A natural-gradient field tracer test for evaluation of pollutant-transport parameters in a porous-medium aquifer

Y.S. Yang · X.Y. Lin · T. Elliot · R.M. Kalin

Abstract This paper describes a natural-gradient field tracer test to characterise solute-transport properties in a sand and gravel aquifer in the Hebei Province, northern China. Some laboratory-scale column tests on aquifer material and a local-scale field borehole-dilution test have been conducted previously, but the field test reported herein represents the only large-scale tracer test in the aquifer, which is the sole water supply to the city of Shi Jiazhuang and which is threatened by urban pollution. The aim of the study was to quantify the transport behaviour of nonreactive pollutants in this aquifer. Little quantitative data are available concerning its solute-transport properties; thus, the results of the tracer test are significant and critical for understanding pollutant transport and fate. The in-situ tracer test was carried out in the aquifer using a slug injection of the geochemically conservative, radioactive iodine tracer ^{131}I. The longitudinal (α_L) and transverse (α_T) hydrodynamic dispersivities for solute transport in the field are 1.72 and 0.0013 m, respectively. The ratio of longitudinal dispersivity α_L and the flow length at the field scale is 1:10. The ratio between α_L and α_T from the in-situ test (~1,300:1) demonstrates a dominant longitudinal dispersion in this fluvial sand and gravel aquifer. The tracer test further indicates a relatively short transit time for the aquifer (linear velocities ~13 m/d) under natural-gradient conditions.

Résumé Ce papier décrit un essai de traçage en gradient naturel sur le terrain pour caractériser les propriétés de transport de soluté d'un aquifère de sables et de graviers dans la province de Hebei, dans le nord de la Chine. Quelques essais sur colonne en laboratoire sur du matériel de l'aquifère et un essai local de dilution en forage sur le terrain ont été réalisés au préalable, mais l'expérience de terrain présentée ici est le seul essai à l'échelle régionale dans l'aquifère, qui est l'unique ressource en eau potable pour la ville de Shi Jiazhuang et qui est touché par la pollution urbaine. Le but de cette étude était la quantification du mode de transport de polluant non réactif dans cet aquifère. Peu de données quantitatives étaient disponibles sur les propriétés du transport de solutés; ainsi, les résultats de l'essai de traçage sont significatifs et délicats pour comprendre le transport et le devenir du polluant. L'essai de traçage in situ a été réalisé dans l'aquifère au moyen d'un essai d'injection d'un traceur ioduré radioactif, géochimiquement conservatif, ^{131}I. Les dispersivités hydrodynamiques longitudinale (α_L) et transversale (α_T) pour le transport de soluté sur le terrain sont respectivement 1,72 et 0,0013 m. Le rapport de la dispersivité longitudinale α_L à la longueur de l'écoulement à l'échelle du terrain est 1:10. Le rapport entre α_L et α_T de l'essai in situ (environ 1,300:1) montre une dispersion longitudinale prédominante dans les sables et les graviers de l'aquifère. L'essai de traçage indique de plus un temps de transit relativement court pour l'aquifère (vitesses linéaires de l'ordre de 13 m/j) dans des conditions de gradient naturel.

Resumen El presente artículo describe un ensayo de trazadores de campo efectuado en condiciones de gradiente natural con el fin de caracterizar las propiedades de transporte de solutos en un acuífero de arenas y gravas en la provincia de Hebei (China septentrional). Previamente, se efectuaron ensayos de laboratorio en columnas con material del acuífero y un ensayo local de campo mediante dilución natural en el sondeo. No obstante, el ensayo de campo que se detalla aquí es el único ensayo de trazadores a gran escala llevado a cabo en el acuífero, el cual representa la única fuente de abastecimiento a la ciudad de Shi Jiazhuang y está amenazado por contaminación de origen urbano. El fin del estudio era cuantificar el comportamiento de contaminantes no reactivos en el acuífero. Dado que no había suficientes datos cuantitativos sobre las propiedades de transporte de solutos, los resultados del ensayo de trazadores son una clave para comprender la evolución de los contaminantes en el acuífero. El ensayo de trazadores *in situ* fue realizado mediante un ensayo slug de ioduro radioactivo, ^{131}I, que

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es conservativo desde el punto de vista geoquímico. Las dispersividades longitudinal (α_L) y transversal (α_T) estimadas a partir de los datos de campo valen 1,72 y 0,0013 m, respectivamente. El cociente entre la dispersividad longitudinal, α_L, y la longitud de flujo a escala de campo es 1:10. El cociente entre α_L y α_T (del orden de 1.300:1) demuestra que la dispersion longitudinal domina en este aquífero aluvial formado por arenas y gravas. El ensayo de trazadores indica, además, que el tiempo de tránsito es corto bajo condiciones de gradiente natural (velocidad de unos 13 m/d).

Keywords tracer tests · contamination · groundwater hydraulics · porous medium aquifer · China

Introduction

This paper describes a tracer test conducted in the sand and gravel aquifer underlying the city of Shi Jiazhuang, Hebei Province, China. The principal aim of this study was to quantify the transport behaviour of nonreactive pollutants in the sand and gravel aquifer, which is the sole water-supply source for the city. In urban areas of developing countries with rapid growth of industry and agriculture, rapid increase of the urban population and concentrated and increased exploitation of groundwater can result in dramatic changes in the groundwater environment (Yang et al. 1999). In the Shi Jiazhuang aquifer, the water quality generally is within the range of the World Health Organization's guideline values for drinking-water quality (World Health Organization 1993); however, the aquifer is contaminated due to industrial pollution (e.g., phenols, Cr, Hg) in parts of the urban area and also due to improper management of the sewerage system (e.g., BOD, hardness) in the city region (Lin and Jiao 1989). Nevertheless, little quantitative data are available to characterise solute-transport properties of the aquifer in this study area; therefore, in-situ tracer tests become significant and critical for regional modelling of pollutant transport and fate.

Modelling of a groundwater system generally is an important tool to predict the evolution of groundwater flow and the transport/fate of solutes and contaminants in aquifers, in order to protect valuable supply sources for drinking and industrial use. A variety of mathematical models solved with various analytical and/or numerical methods has been developed by groundwater modellers to help understand and predict solute and contaminant transport in aquifers (e.g., Bear and Arnold 1993; Sun 1994; de Marsily et al. 1998). However, the accuracy of the transport modelling efforts is often limited due to lack of field data at an appropriate length scale for relevant aquifer parameters, e.g., the transport and fate of contaminants in groundwater are greatly affected by the heterogeneity of aquifer systems. It is crucial to incorporate this field-scale heterogeneity into the quantitative evaluation of physical and chemical properties that govern the transport. In-situ field tracer tests that can determine the hydrodispersive properties of solutes and groundwater velocity provide a particularly useful way to obtain field-representative parameters and data at a given scale (Jakobsen et al. 1993), thereby improving the accuracy of the transport modelling effort.

Tracer tests are widely used to investigate subsurface properties: they are often applied to explore connectivity of fractured rocks in subsurface (e.g., National Research Council 1996), and to determine solute transport properties and chemical reaction parameters, such as the distribution coefficient for mass transfer between liquid and solid phases (e.g., Pickens et al. 1981). Generally, laboratory-scale (e.g., column) tracer studies can be performed with greater confidence in their set-up and operation than field studies because of the greater control over the variable parameters (Freeze and Cherry 1979; Fetter 1993). However, uncertainty arises as to whether laboratory-scale measured parameters are representative of the field-scale reality (e.g., Gelhar et al. 1992; Koltermann and Gorelick 1996). The development and application of in-situ tracer-testing approaches in the field at an appropriate scale are then imperative.

Tracer tests generally can be carried out in aquifer systems using either natural-gradient (e.g., Garabedian et al. 1991; LeBlanc et al. 1991; Boggs et al. 1992; Hess et al. 1992) or forced-gradient (Starr et al. 1996; Pauwels et al. 1998) experiments for various purposes. This paper describes a natural-gradient, in-situ tracer test that was carried out to acquire field solute-transport data (parameters) for further modelling studies on pollutant transport and fate in the urban aquifer (Yang et al. 1999). The approach adopted was to monitor an instantaneous injection of a conservative but radioactive isotopic tracer (iodine, ^{131}I) into the aquifer in the northwestern suburb of the city. ^{131}I was chosen because it has low natural abundance and its activity can be measured sensitively such that even relatively low input concentrations can be used, thereby avoiding potential density-dependent effects on the natural-gradient flows.

The analysis of the tracer test was carried out by selection of an appropriate mathematical model to represent the conceptual model of the test, and parameter values were adjusted manually until model-computed breakthrough curves matched the observed ones using a type-curve matching approach (Fetter 1993; Sun 1994; Hyndman and Gorelick 1996).

Regional Hydrogeology

The study area is located in the centre of northern China; locations are shown in Fig. 1. The region has a semi-arid climate, with average annual values of 500 mm precipitation and 1,972 mm potential evaporation (Yang et al. 1999). The Huto River, north of the city of Shi Jiazhuang, is a major river in the study area, which overlies the axis of the Huto alluvial-diluvial fan deposits on the pediplain. Shigin Canal, an artificial leaky ditch, is near the northern part of the city but south of the field-

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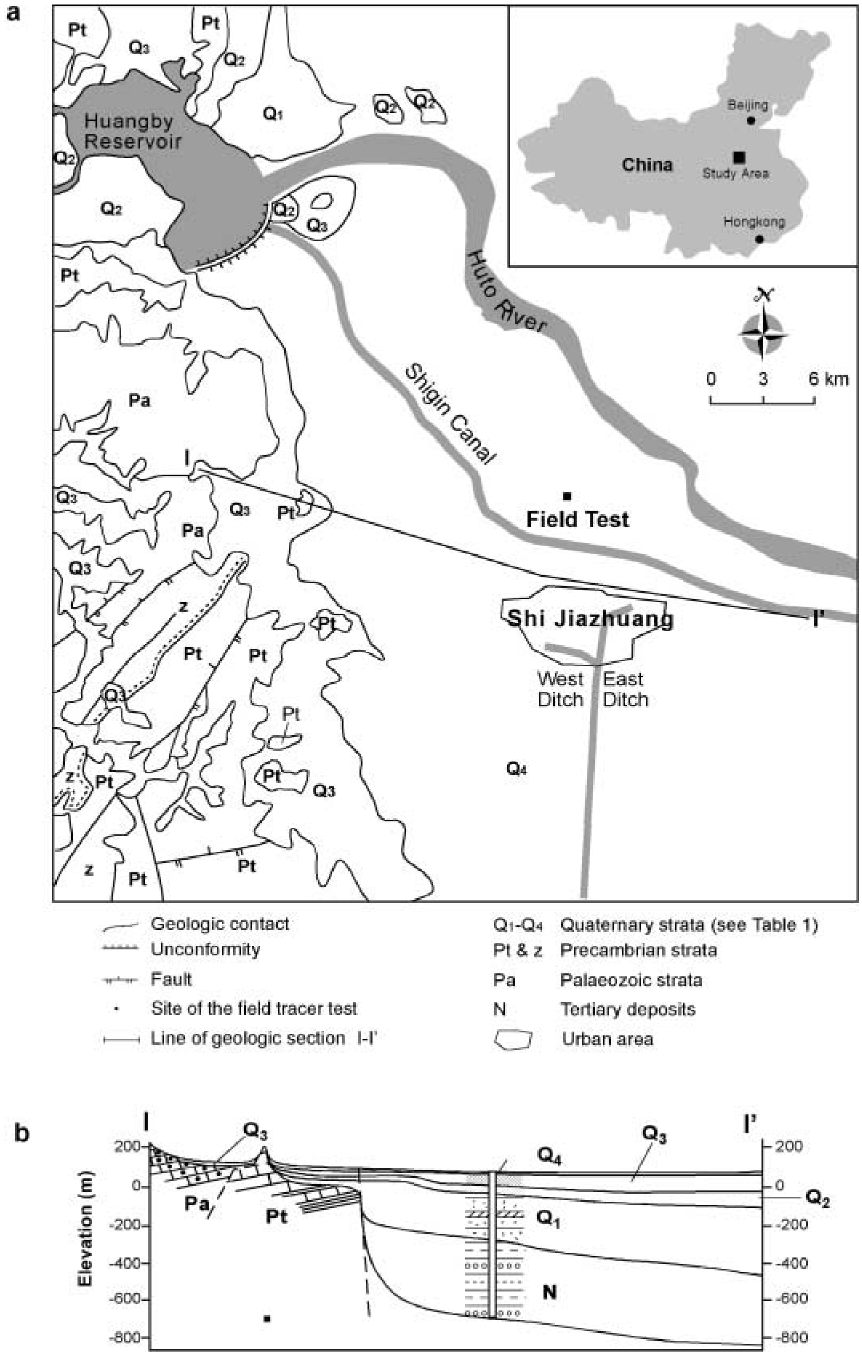

Fig. 1 **a** Regional geology and site location of the field tracer test. **b** Geological section I–I'

test area. To the west are mountains and hills comprising Precambrian and Palaeozoic strata. To the south and east, around the urban area, the aquifer is well-developed for potable and industrial water supply from Tertiary and Quaternary deposits that are as much as 800 m thick (Lin and Yang 1991).

As shown in Table 1, the phreatic aquifer comprises mainly Quaternary cobbles, gravel, sand, and laminated or lensed clay (Yang et al. 1999). The upper Pleistocene group (Q_3) is a major stratum for water supply in the area. The specific capacities are generally 22–56 $m^3\ m^{-1}\ h^{-1}$, with a maximum of 433 $m^3\ m^{-1}\ h^{-1}$. The hydraulic conductivity and specific yield are about 10–500 m/d and 0.1–0.23, respectively (Yang et al. 1999). A lower Pleistocene clay layer (Q_1) underlies the phreatic aquifer, forming a low-permeability aquitard between the aquifer and underlying Tertiary (N) deposits. The natural groundwater flow direction in the area is from northwest to southeast; however, due to heavy pumping, a cone of depression has become established since the 1970s, and flow is now diverted into the centre of the city.

Both a laboratory column test utilising aquifer material and an in-situ localised, single-borehole dilution test were carried out previously in the sand and gravel

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Table 1 Major properties of Quaternary deposits in the study area

Groups (ages)	Lithology	Distribution	Thickness	Quality	Other properties
Holocene (Q_4)	Fine sand and silt with some coarse sand, gravel and cobbles	Along and near the Huto River	Up to 10 m	Total dissolved solids 500 mg/L	Unsaturated in the study area
Upper Pleistocene (Q_3)	Boulder, cobble, gravel and sand, with some laminated or lensed silt and clay layers Major aquifer	North and northwest areas	20–70 m, single layer 20–40 m	Good quality generally,but some urban/industrial pollution	Saturated K=27.5–70.2 m/d K_{max}=703 m/d
Middle Pleistocene (Q_2)	Weathered cobbles and boulders with interbedded clay and silt layers	In the Huto River and to the south	Up to 20 m	No data available	K=2–10 m/d; K=20 m/d under city
Lower Pleistocene (Q_1)	Clay and sandy-clay with a little gravel and cobbles	No data available	No data available	No data available	No pumping-test data available

aquifer (Lin and Jiao 1989), which provided some background knowledge on the aquifer properties and the use of the ^{131}I tracer. In their flow-through 1-D laboratory column test, Lin and Jiao (1989) determined a linear-flow velocity, v, of about 0.13 cm/min for the aquifer material. A similar result (v ~0.18 cm/min; longitudinal dispersivity α_L ~0.12 cm) was obtained by two of the authors of this paper (Yang and Lin; data not shown) in a more recent column test. In this test, gravelly–sand samples of aquifer material were used that had been collected laterally from a quarry site and infilled carefully into the column to simulate field conditions for lateral flow as much as possible. In this test, the flow of conservative, dissolved Cl^- was monitored as the tracer. In the field dilution test (Lin and Jiao 1989), the tracer was diluted, and it drifted away very rapidly after injection: ^{131}I concentrations in the borehole decayed away within 30–40 min after initial injection, and 90% of the tracer mass moved into the aquifer within the first 15–20 min.

Given an estimate of the average linear velocity of the field groundwater system from laboratory tests, an initial estimate of effective porosity can be made from a point-dilution test in the aquifer. Under the conditions of natural hydraulic gradient and instantaneous tracer injection, the decay of tracer concentration injected in an isolated segment of a single well (the injection borehole) due to advective dilution by groundwater flow is (Freeze and Cherry 1979, pp. 429–430):

$$\frac{dC}{dt} = -\frac{Av^{*}C}{V} \tag{1}$$

where A is the vertical cross-sectional area of the test zone ($=2rb$) for a section of depth b and borehole radius r ($=d/2$, where d is borehole diameter); V is the volume of the test zone ($=\pi r^2 b$); and v^* is the average bulk velocity across the centre of the isolated segment, which can be related to the average linear velocity v in the aquifer (as traced by a tracer in the medium) through $v^*=vnF$, where n is the effective interconnected porosity and F is an adjustment factor accounting for the well design. Upon integration,

$$\ln\left(\frac{C}{C_o}\right) = -\frac{4vt}{\pi nFd} \tag{2}$$

where the tracer concentration C_0 is introduced instantaneously into the isolated segment and well mixed at $t=0$, and the concentration C then decays away over time. Values of F for tests in gravel or sand aquifers typically range from 0.5–4. Lin and Jiao (1989) suggest that $F=0.5$ is a reasonable value for wells in the study area. On a semi-logarithmic plot, using the observational data from the borehole dilution test, and for the laboratory-measured value of v, a value of $n=0.37$ was calculated for the sand and gravel aquifer, which is reasonable for the hydrogeological properties in the study area.

Natural-Gradient Field Tracer Test

Tracer Selection

A natural-gradient field tracer test following instantaneous injection of a nonreactive radioisotopic tracer (^{131}I) into the porous aquifer was conducted in the study area. The commonly used nonreactive tracer, dissolved Cl^-, was not used because at this site it would not be a sensitive tracer in the light of the relatively high background concentrations of Cl^- in the groundwater; sufficient input concentrations above background levels would have led to possible density-dependent flow problems that could affect the natural hydraulic gradient in the field. Based on previous successful experience and on the practical conditions of the field test, the radioactive isotopic tracer ^{131}I with $\tau_{1/2}=8.1$ d (Lide 1997) was chosen for the natural-gradient tracer test because of the following:

1. Due to its short half-life, ^{131}I can be easily and sensitively measured to low levels by gamma (γ)-counting.
2. In the absence of significant levels of organic material, ^{131}I has a behaviour that is similar to chloride (chemically conservative), and laboratory tests previously conducted by Lin and Jiao (1989) show that the radio-tracer was not sorbed by the aquifer material, which has little organic-matter content at the test site.

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3. Elemental iodine is nontoxic at low concentrations, and the half-life of the ^{131}I isotope ensures that its radioactivity decays to background levels within a relatively short period, and hence could be used safely in the aquifer.
4. The natural background concentration of the tracer is low, so that it could be easily detected over significant travel distances.
5. At the concentrations needed for input above background activity levels, no concern existed about problems of density-dependent effects on the natural hydraulic gradient.

Operation of the Test

The site of the field tracer test was selected in a suburb of the city, where the geology is representative of the regional aquifer system and the vertical profile of the strata and the groundwater flow conditions were relatively clear and simple (Fig. 1). Due to budgetary and other practical constraints, the field tracer test was designed to measure hydrodynamic dispersion in the 2-D, uniform, natural-gradient groundwater flow field using instantaneous injection of the radioisotopic tracer. Based on a hydrogeological investigation of the groundwater flow system at the test site (Yang et al. 1999), eight radially distributed boreholes were drilled; the layout is shown in Fig. 2. Borehole 1 (diameter 20 cm; screened interval 18.85–40 m below surface) was for the tracer injection, and the other seven wells were for tracer-plume observation. The boreholes are 45 m deep and fully penetrate the sand and gravel aquifer.

They were screened opposite the sand and gravel at 22–38.5 m. Boreholes 1, 3, and 5 were sunk first, and the water-table elevations were monitored to calculate the groundwater flow direction and hydraulic gradient using the three-point method (Domenico and Schwartz 1990). The remainder of the boreholes were then drilled to monitor the distribution of the tracer plume. Borehole 7 is located on the principal groundwater flow line from the injection well.

The ^{131}I tracer has a total activity of 40 mCi diluted in a 5-g/L NaI solution and was injected rapidly (within a few minutes) from special injecting packers into the sand and gravel section of the fully penetrating borehole (no. 1) at a depth of 22–24.5 m. A previous single-borehole dilution test (Lin and Jiao 1989) revealed that the I^{131} concentrations decayed away rapidly, with about 90% of the tracer mass moving into the aquifer in about 15–20 min; this is very rapid in comparison with the total duration of the natural-gradient tracer test (2–3 d). Thus, tracer-injection conditions are considered to be instantaneous for the test. The intensities of radioactivity (concentrations) of ^{131}I downgradient were monitored in the sand and gravel aquifer using gamma-counters at eight depth levels in the observation boreholes. All activities of the tracer ^{131}I were corrected for radioactive decay to the time at which the tracer test was started. The activities are reported as relative concentrations in comparison to the maximum activity (C_{max}) of tracer-labelled water observed at the detectors.

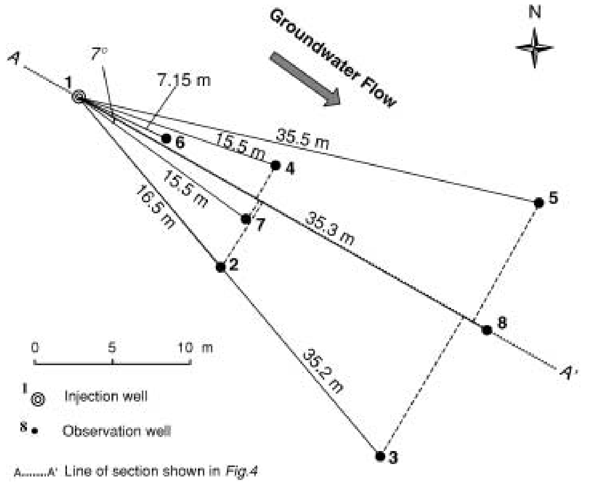

Fig. 2 Layout of boreholes in the field tracer test

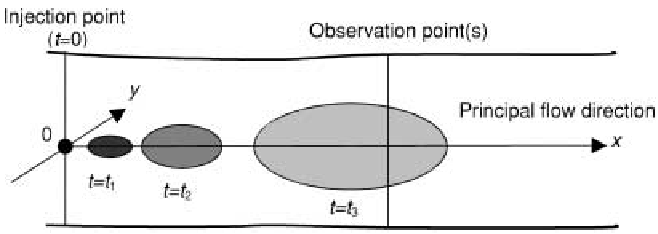

Fig. 3 Conceptual section showing the instantaneous injection and tracer dispersions in a 2-D uniform flow field

Mathematical Model

As shown in Fig. 3, the in-situ tracer test was conceptualised as representing a 2-D advection-dispersion model with instantaneous tracer injection (slug injection) in a uniform groundwater flow system. Assumptions include: (1) 2-D uniform flow is in an infinite plane with constant Darcy velocity ($v^*=nv$); (2) the tracer of mass m is instantaneously injected into the groundwater system at the starting time (t=0); and (3) the porous media of the aquifer is homogeneous and anisotropic. Because high flow velocity was encountered in the shallow sand and gravel aquifer at the site, molecular diffusion was ignored in comparison with the predominant kinematic direction. The distances between the injection well (borehole 1) and the observation wells are assumed large enough that no vertical concentration gradient occurs in the transverse dispersion.

Taking the groundwater flow direction as the x-coordinate, the injection point of the conservative tracer as the origin of the coordinate system, and the x--y plane as infinite, the governing mathematical equation of the 2-D advection-dispersion in the flow system is then (Wang and Yang 1984; Fetter 1993):

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$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 D}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - v\frac{\partial C}{\partial x} \tag{3}$$

with initial and boundary conditions:

$$\begin{cases} C(x,y,0) = 0 \qquad (x,y) \neq (0,0) \\ \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} nCdxdy = m \\ \lim_{x\to+\infty} C(x,y,t) = 0, \quad \lim_{y\to+\infty} C(x,y,t) = 0 (t > 0) \end{cases} \tag{4}$$

where D_L and D_T are the longitudinal and transverse dispersion coefficients [L^2/T], respectively; v is the linear seepage flow velocity [L/T]; and n is the effective (interconnected) porosity [–] of the aquifer. Initial-boundary conditions [Eq. (4)] are: (1) the first condition represents the background concentration of the tracer; (2) the second represents the instantaneous injection of a discrete slug allowed to drift away; and (3) the third indicates the concentrations at the locations far away from the injection.

Equation (3) may be written in the form of the dimensionless variables, x_R and y_R (Sauty 1980):

$$\frac{1}{x_R}\frac{\partial C}{\partial t_R} = \frac{\partial^2 C}{\partial x_R^2} + D_T \frac{\partial^2 C}{\partial y_R^2} - v\frac{\partial C}{\partial x_R} \tag{5}$$

where

$$x_R = \frac{vx}{D_L} \text{ or } x_R = \frac{x}{\alpha_L} \tag{6}$$

$$y_R = \frac{vy}{(D_L D_T)^{1/2}} \text{ or } y_R = \frac{y}{(\alpha_L \alpha_T)^{1/2}} \tag{7}$$

For a given borehole distance (x=X) in the direction along the principal flow direction in a 2-D field, x_R is the so-called longitudinal Péclet number (P_L). For a given borehole distance away from the principal flow line (y=Y), y_R=P_L yields the transverse Péclet number (Sauty 1980). The analytical solution to model Eq. (5) for the given initial-boundary conditions [Eq. (4)] is then (Fried and Combarnous 1971; Sauty 1980):

$$C_R(a,t_R) = \frac{K}{t_R}\exp\left(-\frac{a^2 + t_R^2}{4t_R}\right) \tag{8}$$

where C_R, t_R, and K are also dimensionless variables which can be expressed by

$$C_R = \frac{C}{C_{\max}} \text{ and } t_R = \frac{vt}{\alpha_L} \tag{9}$$

$$K = t_{R_{\max}} \exp\left(\frac{a^2 + t_{R_{\max}}^2}{4t_{R_{\max}}}\right) \tag{10}$$

where $C_{\max}$ is the maximum concentration of the tracer, and

$$a = (x_R^2 + y_R^2)^{\frac{1}{2}} = \left(\frac{x^2}{\alpha_L^2} + \frac{y^2}{\alpha_L \alpha_T}\right)^{\frac{1}{2}} \text{ and}$$

$$t_{R_{\max}} = (4 + a^2)^{\frac{1}{2}} - 2 \tag{11}$$

The variable a in Eq. (11) represents the relationships between the distance and dispersivity in the longitudinal and transverse directions, and is called the *mixed Péclet number* by Sauty (1980).

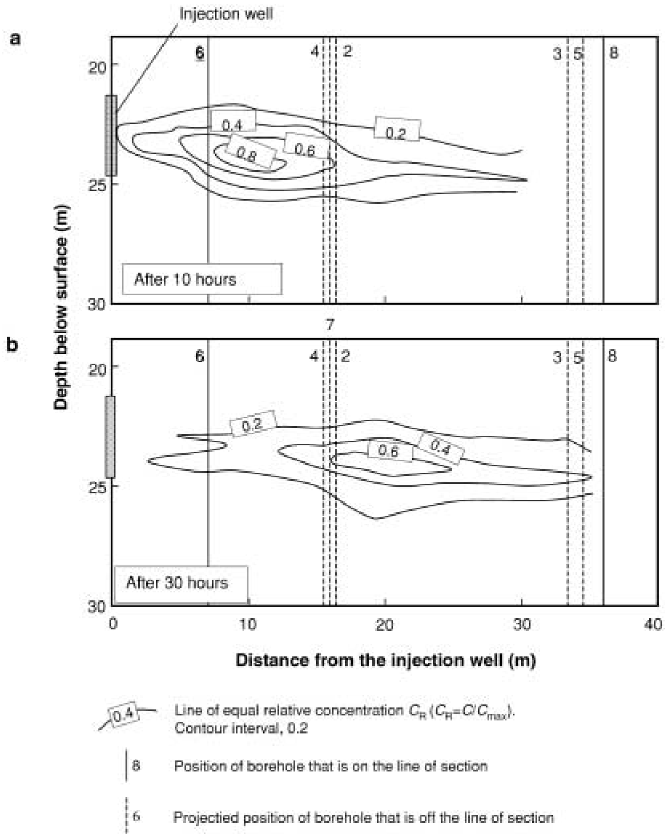

Fig. 4 Sections showing distribution of relative concentration, C_R=$C/C_{\max}$, of the actual tracer plume at **a,** 10 and **b,** 30 h after the injection. Trace of line of section is shown in Fig. 2

A set of type curves for $C_R(a, t_R)$ as a function of the logarithmic time scale t_R can be obtained from Eq. (8) corresponding to different a values (Sauty 1980). Based on the type-curves and the observation data in two observation wells along the direction of groundwater flow, the dispersivities of solute transport for 2-D advection-dispersion can be calculated from Eqs. (6) and (7).

Results and Analysis

Figure 4 shows typical profiles of the relative concentration C_R (=$C/C_{\max}$) for the tracer plume at 10 and 30 h after the tracer injection. From the movement of the tracer plume, the average velocity of solute transport is estimated to be approximately 13.2 m/d from the relative positions of the plume maxima in concentrations over the given period of monitoring.

The best-quality data from borehole 7, located in the principal flow (x–) direction from the injection well, and borehole 6 were selected to construct the breakthrough curves and calculate dispersivities. The breakthrough curves are shown in Fig. 5. The angle between the (x–) flow direction and borehole 6 is only 7°, which introduc-

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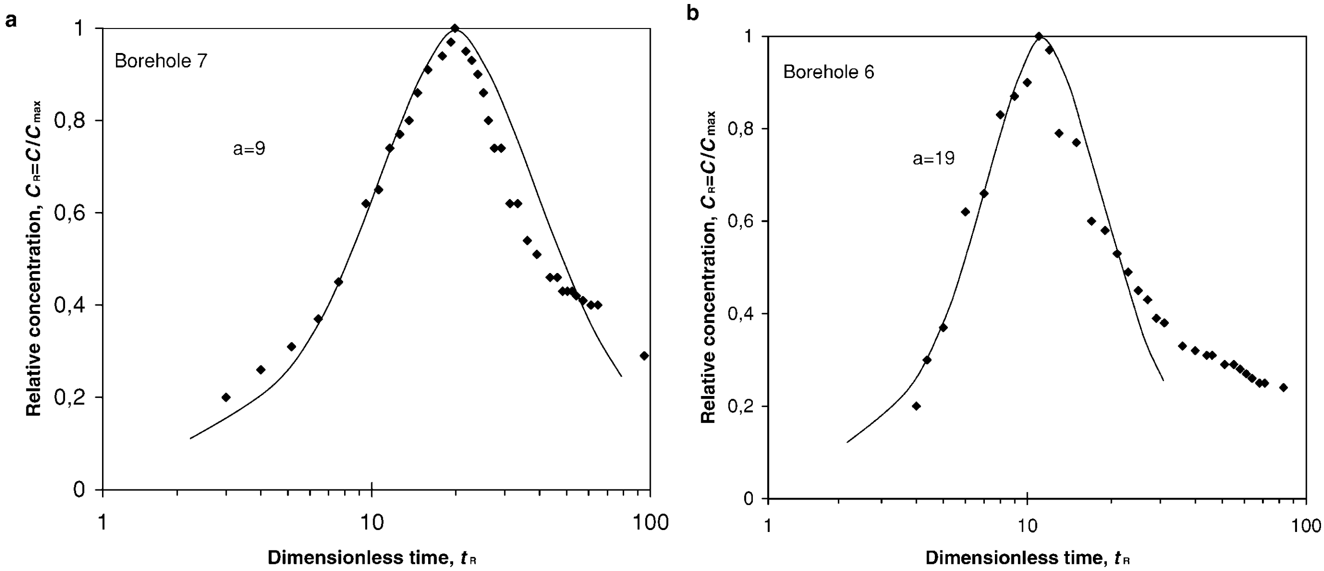

Fig. 5 Breakthrough curves and type-matching of the field test for **a,** borehole 7 at 24-m depth, located in the principal groundwater flow direction from the injection well, and **b,** borehole 6 at 24-m depth

es little error in the interpretation. Using the type-curve matching technique and the geometrical relation for these boreholes, a value for the mixed Péclet number *a*=9 was obtained from borehole 7, and *a*=19 from borehole 6, to gain the best fit between the observed breakthrough curves and the standard curves. The dispersivities (α_L, α_T) along the principal flow direction were calculated from Eqs. (6) and (7):

$$\alpha_L = \frac{x_7}{a_7}; \quad \alpha_T = \frac{y^2}{\alpha_L\left(a_6^2 - x_6^2 / \alpha_L^2\right)} \quad (12)$$

From Fig. 5,

$$\alpha_L = \frac{15.5}{9} = 1.72 \text{ m}$$

$$\alpha_T = \frac{(7.15 \times \sin 7^\circ)^2}{1.72 \times \left[19^2 - (7.15 \times \cos 7^\circ / 1.72)^2\right]} = 0.0013 \text{ m} \quad (13)$$

Discussion and Conclusions

A field tracer test was conducted under natural-gradient conditions using nonreactive ^{131}I as an analog tracer for conservative solute transport (including contaminant) behaviour at the test site for the sand and gravel aquifer. Test results provide estimates for several hydrogeological properties in the aquifer which are useful in understanding the solute transport mechanisms at the field scale for groundwater pollution/contamination. From the movement of the tracer plume, the tracer test shows that the groundwater has a relatively short residence time and relatively fast transit times for conservative solutes in the aquifer; linear velocity is ~13 m/d, which is similar to the value obtained from 1-D laboratory column tests on the aquifer material. The hydrodispersive parameters of longitudinal and transverse dispersivities were also computed from the field tracer test. The longitudinal dispersivity, α_L, was calculated as 1.72 m when the tracer front had travelled 15.5 m; transverse dispersivity was calculated as 0.0013 m. The test results suggest that the ratio of α_L and flow length at the field scale is about 1:10. The ratio between α_L and α_T is about 1,300:1 from the field test under natural-gradient conditions, which demonstrates a dominant longitudinal dispersion in this fluvial sand and gravel aquifer.

The tracer-plume observations (data not shown) also demonstrate that peak sizes decrease with distances of the sampling wells off the principal flow axis. This result is identical with the analysis of Sauty (1980) on the slug injection in 2-D uniform flow, e.g., the peak concentration is only ~5% of the value monitored along the flow axis when a monitoring well is located 20° off the flow direction from the injection well. Failure to take this difference into account would result in an error in estimation of the dispersivity of about 30%. This observation supports the notion that an understanding of the flow field and the location of observation wells are crucial in such field tracer tests.

The calculated longitudinal dispersivity and transverse dispersivity provide a quantitative measurement of these solute-transport characteristics for a nonreactive pollutant and are useful for the assessment of groundwater-quality evolution in the urban aquifer. The hydrodynamic-dispersion parameters obtained in the field tracer test provide an important first-hand evidence for hydrogeological parameter identification and were used directly in further studies of numerical modelling of regional pollutant transport and urban groundwater management in the Shi Jiazhuang sand and gravel aquifer (Yang et al. 1999).

Although the use of radioactive tracers is generally out of vogue due to health, safety, and/or environmental concerns, the present study suggests that the ^{131}I tracer provides a robust and useful field method. Most radioactive tracers (especially γ-emitters) are generally superior to other tracers because they can be detected easily in the field, and small concentrations can be used such that the natural hydraulic gradients are not disturbed (Davis et al. 1985). Use of short half-life radionuclides like ^{131}I pose little environmental threat, because their activity diminishes to background levels rapidly after the field test.

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