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Tracer studies for evaluation of in situ air sparging and in-well aeration system performance at a gasoline-contaminated site

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Abstract

Field-scale tracer studies were conducted at a gasoline-contaminated site in order to evaluate the effectiveness of in situ air sparging (IAS) and in-well aeration (IWA) in controlling the movement of soil gas and groundwater in the subsurface. The field site was comprised of silty sand (SM) and silty clay (CL), underlain by a clay layer at approximately 7.6 m. Depth to groundwater ranged from 2.4 to 3 m. Soil permeability and the natural hydraulic gradient were both low.

Helium was used to trace the movement of soil gas in the unsaturated zone during the IAS field study, and successfully confirmed short-circuit pathways for injected air and demonstrated the limited distribution of injected gases at this site. Fluorescein, bromide, and rhodamine were used to trace the movement of groundwater during the IWA system field study, and successfully documented the inability of the IWA system to recirculate enough groundwater to enhance subsurface dissolved oxygen levels or to remediate groundwater by air stripping at this site.

The inability of the systems to remediate the site was likely due to site conditions which consist of low-permeability soils and decreasing permeability with depth. As a result, relatively impermeable layers exist at the depth of the IAS screen and the lower IWA screen. These site conditions are not conducive to successful performance of either remediation system.

Keywords: Groundwater; Contamination; Tracers; Remediation

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1. Introduction

Field studies of in situ air sparging (IAS) and in-well aeration (IWA) treatment systems were conducted at a gasoline-contaminated site by Hall [1] and reported by Hall et al. [2–4]. IAS systems inject air into the groundwater by forcing the air into an aquifer through a screen at the bottom of a well. Volatile organic compounds (VOCs) are removed from the groundwater by inducing mass transfer to the vapor phase and/or by delivering dissolved oxygen to the groundwater to enhance aerobic biodegradation.

Sparged airflow has been observed to create discrete, stable gas channels in the subsurface rather than dispersed gas transport [5,6]. Channeling limits the contact between the air and water phases, resulting in poor gas transfer efficiency. The effects of channeling may be mitigated somewhat by heterogeneities, such as clay lenses, which may split rising gas channels [7], or by operational strategies, such as pulsed sparging [5], which involves encouraging the formation of air channels at different locations by regularly shutting down and restarting the sparging system.

IWA systems introduce air into aquifers to enhance biodegradation of organic contaminants [8,9] and/or to circulate groundwater through the well where VOCs are removed by air stripping [10]. IWA systems employ vertical circulation wells, which are designed with two screened intervals. Commonly, the upper screen straddles the water table while the lower screen is located near the base of the aquifer [9]. Groundwater circulation is induced by bubbling air into the bottom of the well to create an air lift pump effect. Ideally, water is drawn into the well through the lower screen and expelled from the well through the upper screen. The air oxygenates the water as it passes through the wellbore and strips VOCs from the circulating groundwater.

Several patented methods for creating the vertical gradient have been designed, including the Grundwasser–Zirkulations–Brunnen (GZB), the vacuum vaporizer well (UVB), the groundwater flushing circulation well (SZB) [10], and the density-driven convection (DDC) well [9]. A DDC system was installed at Hall and coworkers [1–4] field site by Wasatch Environmental Inc.

A number of studies have been conducted using a variety of monitoring techniques to provide quantitative information regarding the performance of these air-based remediation systems under actual field-operating conditions. Some of the first tracer work conducted to evaluate air distribution during IAS was reported by Johnson et al. [11] in 1997, with subsequent results reported by Bruce et al. [12] using dissolved oxygen and SF6 tracers to evaluate gas transfer during in situ air sparging at a field site at the Port Hueneme National Test Site. These results showed short circuiting in their well system, highly variable gas delivery rates, and an influence area less than 3 m from air injection wells even in a relatively permeable field site. Wojick [13] evaluated vapor-phase partitioning tracers, soil-gas oxygen and VOC measurements, and conventional soil core and groundwater concentration measurements as indicators of IAS/SVE performance at an LNAPL site on Hill Air Force Base, Utah. These combined results indicated ineffective volatilization of contaminant from the saturated zone via air sparging under site conditions similar to those observed at Hall and coworkers [1–4] field site. Marnette et al. [14] used a bromide tracer in a divergent tracer test configuration to document the effectiveness of mixing at a field-scale site with a radius of influence of approximately 4 m.

IAS and IWA field studies were performed at a gasoline-contaminated site in Layton, Utah. Underground petroleum storage tanks were located at the site for approximately 32 years. The tanks were removed in 1990, but evidence of product release was cited in the Closure Assessment Report and implementation of an in-place biotreatment system was recommended for remediation of the site [15]. The applicability of intrinsic bioremediation at the site was then studied by Dupont et al. [16], who found that although the contaminant plume was stable, the time required for on-site residual mass assimilation to below the benzene MCL was unacceptably long. Field-scale studies were then implemented to investigate enhancement of biodegradation rates at the site.

The site is underlain by a shallow, unconfined aquifer overlying a thick confining layer and deeper confined aquifers [15]. Water levels are 2.4–3 m below grade [16]. The unconfined aquifer was determined to extend to at least 6 m. No test holes were drilled deeper than 6 m. Silty, fine-grained sand (SM) and silty clay (CL) were the primary unconsolidated sediments encountered during installation of the monitoring network for the IAS/IWA project. Groundwater flow to the south–southwest was observed during three of six groundwater sampling events performed between 1992 and 1994 [16]. The flow direction was west, northwest, and southwest in one sampling event each. The magnitude of the hydraulic gradient ranged from 0.008 to 0.014. Slug tests resulted in hydraulic conductivity estimates ranging from 24 to 94 cm per day [16].

This paper focuses on the tracer studies that were conducted in conjunction with the IAS and IWA field studies to aid in evaluating system performance. Tracer data were used to evaluate flow patterns, groundwater velocity, volume of influence, off-site migration, and in-well flowrates. Hall and coworkers [1–4] measured parameters such as oxygen concentrations in the saturated and unsaturated zones, hydraulic head, temperature, and volatile organic contaminant concentrations during the field tests, and these data were available for comparison with the tracer test results.

2. Materials and methods

2.1. Tracers

Four tracers, listed in Table 1, were used at the Layton site to evaluate the performance of the IWA and IAS treatment technologies. Helium was used as a gas phase tracer to track the movement of sparged air during the IAS tests. Fluorescein, rhodamine, and bromide were used as aqueous phase tracers to track the movement of groundwater during the IWA tests.

Background concentrations of the four tracers were measured prior to conducting the tracer tests (Table 2). Method detection limits (MDL) were calculated from laboratory calibration curve data using Eq. (1).

$$\mathrm{MDL} = t_{(n-1,\alpha=0.99)} \times s \tag{1}$$

where $t_{(n-1,\,\alpha=0.99)}$ is the one-sided t statistic appropriate for the number of samples used to determine s at the 99% confidence level, and s is the standard deviation obtained from a minimum of three analyses of a matrix spike containing the analyte at a concentration three times the estimated MDL.

Table 1
Tracers selected for the Layton project

Tracer	Advantages	Disadvantages	Source(s)
Helium	Nonsorptive, nonpartitioning	Detectable levels are expected only in vadose samples	Helium gas (99.7% by volume); Whitmore gas supply, Ogden, Utah
Fluorescein	Nonvolatile	Some sorption and partitioning expected	Fluorescein concentrate; Cole-Parmer, Vernon Hills, IL (Cat. E-00298-17)
Bromide	Nonvolatile, Nonsorptive	Relatively high analytical detection limit; high concentrations may cause toxicity and density effects	Sodium bromide; USU Chemistry Store, Logan, Utah
Rhodamine	Nonvolatile	Susceptible to sorption and partitioning	Rhodamine concentrate; Cole-Parmer, Vernon Hills, IL (Cat. E-00298-16)

2.2. *Groundwater and vadose zone sampling network*

A network of 16 vadose zone and 33 saturated zone monitoring points (MPs) surrounded the treatment well. The MPs were constructed of 5.1-cm diameter stainless steel casing with a 46-cm screen. The MPs were installed by drilling a pilot hole with 12.7-cm augers, then driving the MP the last 1–1.5 m, allowing the screen to be in direct contact with the formation. A 0.6-m bentonite seal was placed in the annulus above the driven section and the remainder of the borehole was backfilled with uncontaminated drill cuttings and sand. The MPs were screened at depths of 1.5–2.0 (Level 1) or 1.8–2.3 m (Level 2) in the vadose zone, and at depths of 2.9–3.4 (Level 3), 4.1–4.6 (Level 4), or 5.9–6.4 m (Level 5) in the saturated zone. The MPs were located at radial distances of 0.9 (Radius a), 1.5 (Radius b), 3.1 (Radius c), or 6.1 m (Radius d) from the treatment well. MP locations are shown in Fig. 1. The numbers refer to the screen level, the radial distance from the treatment well, and the first, duplicate, and triplicate well of a given depth and radial distance. For example, 4d3 refers to the third, Level 4 MP located 6.1 m from the treatment well. A more detailed description of the sampling network is presented in Hall et al. [2].

Table 2
Background concentration of tracers

Compound	Background concentration range	Method detection limit (MDL)	Sample collection date
Helium	Not detected	1.0 mg/l	11/96
Bromide	<MDL—4 mg/l	1.3 mg/l	10/96
Fluorescein wavelength fluorescence[a]	<MDL—5 ppb	3.2 ppb	1/97
Rhodamine wavelength fluorescence[a]	<MDL—36 ppb	5.7 ppb	9/97

[a] The analytical method for fluorescein and rhodamine measures fluorescence at a given wavelength, thus the background fluorescence is probably due to other constituents in groundwater which emit a small amount of fluorescence at these wavelengths.

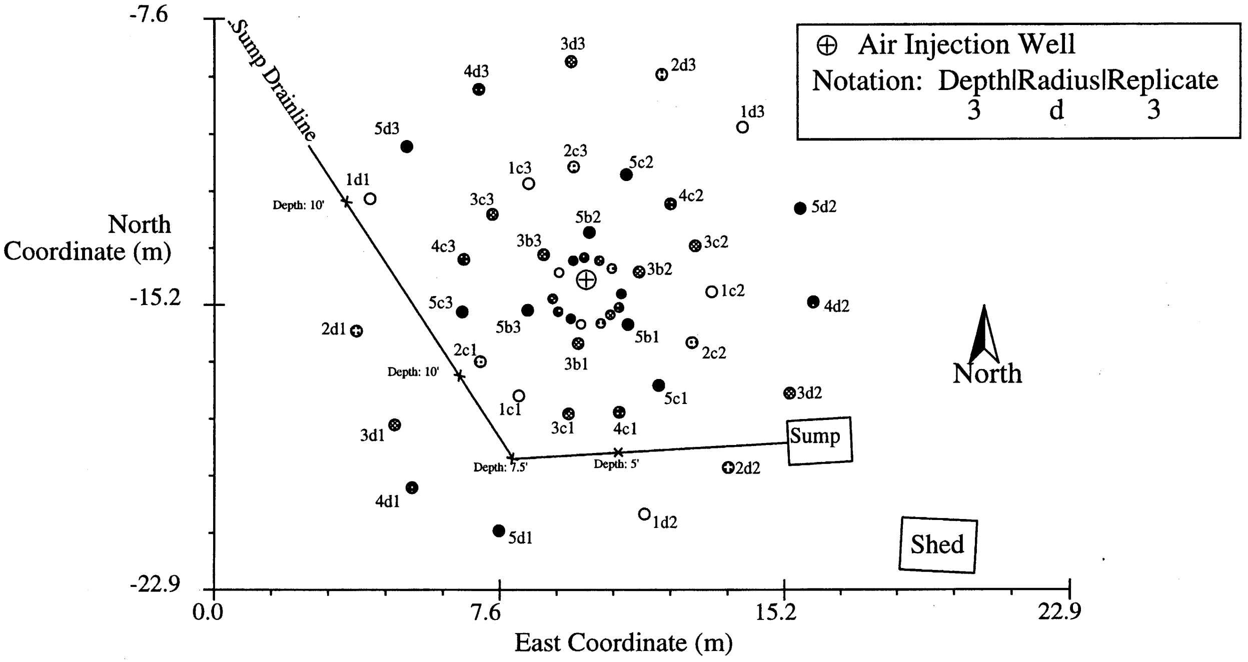

Fig. 1. Plan view of Layton site sampling points [1,3,4].

2.3. IAS system and tracer tests

The IAS system consisted of one 3.2-cm diameter sparge well screened from 6 to 6.5 m. Atmospheric air was injected using a compressor for 30-min intervals at a rate of 5.1 m^3/h. Nine short-term IAS tests were conducted by Hall and coworkers [1,3] prior to the helium tracer tests, who concluded that the injected air traveled in channels between the sparge well and several MPs rather than evenly dispersing through the aquifer. Thus, the system only oxygenated a small portion of the wellfield.

Two helium tracer tests were conducted. The first helium tracer test was conducted on 20 February 1997. Helium was injected at an average rate of 4.2 m^3/h for 7 min. After the 3.4-m^3 cylinder of compressed helium was depleted, air was injected for 20 min at an average rate of 5.1 m^3/h. The total volume, adjusted to standard temperature and pressure, and mass of helium injected was 810 l and 144 g, respectively. The second helium tracer test was conducted on 4 March 1997. Helium was injected at an average rate of 4.0 m^3/h for 12 min. After the helium tank was depleted, air was injected for 3.25 h at a rate of 5.1 m^3/h. The total volume, adjusted to standard temperature and pressure, and mass of helium injected was 1.030 l and 184 g, respectively.

Samples were collected from the a-, c-, and d-radii vadose zone MPs following helium injection. Gas samples could not be obtained from MP 2d3 because it was full of water. Some samples were collected during air sparging, while others were collected after the compressor was turned off. A sample was also collected during the first test from a saturated zone MP, 4a2, which was dewatered by the sparging.

2.4. IWA system and tracer tests

After completing the IAS tests, the IAS well was removed and the IWA well was installed at the same location. The well was reinstalled twice prior to conducting the IWA tests as a result of silt flowing into the borehole at a depth of about 5 m. Silt also migrated into the well while it was operating. The IWA well was constructed of 10-cm diameter PVC with 0.51-mm slotted screens from 1.5 to 4.6 and 5.3 to 7.6 m. The lower screen was covered with a fabric filter sock to reduce the amount of silt entering the well. The annulus of the 20-cm diameter borehole was filled with sand from 0 to 4.7 and 5.2 to 7.6 m, and a bentonite seal was placed from 4.7 to 5.2 m.

Two IWA tests were performed. The first test lasted for 41 days, during which in situ sensors continuously monitored pressure and oxygen concentrations in the a-, b-, and c-radii MPs. The sensors were removed for the second test, which lasted for 20 days. Water levels were measured manually prior to and during the test. No increase in oxygen concentrations was observed in either the saturated or vadose zone MPs during the first test, and no changes in hydraulic head attributable to the operation of the IWA system were observed at any MPs outside of the IWA annulus during either test [1,4].

Three types of tracer tests were conducted on the IWA system. Flowrate tests were conducted by injecting a tracer into the bottom of the IWA well at a known flowrate and sampling at the top of the IWA well. Divergent tracer tests were conducted by injecting tracers into the annulus of the IWA well and sampling for tracers in the surrounding monitoring points. Convergent tracer tests were conducted by injecting tracers into the Level 5, Radius ‘a’

Table 3
Timeline of IWA tracer test events

Event	Time from start of IWA Trial 1 (days)	Time from start of IWA Trial 2 (days)
Inject fluorescein for divergent test	Fluorescein injected in previous pilot test attempt	N/A[a]
Start IWA Trial 1	0	N/A
Bromide flowrate test 1	3	N/A
Bromide flowrate test 2 and divergent test	20	N/A
End IWA Trial 1	41	N/A
Start IWA Trial 2	78	0
Convergent test injections	80	2
End IWA Trial 2	98	20

[a] N/A: not applicable.

wells, and sampling for the tracers in the IWA well. Table 3 outlines the timing of tracer injections and IWA operation.

Two flowrate tests were conducted using bromide as a tracer. The first test was conducted after 3 days of IWA system operation. A sodium bromide solution containing 5 g/l bromide was injected through a tube in the annulus of the IWA well at 7.3 m depth. The bromide solution was injected using a peristaltic pump at a flowrate of 176 ml/min for 170 min. The total volume and net mass of bromide injected were 30 l and 132 g, respectively. The second flowrate test was conducted after 20 days of IWA system operation using a higher concentration of bromide so it could also serve as a divergent test. A sodium bromide solution containing 50 g/l bromide was injected through a tube in the annulus of the IWA well at 5.8 m depth. The bromide solution was injected at a flowrate of 247 ml/min for 223 min. The total volume and net mass of bromide injected were 55 l and 2.038 g, respectively. (This figure accounts for tracer lost due to overflow from the IWA well, as well as water intentionally withdrawn by pumping.) During injection, water was simultaneously withdrawn, at a rate of 132 and 80 ml/min, during the first and second tests, respectively, from a tube in the annulus of the IWA well at 3.1 m depth.

A total of 5.2 l of fluorescein dye concentrate had been injected into the first IWA well, which had been improperly installed and was reinstalled at the same location. Groundwater was sampled and analyzed for fluorescein prior to operating the new well. Since there was still a high fluorescein concentration in the IWA well and there was no fluorescein in the surrounding MPs, fluorescein was monitored as a divergent tracer during the 41-day operation of the IWA well. The amount of fluorescein lost during reinstallation and development of the new IWA well is unknown.

The second bromide injection, as described above, was also used as a divergent tracer test. Samples from the surrounding MPs were analyzed for bromide, in addition to fluorescein, from the day of injection (Day 20) to the termination of IWA system operation (Day 41).

Convergent tracer tests were conducted during a second run of the IWA system using bromide, fluorescein, and rhodamine. Tracers were injected after 2 days of system operation. The IWA well and surrounding MPs were sampled for tracers over a 14-day period. All injections were conducted in Level 5, Radius ‘a’ MPs. Each well screen was isolated with a sealed bundle housing [1,2] equipped with sampling tubes. As much water as possible was removed from each injection interval using a peristaltic pump immediately prior to tracer injection. This volume of water was then replaced with an equivalent volume of tracer to minimize water level changes resulting from injection of the tracer.

3. Results and discussion

3.1. IAS tracer tests

The mass of helium recovered was calculated using the Thiessen area method [17] and vertical heights of 1.8 and 0.4 m for Levels 1 and 2, respectively. An average volumetric air content of 0.2 was assumed. No helium peaks were detected in background samples collected prior to tracer injection; however, since the background helium concentration was not zero at the beginning of the second tracer injection, recoveries for sample rounds 2.1 through 2.4 are based on the sum of injection masses from both tracer tests.

Mass recovery of the injected helium from the vadose zone was very low, ranging from 0 to 52%. The highest mass of helium (52%) was recovered during sampling event 1.1, which occurred 1 h after the start of the first injection. Helium was recovered from all a-radius vadose zone MPs during this sampling event. No helium was recovered during sampling event 1.2, which occurred just 2 h later. Mass recovery for sampling events 1.3 through 2.4 ranged from 1 to 4%, but most of the helium was recovered from MP 1d1, which is located in sandy backfill material placed after excavation of the underground storage tanks.

In tracer test 1, helium moved to 1d1 within 25 h after air injection was terminated. When tracer test 2 was started 11 days later, the helium concentration in 1d1 was still about 1.2 mg/l. The helium concentration then increased to 3.0 mg/l in sampling round 2.4, which occurred 23 h after the second air injection was terminated. Helium was still present in MP 1d1 at a concentration of 1.1 mg/l when a final round of samples was collected 44 days after the second helium injection. At a uniform concentration of 1.1 mg/l, an area of 670 m^2 is needed to account for 100% of the mass of helium injected during the two tracer tests. By comparison, the cylindrical sampling grid covers an area of approximately 117 m^2.

Because most of the vadose zone MPs had helium concentrations below the method detection limit, it seems likely that a large portion of the helium was channeled to the surface in a relatively short period of time. This conclusion is also supported by field observations of gas bubbling upward through the wellbores of MPs 4a2 and 5a2 during helium and air sparging tests. MP 4a2 was dewatered during the tracer tests. A gas sample obtained from this MP at the end of the first helium injection contained 46% helium by volume, implying that large quantities of helium were channeled immediately to the surface through MP 4a2. Gas sampling was attempted from MP 5a2, but was not successful because this MP was not completely dewatered. However, gas could be heard bubbling through MP 5a2, and it is believed to be another direct channel for the loss of helium to the surface. Assuming the helium concentration in the air channeled through these two MPs was 46% by volume, a total airflow through these MPs of 0.9 and 1.6 m^3/h for 1 h would account for 50 and 90%, respectively, of the injected helium. Thus, since the sampling grid covers an area of less than 18% of that needed to account for 100% of the mass of helium injected during the two tracer tests at a uniform concentration of 1.1 mg/l, as was stated in the previous paragraph, it seems most likely that the majority of the helium was channeled to the surface through these two MPs in a relatively short period of time.

3.2. IWA tracer tests

Flowrates were estimated from the bromide concentrations measured during the two flowrate tracer tests using Eq. (2), which was derived from mass balance principles.

$$Q_{\mathrm{IWA}} = \left(\frac{C_{\mathrm{i}}}{C_0}\right) \times Q_{\mathrm{i}} \tag{2}$$

where Q_{IWA} is the flowrate in the IWA well (l/min); C_{i} the bromide concentration of the injected tracer solution (mg/l); C_0 the steady-state bromide concentration in the upper screen of the IWA well (mg/l); and Q_{i} is the tracer injection rate (l/min). The bromide concentrations of the injected tracer solutions were 5000 and 50,000 mg/l during the first and second tests, respectively. Fig. 2 shows the bromide concentration in the upper screen of the IWA well during the injection period. The C_0 values for each test were calculated using a time weighted average of the concentrations of samples collected between 160 and 260 min for test 1 and between 86 and 256 min for test 2. The resulting steady-state bromide concentrations were 1397 ± 41 and $26{,}170 \pm 1547$ mg/l, and the estimated IWA flowrates were 0.63 ± 0.02 and 0.47 ± 0.03 l/min for tests 1 and 2, respectively. An average flowrate of 0.55 l/min, based on the steady-state test results, was used for all subsequent calculations in this paper.

Both fluorescein and bromide were detected in MPs 3a1, 3a2, 3a3, 4a2, 4a3, and 3b1 during the divergent tracer test. Fluorescein was also detected in MPs 3b2, 3b3, 5a1, 5b1, and 4c1. Tracer arrival and peak data are summarized in Tables 4 and 5, and Fig. 3 presents tracer curves from monitoring point 3a1 as examples.

Differences between the fluorescein and bromide tracer data can be attributed to one or more of four possible factors: (1) fluorescein was injected prior to reinstallation of the IWA well and was subject to movement by natural groundwater flow and well reinstallation

Table 4
Time of fluorescein tracer arrivals and tracer peaks at groundwater monitoring points

Monitoring point	Time of first detection (days after injection)	Time to peak concentration measured (days after injection)	Peak concentration (ppb)
3a1	1	4	69,200
5a1	4	4	79
3a2	3	15	14,100
4a2	41	>41	>17
3a3	3	20	16,200
4a3	20	>41	>544
3b1	4	20	167,000
5b1	4	6	61
3b2	9	>41	>480
3b3	41	>41	>12
4c1	9	9	28

The symbol ‘>’ indicates that the tracer concentration had not peaked by the end of the test.

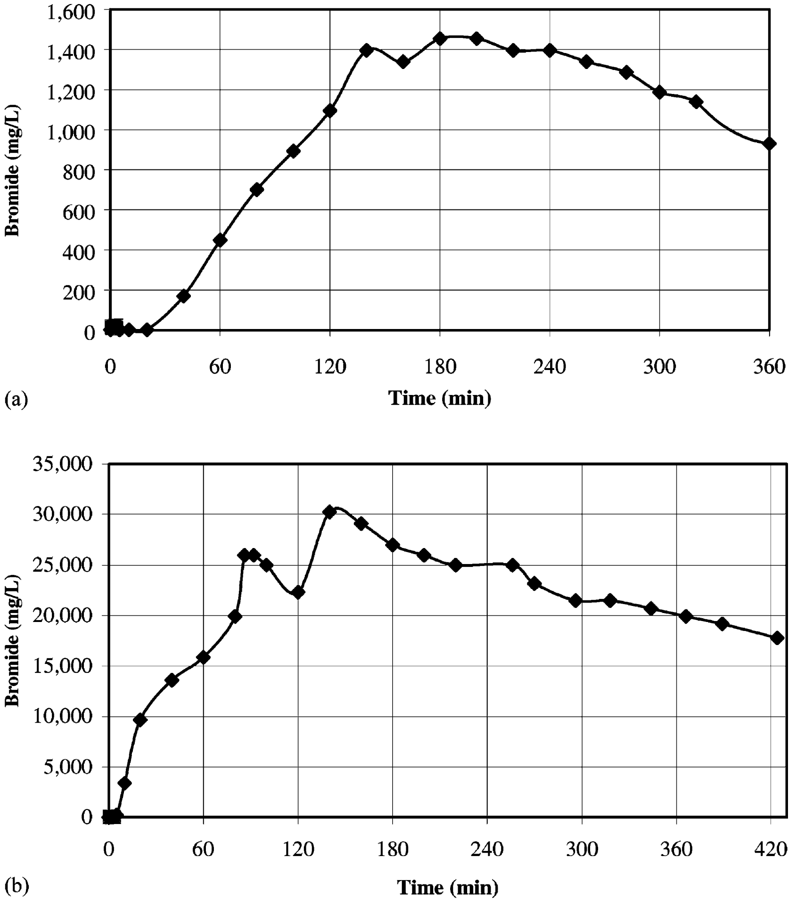

Fig. 2. Results of (a) first, and (b) second bromide flowrate tracer tests from IWA annulus at a depth of 3.1 m.

Table 5
Time of bromide tracer arrivals and tracer peaks at groundwater monitoring points

Monitoring point	Time to first detection (days after injection)	Time to peak concentration measured (days after injection)	Peak concentration (mg/l)
3a1	0.2	>21	>190
3a2	3	>21	>220
4a2	21	>21	>13
3a3	0.2	15	200
4a3	15	>21	>230
3b1	3	>21	>76

The symbol '>' indicates that the tracer concentration had not peaked by the end of the test.

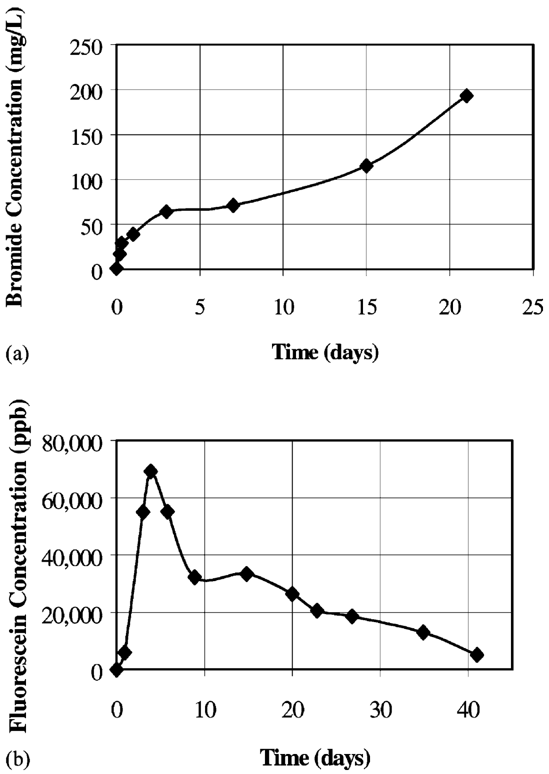

Fig. 3. Divergent tracer curves for (a) bromide, and (b) fluorescein in 3a1.

and development activities, although samples collected just before starting the IWA system showed that fluorescein had not yet migrated to the a-radius MPs; (2) the estimated retardation factor for fluorescein is 1.2–2.0 in Layton site soils, while bromide is considered to be a conservative tracer; (3) the bromide tracer test was started 20 days after the fluorescein test, and the performance of the IWA well and the hydraulic gradients between the MPs may not have been constant throughout this time period; and (4) fluorescein was injected at a concentration seven orders of magnitude above background fluorescence levels, while bromide was injected at a concentration four orders of magnitude above background levels.

Both tracers demonstrate that the radius of influence at the end of the divergent tracer test ends somewhere between the b- and c-radii. However, the radius of influence indicated by hydraulic head measurements does not even extend to the a-radius. Hydraulic head should be more responsive than chemical parameters and would be expected to show a greater radius of influence than the tracer tests if tracer movement was only due to operation of the IWA system.

Average radial groundwater flow velocities between the IWA well and the 3a, 3b and 4a MPs were estimated from the divergent tracer test data using the time at which the peak

Table 6
Comparison of groundwater flow velocities derived from tracer test data and groundwater flow velocities derived from measured hydraulic conductivity and hydraulic head data

From: well 1	To: well 2	Average radial velocity from fluorescein tracer data (cm per day)	Average radial velocity from bromide tracer data (cm per day)	Average radial velocity from *K* and *h* data (cm per day)
IWA	3a1	23	<4.3	53
IWA	3a2	6.1	<4.3	140
IWA	3a3	4.6	6.1	150
IWA	4a2	<2.1	<4.3	3.5
IWA	4a3	<2.1	<4.3	No data
3a1	3b1	4.0	N/A	0
3a2	3b2	<2.4	N/A	0.4
3a3	3b3	<3.1	N/A	0

N/A: not applicable because bromide was not detected in the b-radius wells.

concentration of each tracer was detected and the horizontal distance between two MPs or one MP and the IWA well (Table 6). Peak concentrations were not reached in all MPs by the end of the test due to the low groundwater flow velocities, and these velocities are designated as less than the value calculated using the final sampling time. Slug test hydraulic conductivity data and measured hydraulic head data (Table 7) were also used to calculate

Table 7
Hydraulic conductivity estimates from Layton site wells and hydraulic head data after 1.9 days of IWA operation

Well	Hydraulic conductivity (cm per day)	Groundwater elevation (m)
IWA at 3.1 m	No data	28.234
IWA at 5.8 m	No data	27.048
3a1	18	27.304
3a2	49	27.313
3a3	52	27.310
3b1	3	27.304
3b2	6	27.310
3b3	15	27.310
3c1	3	No data
3c2	9	No data
3c3	12	No data
3d1	1.5	No data
4a1	0.6	27.304
4a2	1.2	27.307
4a3	3	No data
4c3	2.4	No data
4d3	0.3	No data
5a1	No data	27.274
5a2	No data	27.292
5a3	No data	27.316
5b2	0.09	27.283
5b3	0.09	27.277

groundwater flow velocities using Darcy's Law, shown in Eq. (3).

$$v = -K \times \frac{h_1 - h_2}{n_e \times L} \tag{3}$$

where v is the average linear velocity (cm per day), as defined by Fetter [18]; K hydraulic conductivity (cm per day); h hydraulic head (m); n_e effective porosity; and L is radial distance between MPs (m). An effective porosity of 0.35 was assumed.

Comparison of the velocity estimates indicates that the tracers traveled to the Level 3, a-radius wells 2–30 times slower than groundwater flow velocities calculated using Darcy's Law. Because bromide is considered to be a conservative tracer and the retardation of fluorescein is relatively low at the site, this is probably due to recirculation of the tracers within the IWA wellbore and in the subsurface region less than 0.9 m from the IWA well. Radial velocity estimates made from the tracer data for travel between the IWA well and wells 4a2 and 4a3 are similar to or lower than the velocity calculated from Darcy's Law.

The fluorescein detected in MP 5a1 is suspected to be from outward movement of the tracer during reinstallation and development of the IWA well, which occurred after the fluorescein was injected. The fluorescein detected in MPs 5b1 and 4c1 is suspected to be the result of accidental contamination from a surface fluorescein spill. Even if the fluorescein detected in these MPs was attributed to the performance of the IWA well, comparison with data from a laboratory tank test [19] shows that the mixing of groundwater between the three and five levels in the field is not comparable to that achieved in the laboratory simulation. Ratios of the areas under tracer curves and ratios of peak concentrations show that the relative amount of fluorescein detected in points 5a1, 5b1, and 4c1 during the field test was insignificant compared to that of an ideally mixed system. Bromide was not detected in points 5a1, 5b1, and 4c1.

It is suspected that the IWA well established small recirculation cells within the upper, more conductive soil layers, but that the recirculation cells were not large enough to encompass the MPs available for hydraulic head measurements. Although recirculation was not observed in a-radius hydraulic head measurements, groundwater and tracer recirculation is indicated by a second peak on the fluorescein tracer curves from the IWA well during the divergent test (Fig. 4). The bromide tracer curves (Fig. 5) do not exhibit a second peak, but the second peak may have been missed if it occurred between sampling events, as the bromide recirculation peak was likely of a shorter duration than the fluorescein recirculation peak due to differences in retardation. The second bromide peak may have occurred at around Day 1, where a slope break is evident in the two tracer curves shown in Fig. 5.

Tables 8–10 present tracer curve data from the convergent tracer tests. Individual tracer curves are presented in Berkey [19]. The data show that the majority of the injected tracer mass remained in the injection MPs. This was anticipated due to the very low hydraulic conductivity (0.09 cm per day; see Table 7) measured in the Level 5 MPs, the very low natural hydraulic gradient, and the absence of any measurable head change in the a-radius MPs during IWA operation.

The convergent tracer test data suggest that the IWA well pulls in little water from Level 5. A relatively small amount of rhodamine was detected in the IWA well, but was also detected in MP 5a1 at the same times. This probably indicates a small amount of groundwater flow in a south–southeasterly direction or diffusion rather than a capture zone created by the

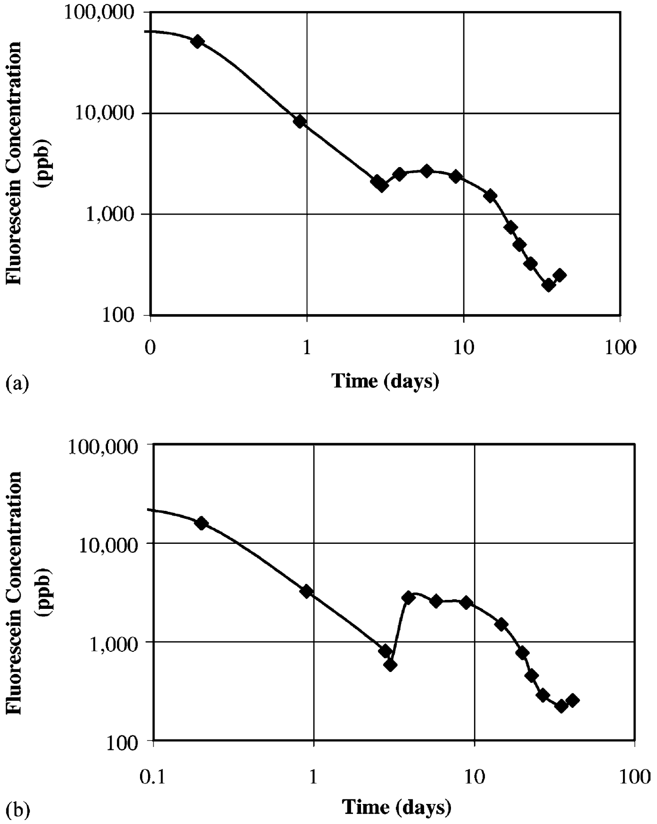

Fig. 4. Divergent fluorescein tracer curves from IWA annulus at depths of (a) 3.1, and (b) 5.8 m.

Table 8
Fluorescein tracer curve data from convergent tracer test

Location	5a1	5b1	IWA at 3.1 m	IWA at 5.8 m
Day 0	<10	<10	570	560
Day 0.2	No data	No data	570	520
Day 1	No data	<10	440	440
Day 3	3,700,000	<10	440	470
Day 6	5,000,000	<10	650	640
Day 10	5,000,000	12	480	470
Day 14	No data	45	280	290
Day 18	5,000,000	35	300	300

Fluorescein was injected into MP 5a1 at a concentration of 1×10^8 ppb. The total volume and mass of fluorescein injected were 520 ml and 52.0 g, respectively. Wells in which no fluorescein was detected are not listed. Fluorescein concentrations are in ppb.

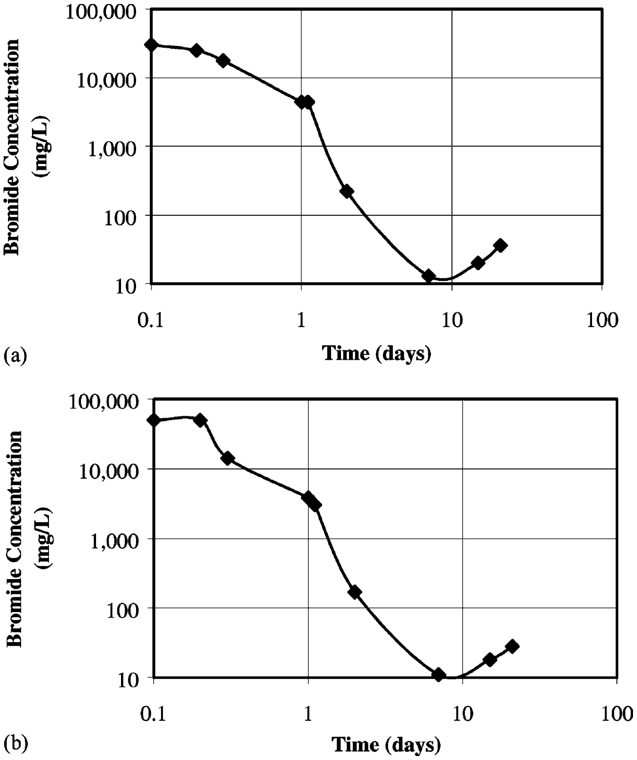

Fig. 5. Divergent bromide tracer curves from IWA annulus at depths of (a) 3.1, and (b) 5.8 m for test 2.

Table 9
Rhodamine tracer curve data from convergent tracer test

Location	5a1	5a2	IWA at 3.1 m	IWA at 5.8 m
Day 0	<10	11	<10	<10
Day 0.2	No data	No data	<10	<10
Day 1	No data	No data	<10	<10
Day 3	No data	5,100,000	<10	<10
Day 6	170	4,800,000	410	390
Day 10	140	5,000,000	200	200
Day 14	No data	No data	190	200
Day 18	260	4,700,000	130	130

Rhodamine was injected into MP 5a2 at a concentration of 1×10^8 ppb. The total volume and mass of rhodamine injected were 735 ml and 73.5 g, respectively. Wells in which no rhodamine was detected are not listed. Rhodamine concentrations are in ppb.

Table 10
Bromide tracer curve data from convergent tracer test

Location	5a3	IWA at 3.1 m	IWA at 5.8 m
Day 0	<10	49	51
Day 0.2	No data	70	76
Day 1	No data	44	42
Day 3	11,000	25	23
Day 6	19,000	16	18
Day 10	16,000	13	13
Day 14	No data	13	14
Day 18	11,000	14	15

Bromide was injected into MP 5a3 at a concentration of 50 g/l. The total volume and mass of bromide injected were 695 ml and 34.8 g, respectively. Wells in which no bromide was detected are not listed. Bromide concentrations are in mg/l.

IWA well. Similarly, a small amount of fluorescein was detected in 5b1, which would also indicate south–southeasterly groundwater flow. Fluorescein and bromide concentrations in the IWA well decreased during the convergent tracer tests, indicating that the IWA well did not pull in water from the vicinity of MPs 5a1 and 5a3.

4. Conclusions

In general, the tracer studies were successful in aiding the evaluation of the effects of IAS and IWA on the movement of soil gas and groundwater in the subsurface. Specific conclusions drawn from the tracer studies are presented below.

Conduits created by monitoring points were a factor in IAS system performance, as most of the gas injected into the subsurface was transferred to the surface almost immediately through the wellbores of MPs 4a2 and 5a2. This result was observed during air injection field tests as well as helium tracer tests. A relatively small amount of the injected gas that was not lost to those channels traveled radially outward from the sparge well while in operation. The amount could not be quantified in this study because a soil vapor extraction system was not used. After operation of the sparge well was terminated, the injected gas moved by diffusion, following a path through the more permeable backfill materials toward MP 1d1. The helium tracer test was successful in confirming short-circuit pathways for injected air, and in demonstrating the limited distribution of injected gases in a heterogeneous, low-permeability soil system.

The rate of groundwater flow through the IWA well was estimated from tracer test data to be 0.55 l/min. Tracer test results indicated fairly rapid radial flow of groundwater outward from the IWA well to a distance of 0.9–1.2 m, followed by slow outward flow to a distance of greater than 1.5 but less than 3.1 m. Groundwater flow occurred primarily in the more permeable upper layers of soil. Some recirculation of tracers through the IWA well was observed, but tracer data and hydraulic head data indicate the recirculation only occurred within a distance less than 0.9 m from the IWA well. The tracer studies were successful in confirming the inability of the IWA well to recirculate enough groundwater to be a feasible treatment technology at this field site.

The nature of the site was not conducive to movement of air or groundwater by the remediation systems. Slug test data showed a sharp decrease in horizontal hydraulic conductivity of the soils with depth (Table 7). This type of stratigraphy complicates attempts to remediate the site using technologies that are dependent on the ability to move fluids, especially in a vertical direction.

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