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Aquifer Heterogeneity and Its Influence on Solute Transport: Results from a Natural Gradient Tracer Test

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Summary A natural gradient tracer test was conducted in a 7 m by 11 m by 4 m saturated depth section of the Botany Sands aquifer, Sydney, Australia. Three hundred litres of a solution containing 100 mg/l of boron, 186 mg/l of bromide, 742 mg/l of chloride, 124 mg/l of lithium and five heavy metals - Cd, Cu, Ni, Pb and Zn at lower concentrations, was introduced into the aquifer, using three injection wells. Movement of the tracer was monitored by 49 multi-level piezometers (vertical sample point spacing 0.15 or 0.2 m) installed on a 1 m by 1 m grid, giving a total of 815 sampling points. During the 32 days following injection, 10 sampling sessions were carried out. Hydraulic conductivity estimates based on 556 falling head tests varied between 1.5 m/day to more than 50 m/day, in the three central monitoring lines of the site. These variations in hydraulic conductivity resulted in extensive spreading and splitting of the plume along the flow path. Groundwater gradients, flow direction and velocity also varied both spatially and temporally. As a result, a complex plume shape, with several zones of high tracer concentrations was observed. During the experiment, measured concentrations of tracers in solution decreased by 90% along the flow path. The experiment showed the difficulty in accurately delineating a small contaminant plume in a heterogeneous aquifer, using conventional investigation techniques and to plan, design and implement remediation schemes, based on data from such investigations.

1 INTRODUCTION

Five natural gradient tracer tests in saturated sand aquifers are discussed in the recent scientific literature (Boggs et al, 1992; Boggs and Adams, 1992; Garabedian et al, 1991; Jensen et al, 1993; Le Blanc et al, 1991; Mackay et al, 1986; Mackay, Freyberg et al, 1986). These tests provided detailed hydrogeological information on the parameters that influence the transport of solutes. This included data, which confirmed the validity of the theoretical dispersion equations. The majority of these tracer tests used bromide and/or chloride as conservative tracers. Lithium (Garabedian et al, 1991; Le Blanc et al, 1991) and a variety of organic compounds were used as reactive tracers, in some of the tests (Boggs et al, 1992; Boggs and Adams, 1992; Mackay et al, 1986). Transport of the tracers was monitored over distances between 20m and 282m, with samples collected every few weeks or months (Le Blanc et al, 1991; Moltyaner and Killey, 1988). Dispersivity and aquifer heterogeneity were identified as the major processes that affect conservative tracer transport, as they are the dominant processes that cause mixing between the tracer and the groundwater, resulting in the reduction of tracer concentrations, over long transport distances.

The aim of the small-scale tracer test described here was to investigate the effect of aquifer heterogeneity on the movement of a small plume in a fast flowing groundwater environment. From earlier studies (Evans, 1993; Lawrence, 1994) it was indicated that at a small scale, heterogeneity of the lithology and hydraulic conductivity are the dominant aquifer properties that affect tracer transport.

2 SITE DESCRIPTION

The Eastlakes Experimental (ELE) site was installed in 1992, to study the effects of dispersion, advection and sorption on the transport of conservative and reactive tracers, under natural gradient flow conditions. The ELE site is located in the central portion of the Botany Sands aquifer, which occupies the Botany Basin. A total of 3 injection and 49 multilevel samplers were installed on a 1m by 1m grid over a 7m by 11m area (Figure 1). Sampler points were spaced at vertical distances of 0.15m or 0.2m on each sampler, resulting in a total of 815 sample points at the site. Figure 2. shows the sample point locations along the central monitoring line (Line D) at the ELE site. Multilevel samplers were installed using vibrocoring (Jankowski et al, 1994), which enabled detailed resolution of the ELE site geology. The dense three-dimensional sampler network also allowed detailed study of the site hydrogeology and hydrogeochemistry (Evans, 1993; Jankowski et al, 1994; Jankowski et al, 1997).

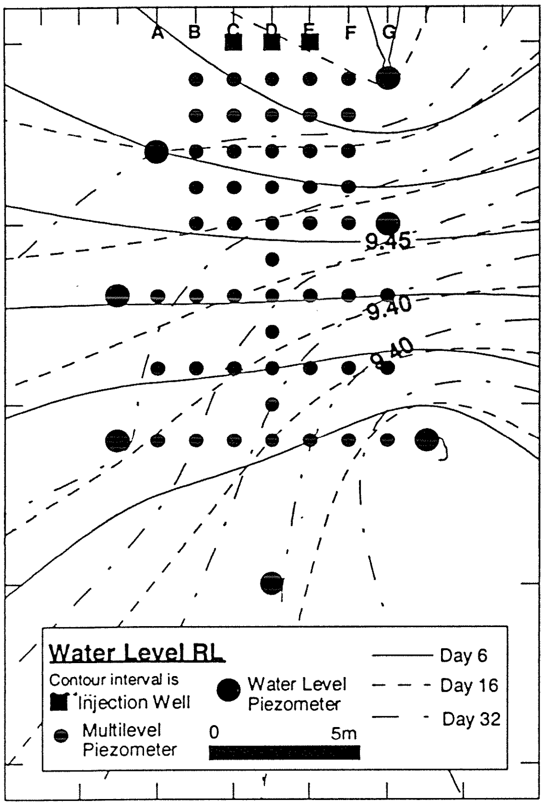

Figure 1. Location of injection wells, multilevel piezometers and water table contours for Days 6, 16 and 32 after tracer injection.

2.1 ELE Site Geology

Quartz sand is the dominant lithology encountered at the ELE site. Visual, settlement column and sieve analysis indicates that the sands are 77-95% medium grained, 3-10% fine grained with 2-14% silt and clay fines. Settlement column and sieve analysis results indicate the highest fines content to be located between the 7.5m and 8.5m a.s.l. The fine sand content (5-8%) is also higher in this zone than in the lithological units above and below (3-4%).

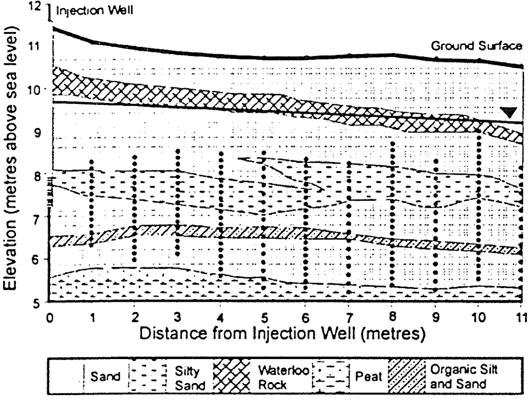

Figure 2. Geological cross-section through the ELE site

Figure 2 presents a composite geological section through the ELE site. The composite section was compiled from logs of vibro-cored samples and observation of drill cuttings during the installation of the ELE site.

2.2 ELE Site Hydrogeology

The ELE site has an average saturated thickness of 4m due to variations in the water table between 1.7 and 1.87 m below ground level. Hydraulic gradient at the site varies between 0.003 and 0.009 with an average of 0.007.

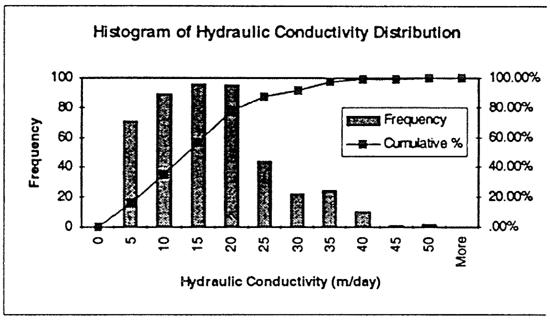

Figure 3. Frequency distribution of hydraulic conductivities.

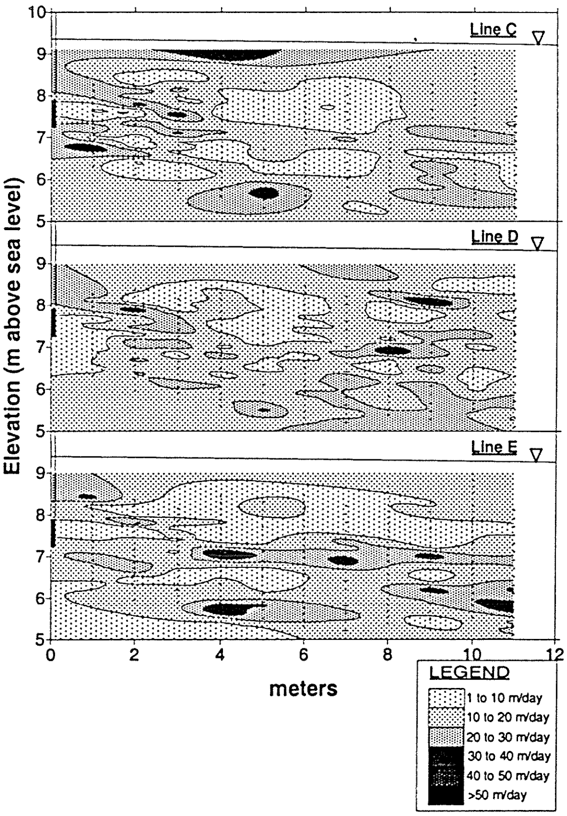

Figure 4. Distribution of hydraulic conductivity (m/day) along lines C, D and E.

Distribution of the hydraulic conductivity at the ELE site was estimated by 556 falling head tests, which were carried out, in the three central monitoring lines of the site. Although subject to errors falling head tests were the only viable option for hydraulic conductivity estimation due o the small diameter of the multilevel samplers. Hydraulic conductivity estimates varied between 1.5 m/day and more than 50 m/day, with a mean estimated value of

14.6 m/day and a standard deviation of 9.2 m/day. Due to potential errors as a result of the use of the falling head test method the estimated conductivity values may be subject to some inaccuracy. However, the relative differences in the estimated are considered a reasonably accurate representation of the relative differences and distribution of hydraulic conductivities. Figure 3 shows the distribution of the estimated hydraulic conductivity values. Figure 4 shows the variation in the hydraulic conductivity values in the three central monitoring at the ELE site. The presence of the silt and clay fines in the zone between 7.5 and 8.5 m a.s.l. is reflected in the relatively lower hydraulic conductivity values, observed on Figure 4, between these elevations. The hydraulic conductivity due to the presence of the silt and clay fines is up to an order of magnitude lower than in the lithologies above and below. There are also several low hydraulic conductivity zones and lenses at the ELE site, which could act as mini aquitards, causing semi-confined conditions for parts of the aquifer, as well as affect solute transport. The hydraulic conductivity distribution at the ELE site had a profound effect on the previous tracer test (Evans, 1993; Lawrence, 1994).

3 BACKGROUND CHEMISTRY

Samples for analysis of the background chemistry at the ELE site were collected from 88 samplers in five vertical profiles in the central monitoring line. Chemical analysis results and processes are discussed in detail by Jankowski et. al. (1997). Background concentrations of the major cations and anions as well as the tracer elements were measured. Results for those elements described here are summarised in Table 1.

Table 1. Summary of background element chemical analysis (mg/l)

Element	Min	Max	Mean
B	ND	0.15	0.07
Br	ND	ND	ND
Cl	26.2	53.1	38.5
Li	ND	ND	ND

ND = Not Detected

4 TRACER INJECTION AND SAMPLING

The 300 litres of tracer (100 litres per well), containing B, Br, Cd, Cl, Cu, K, Li, Ni, Pb and Zn, were injected over a 1 hour period (Figure 1 and 2). The tracer solution EC and pH were 2877 µS/cm and 5.8, respectively. Concentrations of the four tracers discussed here are summarised on Table 2. The data analysis of the conservative element transport was to be used to estimate longitudinal, horizontal-transverse and vertical-transverse dispersivity.

Table 2. Summary of injection concentration of the four conservative tracers

Element	Concentration (mg/l)
B	110.07
Br	186.08
Cl	741.89
Li	123.72

Ten sample sessions were undertaken over a 32 day period after tracer injection. A total of 2500 samples were collected and preserved on Days 2, 4, 6, 8, 12, 16, 20, 24, 28 and 32 after injection.

Samples were analysed for boron and lithium concentration using inductively coupled plasma spectroscopy, while bromide and chloride concentrations were analysed by a combination of ion selective electrodes and ion chromatography.

5 RESULTS

Water table contours for Days 6, 16 and 32 after injection are shown on Figure 1. As can be observed the flow direction of the groundwater changes over the cause of the tracer test. Initially flow is from the injection wells towards line A of the sampling grid, then changes towards line G later in the test.

Figures 5, 6, 7 and 8 show cross-sections through the boron, bromide, chloride and lithium plumes along line E of the sampling grid. Boron, bromide and chloride appeared to behave conservatively throughout the tracer test. Conservative tracer behaviour was similar to that observed during the previous chloride tracer test at the ELE site (Evans, 1993). The mean solute transport velocity during the previous tracer test was around 0.35 m/day. Travel velocities during the tracer test described here were somewhat lower with a mean velocity of around 0.28 m/day and a velocity of 0.34 m/day in the higher hydraulic conductivity zones. Boron behaved almost identically to bromide and chloride, which indicates that boron behaves conservatively and can be added to the list of potential conservative tracers available. Lithium behaved semi conservatively during the tracer test.

By Day 6 after tracer injection boron, bromide, chloride and lithium had travelled up to 3m downgradient of the injection wells. The maximum tracer concentrations, which were up to 80% of injected concentrations, were located between 1 and 2 m for boron and lithium and at 2 m for bromide and chloride, from the injection wells. The lithium plume also appears to be slightly smaller than the three conservative element plumes.

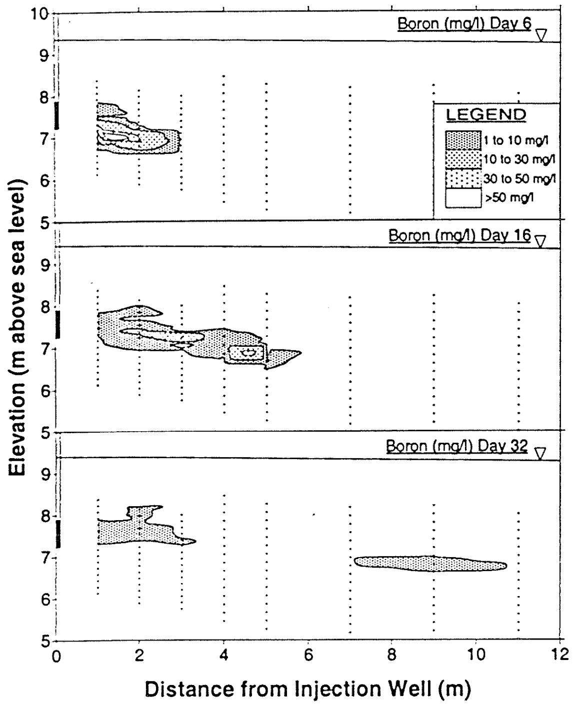

Figure 5. Vertical distribution of boron tracer.

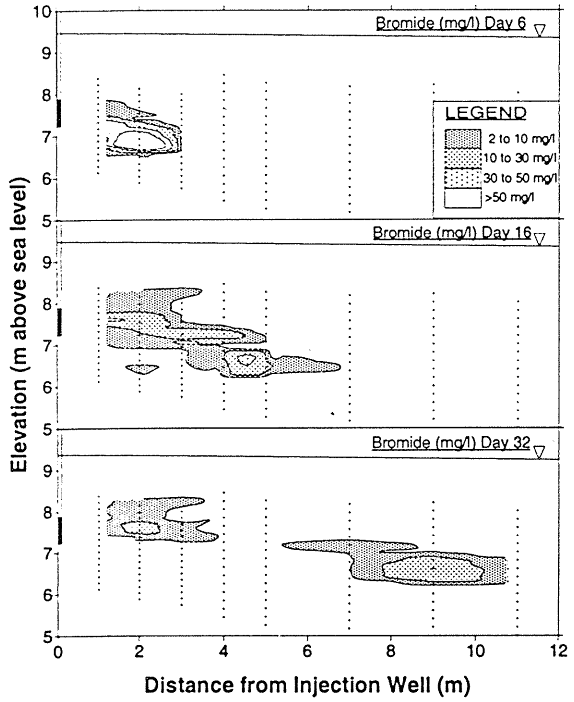

Figure 6. Vertical distribution of bromide tracer.

By Day 16 after tracer injection bromide and chloride had travelled 7 m and boron 6 m, down-gradient of the injection wells. The maxima of the three conservative element plumes were located between 4 and 5 m downgradient from the injection wells at this time. Lithium had undergone some retardation by Day 16 after injection and had only travelled a distance of 3.5 m.

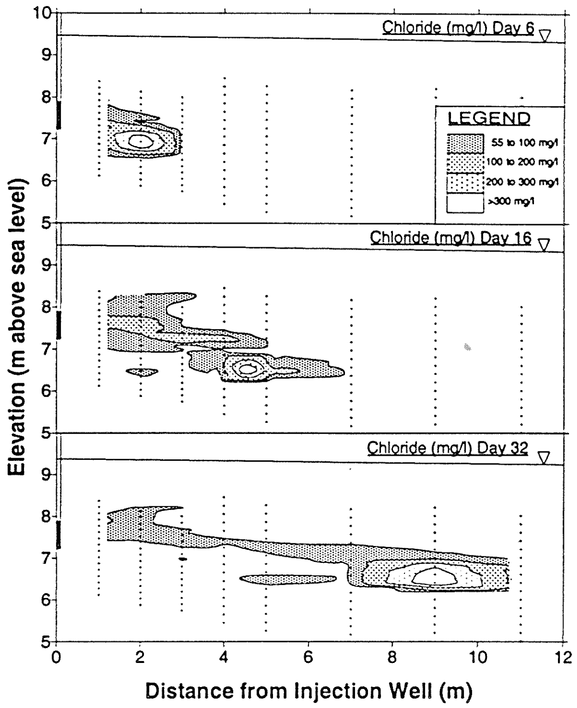

Figure 7. Vertical distribution of chloride tracer.

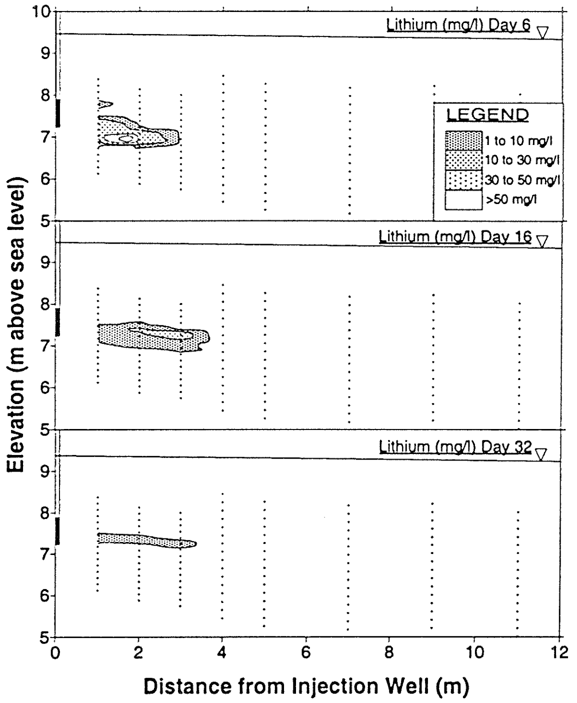

Figure 8. Vertical distribution of lithium tracer.

The boron, bromide and chloride plumes split into two parts between Days 16 and 24 after injection. By Day 32 after injection, boron and bromide had two distinct plumes, one located between 7 and 11 m for boron and 6 and 11 m for bromide, from the injection wells. The second boron and bromide plumes were located between the injection wells and 4 m. Chloride had a highly elongated plume stretching between the injection wells and 11m down-gradient. By Day 32 chloride also had two plumes, but, these occurred in two levels, with the second plume located 0.5 m below the main plume. The second plume was located between ~4.5 and ~6.5 m from the injection wells. The lithium plume had only travelled ~3.2 m from the injection well after 32 days of travel. Lithium also had the lowest relative concentration of the four elements, having a maximum concentration of approximately 3% of the injection concentration. The maximum boron, bromide and chloride concentrations were located 9m down-gradient from the injection wells.

6 DISCUSSION

The three tracers (B, Br and Cl) behaved conservatively over the duration of the test and travelled at a velocity of around 0.3 m/day in the low fines content sands, which is similar to the value of 0.32 m/day, calculated for quartz sand, using Darcy's law. Although there were slight differences in the travel distance of the boron, bromide and chloride maxima during the test, all three element maxima had travelled the same distance by Day 32 after tracer injection. However portions of the plume moved at significantly lower velocities in the low hydraulic conductivity zones.

The B, Br, Cl and Li plumes all travelled preferentially along the highest hydraulic conductivity zones, with the base of the plume generally following the top of the organic silt and sand layer. The average longitudinal dispersivities of the three conservative tracers were estimated using several sample point breakthrough averaged around 0.0388. The longitudinal dispersivity is observed to be significantly higher than the vertical transverse dispersivity (estimated at 0.0039), which results in the development of the long thin plumes shown on Figures 5, 6, 7 and 8.

Bromide and chloride behaved virtually identically during the first half of the tracer test, as can be observed on the plume cross-sections for Days 6 and 16 (Figures 5, 6, 7 and 8). The minor differences in plume shape may be due to the poorer resolution achievable for the chloride plume, due to its higher background concentration when compared to the other conservative tracer elements. The best achievable resolution of chloride was 7.5% of the injection concentration, while plume delineation to 1% or better was achievable for the other conservative tracer elements. Boron generally had a thinner plume than either bromide or chloride, which is possibly due to some minor sorption processes around the edges of the plume. However, sorption did not appear to be significant enough to cause retardation in transport velocity or affect concentrations in any significant way and boron can therefore still be considered to behave as a conservative tracer.

Lithium behaved as a conservative tracer until at least Day 6 after tracer injection, when the lithium plume had a similar shape to the boron, bromide and chloride plume (see Figure 8), indicating only minor sorption processes. During the later part of the test lithium became a reactive tracer, being subject to retardation and mass loss due to sorption processes. This behaviour of lithium was likely to be the result of competitive sorption processes with the heavy metal tracers. While heavy metals remain in solution they sorb in preference to lithium, causing the observed conservative transport, during the early part of the tracer test. When the majority of the heavy metals are sorbed out of solution, lithium begins to sorb causing the observed reactive transport behaviour. As a result lithium only travelled a maximum distance of ~3.2 m, compared to ~11 m for the conservative tracers, boron, bromide and chloride.

A 7.75 times greater density of the plume compared to the groundwater did not appear to cause the tracer to sink to any significant degree. This observation is likely to be caused by the lower hydraulic conductivity lenses and bands, which restrict potential vertical movements.

Variability in the geology, caused by the deposition environment, leads to a complex distribution of highly variable hydraulic conductivity at the ELE site. This, coupled with the changing groundwater flow direction results in complex plume shapes for the natural gradient tracer test, carried out at the site. Even with the complex dense three dimensional network of monitoring points available at the site, some interpolation of the plume maxima locations was required. On a localised scale of individual contaminated sites, similar variations in geology and hydrogeology could be expected. The tracer test described here highlights the possible difficulties in detecting and accurately delineating a small contaminant plume, using conventional single screen or nested piezometer monitoring points at sites located in the Botany Sands aquifer, or similar heterogeneous unconsolidated sand aquifer.

Aquifer heterogeneity will also have a significant influence on the performance of remediation schemes, in particular pump and treat systems. Contaminant transport would be slower in the low hydraulic conductivity lenses, thus lengthening the treatment process over and above the clean up time frame estimated from conventional hydrogeological investigations.

As demonstrated in the tracer test described here, the distribution of the hydraulic conductivity within the aquifer has a significant influence on the movement of the conservative tracers and can be successfully investigated using multilevel samplers.

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