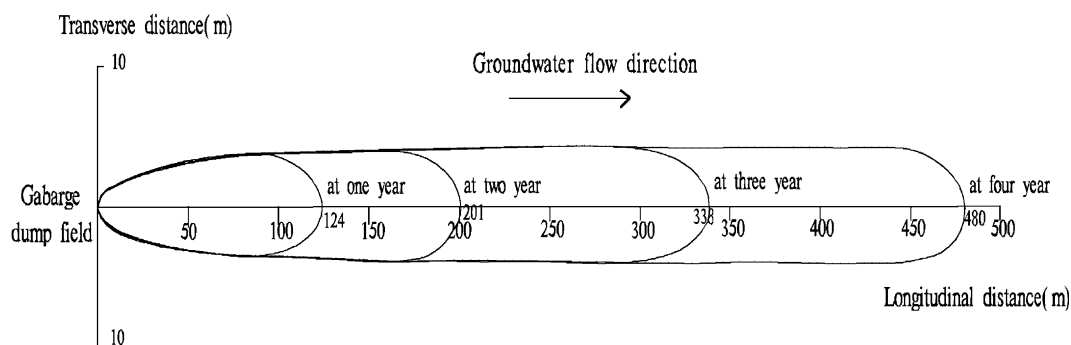

Fig. 5 The transport velocity and scope of diffusion from the garbage dump field into the aquifer

Table 3 Ratios of the diffusive zone to the convective zone in the Qingheying garbage dump field

Time (days)	Width of convective zone (CZ)	Width of longitudinal diffusive zone (LDZ)	Sum of LDZ width and CZ width	Width of transverse diffusive zone (TDZ)	Ratio of LDZ width to CZ width
90	27.45	4.79	32.24	2.71	8.41
181	57.63	5.37	63	3.07	4.87
212	68.575	5.42	73.995	3.23	4.37
243	78.9	5.44	84.34	3.33	3.95
273	89.65	5.46	95.11	3.56	3.74
310	93.43	5.47	98.9	3.71	3.75
365	118.52	5.46	123.98	3.78	3.39
730	195.3	5.62	200.92	4.11	2.046
1,095	333.06	5.61	338.67	4.04	1.191
1,465	474.3	5.56	479.86	4.22	0.852

attenuated rapidly. Except for NO_3^-, which attenuated up to 84%, all other pollutants attenuated over 94%. Outside this distance, they attenuated at a much slower speed. This suggests that pollutants can be efficiently removed within the first 50-m distance. After having traveled 420 m, all pollutants attenuated up to 95% or more.

Attenuation of pollution indices in the aquifer with distance

The single-factor pollution index of each pollutant is presented in Table 5. The table shows that within the first 15-m distance from the pollution source, most of the indices vary between 2 and 4, while that of NO_2^- exceeds 48, suggesting a higher pollution degree. Excepting for NO_2^-, the indices of other pollutants tend to one after 420-m distant. The overall pollution index attenuates with distance by the law of $Y = 1.08 \exp(33.533/X)$. It decreases from 10.21 m in the 15-m distance to 1.06 m in the 420-m distance, indicating that the 4 year pollution range of the aquifer by the garbage dump field is approximately 420 m.

Conclusions

1. The result of experimental studies and numerical calculations of pollutant transport/ diffusion distances in groundwater by the end of the 4 years is 479.86 m, while the result obtained by field investigation and assessment is 420 m, with deviation of 12.47%, indicate that the results are accurate.
2. The transport of garbage pollutants in the aquifer can be described with the solute transport equation applicable to 1D steady flow. During the 4-year utilization of the dump field, the pollutants in the aquifer traveled a maximum distance of 479.86 m at an annual velocity of about 120 m. The maximum lateral transport distance is only 4.22 m. This shows that the transverse diffusion width is very small in comparison with the longitudinal transport distance.
3. The field investigation results show that the concentrations of pollutants such as Cl⁻, TDS, COD, NO_3^-, NO_2^- and NH_4^+ predominantly attenuated with distance in groundwater flow. Pollutants attenuated very fast within the first 50 m from the pollution source;

Table 4 Concentration of garbage pollutants in the aquifer

Pollutants	Sample									
	Leachating liquid	K1	K2	Attenuation rate (%)	K3	K4	K5	K6	Attenuation rate (%)	K0 (comparison sample)
NH_4^+	18.02	0.37	0.27	98.48	0.24	0.26	0.22	0.19	98.94	0.18
NO_3^-	109.34	65.12	31	84.53	25.34	18.6	19	17.43	95.13	16.72
NO_2^-	2.36	0.78	0.07	97.71	0.04	0.032	0.03	0.024	98.98	0.019
TDS	3,610	1,720	989	95.57	89.9	88	859	868	99.65	860
COD	248.21	46.56	26.07	95.5	20.45	19	16.9	15.65	99.97	15.6
Cl⁻	716.35	173.6	141.25	94.5	135.85	132.62	124.03	116.44	98.57	107.82
Distance from the dump	0 m	15 m	50 m		120 m	250 m	300 m	420 m		120 m (Upper reach to the dump)

and they attenuated slowly outside this distance. This indicates that the pollutants could be efficiently purified within the first 50-m distance in the aquifer. Having traveled 420 m, the pollutants all attenuated up to and over 95%. The overall pollution index decreases with distance by the law of $Y = 1.08 \exp(33.533/X)$. It decreases from 10.21 5-m distant to 1.06 420-m distant, suggesting the transport distance of garbage pollutants in the groundwater had been about 420 m by the end of the fourth year.

4. The pollution index of each pollutant decreases with distance. The pollution becomes less serious as distance increases, and the pollution degree is relatively higher within the 15-m distance from the pollution source but lower outside this distance.

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