Journal of Hazardous Materials B74 (2000) 165–186
Journal of Hazardous Materials
www.elsevier.nl/locate/jhazmat

Field monitoring and performance evaluation of an in situ air sparging system at a gasoline-contaminated site

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Received 30 May 1999; received in revised form 18 November 1999; accepted 3 December 1999

Abstract

In situ air sparging (IAS) has been used since the mid-1980s, but few carefully designed field studies have been performed to evaluate its effectiveness. In this study, 27 discrete monitoring points (MPs) were installed at a gasoline-contaminated site to investigate the efficacy of IAS. Each MP was instrumented with a pressure transducer and a Technalithics dissolved oxygen (DO) probe, and located so they could be used to characterize subsurface changes in total head and DO with depth, distance and orientation around a central injection well. Because the blower over-heated and automatically shut down after approximately 30 min and short-circuiting of air into two MPs occurred within 2 min, the study was designed as three sets of three 30-min trials. Longer trials would not have yielded different nor more insightful results.

A volume of soil was not oxygenated during any injection. Instead, air traveled directly to at least four of seven different MPs during eight of the nine trials, probably as a result of an air bubble forming beneath a confining layer. The order of air arrival at the MPs varied during the first few trials, but once a preferential pathway was established, it did not collapse between trials and provided the shortest distance to the vadose zone during subsequent trials. Oxygen uptake rates estimated for MPs that received air during any trial exceeded the consumption rates of the Technalithics DO probes, and indicate that the probes could be used for estimating oxygen transfer during system operation or for oxygen uptake measurements during shut-down tests.

The data from the monitoring system indicate that IAS is infeasible for remediation of soil and groundwater at this site due to its low horizontal hydraulic conductivity. Similar behavior is

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PII: S0304-3894(99)00189-2

anticipated when IAS is applied at other sites with low hydraulic conductivity materials.

Keywords: Groundwater; Contamination; Monitoring; Remediation

1. Introduction and review of literature

Many technologies are being used to address soil and groundwater contamination, including some that increase the rate that contaminants are removed or transformed into non-toxic substances by injecting air into the contaminated region. Injection of air into the vadose zone has been successful at many sites [1–3]. Injection of air into the saturated zone has led to mixed results and is the subject of this paper.

In situ air sparging (IAS) involves injection of air below the water table to introduce oxygen into the groundwater to enhance aerobic biodegradation and to induce mass transfer of volatile contaminants into the vapor phase. Vapors move into the vadose zone where they may be biodegraded or removed by a vapor extraction system [4].

While much anecdotal evidence from case studies exists to substantiate the success of IAS, a review of the published literature indicated that few carefully designed field studies with adequate instrumentation for assessing IAS had been performed. Therefore, a project that included both laboratory and full-scale field evaluations of IAS was conducted [5]. Results of the laboratory-scale work, which support the conclusions presented here, are presented elsewhere [6]. This paper presents the results of the full-scale field portion of the study that included installation of an IAS well at a contaminated site along with a monitoring system for evaluation.

IAS for soil and groundwater remediation has been practiced in the US since the mid-1980s [7]. Hundreds of case studies have been documented in the literature at sites with a wide variety of characteristics. In general, systems at these sites were not installed for research purposes but as actual cleanup projects. As such, the information available from the literature pertaining to these studies is generally the result of a review of data which were available as part of routine site monitoring, and conclusions from these sites tend to be anecdotal or based on very few observations. A more limited number of investigations have been done in laboratory settings to more precisely quantify the mechanisms at work in IAS, and very few studies have been done at project sites which are designed for and instrumented to quantify the performance of IAS systems in the field.

Also plaguing the study of air injection technologies is the conventional construction of monitoring wells (MWs) used for performance evaluation. The question of appropriate monitoring techniques has been addressed by comparison between short-term, pilot-scale data and the results of longer-term system operation by Johnson et al. [8]. The results suggest that a network of discrete points, a few conventional wells, and pilot tests much longer than 3 days are necessary to adequately predict the applicability of IAS to a remediation site. The ‘‘infeasibility’’ of IAS at a site may be apparent with a typical pilot test, but longer-term tests are required to predict long-term performance [8].

A network of many small-diameter (1 cm) sampling points was also used in an attempt to develop a three-dimensional picture of changes in trichloroethene (TCE) concentration and groundwater elevation in the subsurface during pulsed and steady flow operation of an IAS system [9]. The monitoring network was installed using Geoprobe® sampling equipment in a grid pattern that surrounded the injection point to minimize disturbance of the site. Sampling from the probes was available at two radii from the IAS point and at three depths. Data from the small diameter probes were not compared with data from conventional monitoring points (MPs). The placement of numerous MPs allowed the researchers to draw reportable conclusions regarding differences in groundwater mounding and changes in TCE concentration at the several elevations and depths used in the study.

Cross-borehole electrical resistance tomography (ERT) was used to define the volume of influence around an IAS well at the initiation of air injection [10]. In this evaluation of IAS in a sandy aquifer, the radius of influence estimated using ERT was only half of that estimated using conventional monitoring techniques. In addition, the authors found that the air distribution was still changing around an IAS well 1 to 2 days after startup. Finally, ERT data seem to verify that air is trapped in the saturated zone even after injection of air has stopped [11,12].

Another monitoring technique that is gaining popularity in the study of air injection technologies is the use of tracers [13–19]. Conservative tracers that are relatively water soluble, non-sorptive, and non-reactive are injected into either the water or vapor phase. Samples collected from points away from the original tracer source can be analyzed for these tracer compounds and the information can be used to understand how water and vapor move in response to injection stimuli.

Many questions remain unanswered regarding IAS but results of case studies and laboratory investigations highlight the two primary concerns which limit the effectiveness of IAS systems: (1) migration of vapors and/or contaminated water away from the point of injection, and (2) the development of preferential pathways for air migration. Laboratory work [20,21] demonstrates that channels will develop for air flow in the saturated zone in all soils but coarse sands and gravel. Depending on the spacing and diameter of the channels, the diffusion path length may be relatively long and can lead to long cleanup times. The native soils at many contaminated sites are denser, lower permeability silts and clays, and extensive air distribution in these soils is not expected.

2. Methods

The first step was to design a monitoring and sampling scheme at a field site that would allow characteristics like oxygen transfer and contaminant removal rates to be estimated. The Wasatch Trailer Sales (WTS) site in Layton, UT, was selected. A sample collection system grid was installed at the site and continuous monitoring, in situ sensors were installed in this grid. The monitoring grid and instrumentation system were used to measure subsurface changes during IAS and to evaluate its efficacy in removing contaminants and distributing DO at the site.

The WTS site was a retail gasoline station with four underground storage tanks (USTs) from 1958 to 1968. From 1968 to 1974, the site was used exclusively for recreational vehicle (RV) sales. Three additional USTs were installed in 1974. All storage tanks were emptied in 1984 when the site was converted back to RV sales. All seven USTs were removed in 1990, and evidence of product release was cited in the Closure Assessment Report [22]. WTS currently leases the property for sale of utility trailers.

Following removal of the USTs in 1990, a site investigation was initiated. As part of the site investigation, a soil-gas survey was conducted at a depth of approximately 1.2 m at 36 locations using a portable organic vapor monitor with a photoionization detector. The highest levels of vapor contamination were located in the two areas where the tanks had been removed. Based on these results, six boreholes were drilled in January of 1991 and 10.2-cm diameter groundwater MWs, screened from 2.1 to 5.2 m below the surface, were installed in three of the boreholes to evaluate water quality and to determine the groundwater flow direction. In the summer of 1992, soil textural data were gathered using a cone penetrometer test (CPT) at 27 locations, and a small-diameter groundwater piezometer with a 61-cm long screen spanning the water table was installed at each of these locations. The CPT points and MWs were used for an evaluation of natural attenuation conducted between 1992 and 1995, which described the plume as stable due to intrinsic processes [23]. However, the time required for assimilation of the residual mass to below the benzene MCL of 5 $\mu g/l$ was unacceptably long (much longer than 20 years). The monitoring grid used for this study was added to the site in September of 1995.

Soils at the site consist of silty clay, sandy silt, and silty sand, with a clay layer beginning at a depth of about 7.6 m. The water level fluctuates between 2.4 and 3 m below the surface, which is covered with asphalt. The total petroleum hydrocarbon (TPH) distribution is illustrated in Fig. 1. The 930 + m^2 plume covers most of the northern end of the property, and the groundwater flow direction is to the west to south–southwest [23].

Slug tests in several of the new well points indicate that the horizontal hydraulic conductivity (K_h) at the site decreases with depth. K_h values for points screened from 3.1 to 3.5 m below the surface are 3 to 50 cm/day, similar to values obtained for the MWs with 3.1 m screens [22]. K_h values for wells screened from 4.3 to 4.7 m and 6.1 to 6.5 m below the surface decrease by one and two orders of magnitude, respectively, (3 to 30 mm/day and 0.9 mm/day).

2.1. Monitoring system

The first step in evaluating IAS at the WTS site was to design and install a grid of MPs. The grid consists of four concentric circles of MPs 0.9, 1.5, 3.4, and 6.1 m (Radii a, b, c, and d, respectively) away from a central IAS well. Three MPs were installed at each radius at each of five depths (1.7, 2, 3, 4.3, and 6.1 m below grade; Levels 1, 2, 3, 4, and 5, respectively). This monitoring grid, illustrated in plan view in Fig. 2, allows comparison across Levels and Radii, and for the evaluation of symmetry around the IAS well with a relatively simple three-factor analysis of variance (ANOVA) model [24]. The grid (or treatment zone) is located in an area at the southern end of the plume shown in Fig. 1 with the highest residual HC contamination.

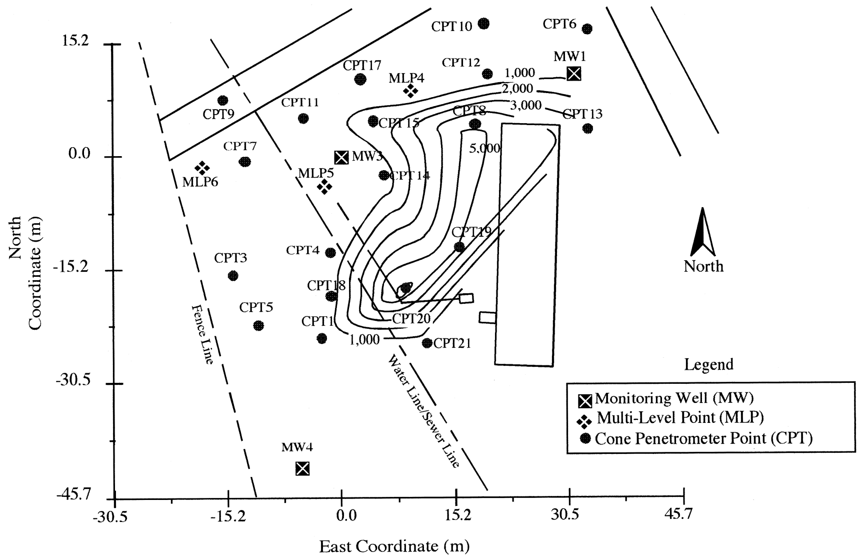

Fig. 1. Distribution of TPH ($\mu g/l$) at Layton site, February 1995.

The stainless steel, 5.1-cm diameter well points with 46-cm long screens were pushed into the soil, with only minimal augering at the surface to create a pilot hole, in order to reduce disruption of the soil caused by traditional well installation procedures. Although each of the 49 MPs shown in Fig. 2 was wired for instrument bundles, after reviewing previously gathered information on IAS and in order to limit the cost of the instrumentation system, only the three inner radii (a, b, and c) were fitted with bundles.

Each saturated zone instrumentation bundle contained a Technalithics Laboratory DO probe, a SenSym pressure transducer, a sampling tube, and a stirring blade. Level 3 points also contained thermocouples. The DO probes were field calibrated every 2 to 3 weeks using air-saturated water, a zero–DO solution generated by adding excess sodium sulfite, and a mid-range DO solution. The pressure transducers and thermocouples did not require recalibration during this study.

Each bundle was sealed in a manner that isolated the sensors from the atmosphere and the groundwater in the casing above them. The sensors were connected to a Campbell Scientific, 21X DataLogger at the surface, which was connected to a computer to allow sampling protocols to be up-loaded to the 21X as needed and sensor response data to be downloaded at regular intervals.

2.2. Air injection system and test protocol

The IAS well consisted of a 3.2-cm diameter stainless steel well point with a 46-cm long screen located from 6.1 to 6.5 m below the surface. The direct-push technique was also used for the IAS well, requiring it to be installed in several sections that were

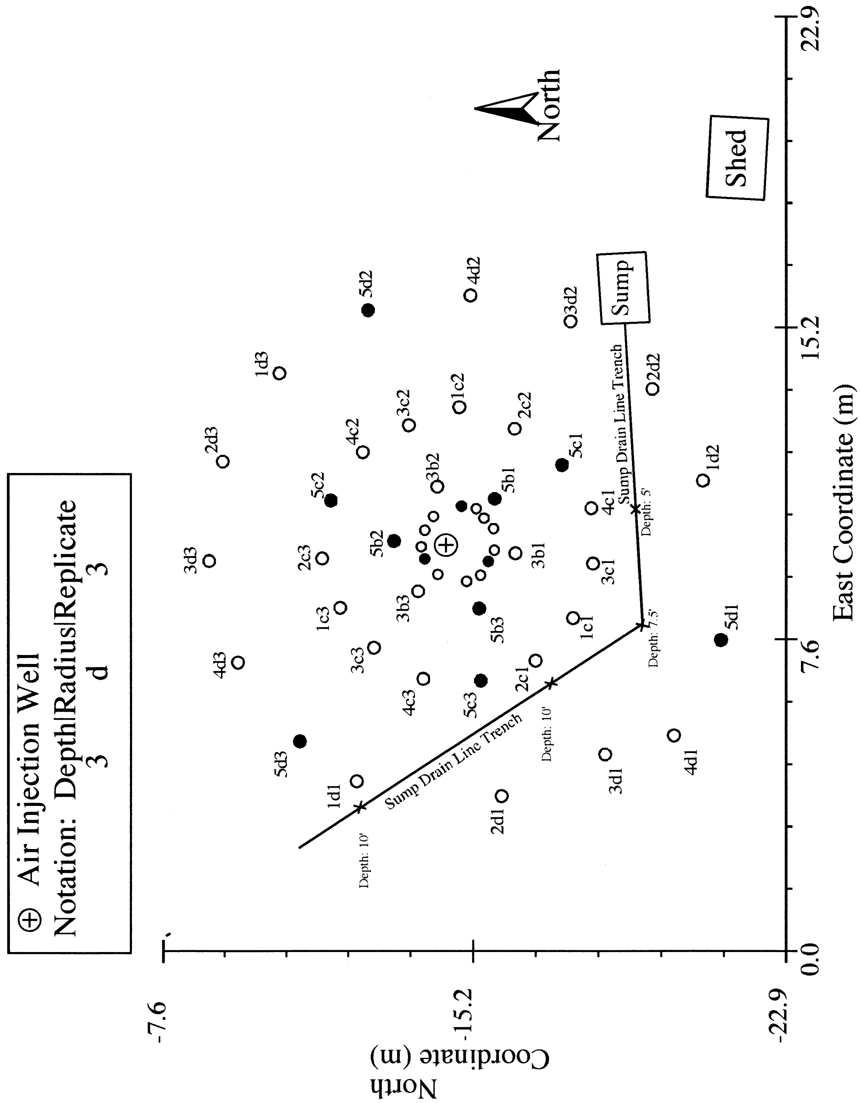

Fig. 2. Driven monitoring point locations.

connected with threaded couplings. The IAS well screen was connected to an air-line at the surface with 3.2-cm diameter black steel pipe.

A Gast 1023 blower, rated at a maximum flow of 8.8 m^3/min and pressure of 170 kPa, provided air to the IAS well. This blower was selected because of the relatively low combination of hydrostatic head and air entry pressure anticipated due to the shallow depth of the IAS well. The air flow rate from the blower was controlled through a flow meter at the top of the IAS well, where a pressure gauge was also available for measuring the wellhead pressure. At the beginning of each injection trial, there was a short period of time (generally less than 1 min) when the blower was required to push against a back-pressure greater than 170 kPa.

During early trials of the system, the air temperature at the site was so high (20° to 27°C) that the blower over-heated and automatically shut down after approximately 30 min. Also, the DO probes indicated that water in several of the MPs may have been displaced by air within minutes (in some cases less than 1 min). Consequently, the run time to a ''steady'' state was very short. For this reason, the study was designed as three sets of three short-term, full-scale trials consisting of 30 min of air injection at 5.1 m^3/h followed by at least 5 days of recovery. Due to performance of the blower and the rapid short-circuiting described below, an evaluation with longer-term trials would not have yielded different, nor more insightful, results. Data from all of the bundles were recorded throughout the injection and recovery periods. Soil gas and groundwater samples were collected 2 weeks after each set of three trials.

3. Results and discussion

Wellhead pressure and air flow characteristics through the nine trials were similar to those reported by others [4,8,25,26]. Within 15 s after the blower was turned on, the wellhead pressure increased to 172 to 207 kPa and then rapidly decreased to a stable value (approximately 138 kPa during the first few trials and down to 3 kPa by the last trial). The rapid decrease in pressure appeared to correspond with the arrival of air at one of the MPs, usually MP 4a2. If a bundle was not sealed properly in a well point, air was released around the bundle. Occasionally, air was released up the sampling tube within a bundle even when all of the bundles were properly sealed. This occurred because during some trials, the pressure was enough to force open the plastic snap clamp used to seal the sampling tube at the surface. There also was a steady decline in the stabilized pressure of 10.3 to 10.8 kPa during each trial. Fig. 3 illustrates the maximum and final wellhead pressures during each trial. The maximum pressures for Trials 1-3 and 2-1 were not recorded, and those for Trials 1-1 and 1-2 were greater than the pressure gage could measure (207 kPa).

3.1. Typical sensor response curves

Pressure and DO data were gathered at each of the 27 instrumented, saturated zone MPs. Rapid increases in both pressure and DO in several MPs indicated that air traveled directly to them from the IAS well. The time of travel was much faster than would be

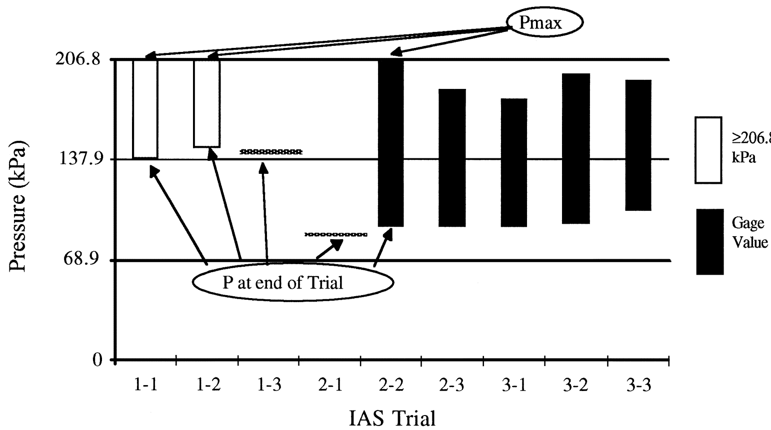

Fig. 3. Maximum and ending wellhead pressures during IAS trials.

anticipated if the air moved by advection uniformly through the subsurface or even through a series of multiple channels, suggesting that a channel formed directly from the IAS well to the MP. For example, air usually reached MP 4a2 (0.9 m away) within 5 s of turning on the blower. In follow-up investigations, the top of the casing for MP 4a2 was sealed with a rubber cap, which popped off immediately when the blower was turned on unless it was secured with a hose clamp.

Values of the maximum change in pressure (ΔP_{max}) and the time to maximum pressure ($t\Delta P_{max}$), as well as the time to maximum DO ($t\mathrm{DO}_{max}$) and the duration of maximum DO ($\Delta t\mathrm{DO}_{max}$), were determined for the 27 instrumented, saturated zone MPs. The actual maximum DO values were not compared because DO increased to near saturation or to a high voltage response in MPs that received air directly, while MPs that did not receive air directly had no change in DO.

Fig. 4 shows pressure and DO response curves during IAS Trial 1-3 for MP 4a3, which did not receive air directly through a channel and is typical of most MPs. The pressure increased rapidly as soon as the blower was turned on, reaching a maximum value during the first minute of operation, and then decreased to a stable value 6.9 to 13.8 kPa above the initial value. Usually, the pressure dropped to below the initial value within 5 min after the blower was turned off, and gradually increased back to the initial pressure after 1.5 to 2 h. The pressure increase occurred so quickly after air injection began that it cannot be due solely to a change in the groundwater level near each MP, and must reflect a subsurface change in air pressure. This change in air pressure agrees with the theory developed by vanDijke and vanderZee [27], which suggests that air density, and thus air pressure, is not constant in the subsurface until air channels exit to the vadose zone.

In MPs not receiving air directly through a channel, the DO remained below the detection limit (0.8 mg/l) for the entire 30-min injection period and subsequent 5-day recovery period during the nine trials. A one-half detection limit value of 0.4 mg/l has been plotted on Fig. 4.

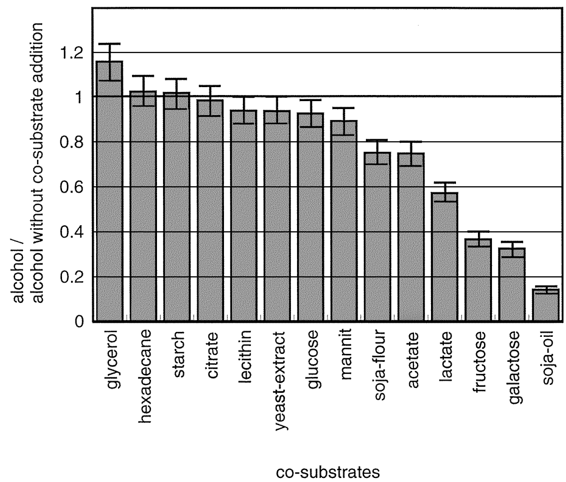

Fig. 4. Typical sensor response curve for a well that did not have air flow (IAS Trial 1-3, MP 4a3).

A typical set of sensor response curves for MPs which received air flow during IAS is shown in Fig. 5. In some MPs, there was a steady increase in pressure throughout the trial. In other MPs, a rapid increase in pressure was followed by a rapid decrease, indicating a release of pressure. During initial trials, this leakage was due to improper sealing of the instrumentation bundle in MP 4a2 or due to pressure build-up in the sampling tube that popped open the snap clamp. However, even after these problems were remedied, occasionally there still was audible bubbling in MP 4a2 during the trials. Approximately 1.8 m of water was above the bundle inside the casing and there was a threaded coupling 1.5 m above the bundle. If air was able to move up the outside of the casing and into it along the threads of the coupling, that air would move through the remaining 30 cm of water in the casing, producing audible bubbling. Although the MPs were installed by a direct-push technique to reduce this type of problem, it is possible that, despite the precautions taken during installation, air was still able to leak continually from MP 4a2.

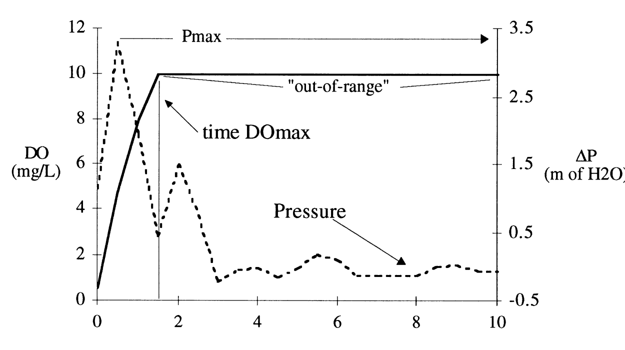

Fig. 5. Sensor response curves for wells that received air flow during IAS (Trial 3-2, MP 4a2).

During the IAS trials, the DO probes in several MPs registered voltage responses that were too high to be recorded by the 21X datalogger. These ‘‘out-of-range’’ values have been plotted as 10 mg/l because the saturated DO in the groundwater at the WTS site is approximately 9 mg/l. Laboratory tests confirmed that the high voltage response occurred when the probes were either operating in rapidly bubbling water or when they were removed from the water entirely. This ‘‘out-of-range’’ response suggests that these MPs received air directly through channels from the IAS well.

3.2. Sensor response analysis

The monitoring grid at the WTS site was designed to allow collection of random samples from MPs representing the entire zone of influence of a remediation system, and for the analysis of the data by a three-factor (two-way factorial in a randomized block design) ANOVA model [24]. Because responses were anticipated through time and the nine trials had to be conducted sequentially, the variance in the data due to time (sequencing) was removed from the error terms so that differences across elevations and radii might be distinguished. Because of ‘‘missing’’ saturated zone MPs on Radius b, this model had to be modified to account for the unbalanced design by using balanced subsets with reduced degrees of freedom and comparing the results from these subsets.

The ANOVA model was run for the Radii a and c subset and then for the Levels 3 and 5 subset to compare characterization parameters that were measured at each available saturated zone depth–radius combination. If the results of the ANOVA regarding a given parameter were the same for both analyses, then no further analysis was done. However, if the results did not agree, an honest significant difference (HSD) [28,29] was determined to identify where differences within factors actually existed. The ANOVA model was used to distinguish differences in the pressure and DO curve signatures for each MP across elevations and distances from the IAS well for each of the nine trials. The mean sensor response values for each Level and Radius and their HSDs are listed in Table 1 and illustrated in Fig. 6. Table 2 summarizes the ANOVA results.

Table 1
Sensor response parameters for monitoring grid. Values include all trials

Parameter	Level 3	Level 4	Level 5	Level HSD
ΔP_{max} (m of water)	0.372	1.35	1.11	0.573
$t\Delta P_{max}$ (min)	4.01	3.78	16.28	10.7
tDO_{max} (h)	0.50	0.18	0.40	0.20
ΔtDO_{max} (h)	22.6	130.9	113.0	NSD
	Radius a	Radius b	Radius c	Radius HSD
ΔP_{max} (m of water)	1.29	0.871	0.454	0.311
$t\Delta P_{max}$ (min)	9.00	8.72	5.91	NSD
tDO_{max} (h)	0.33	0.38	no change	no test
ΔtDO_{max} (h)	104.2	118.2	no change	no test

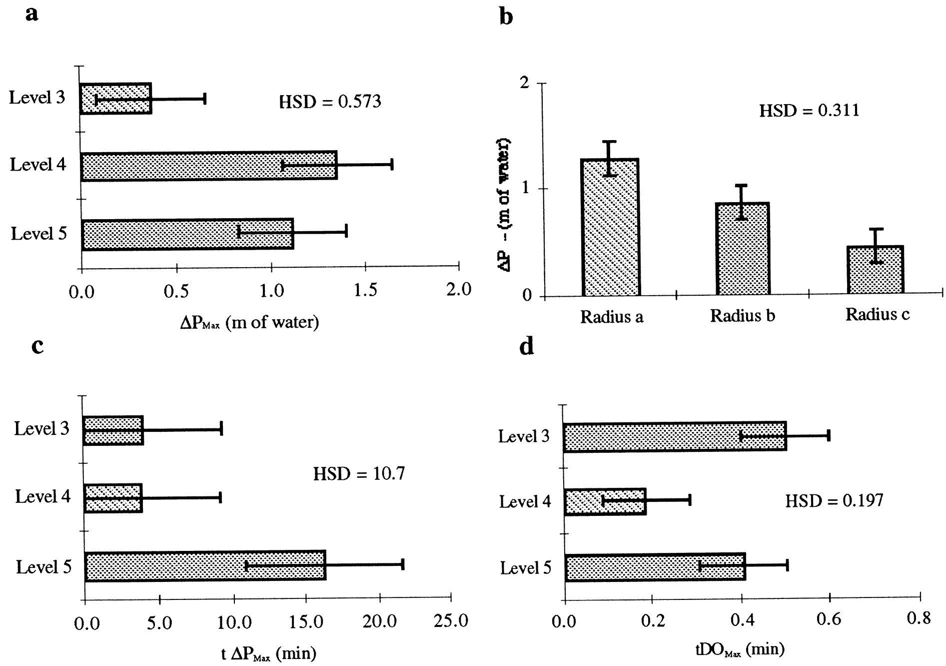

Fig. 6. Sensor results during IAS trials by Level and Radius: (a) and (b) ΔP_{max}, (c) $t\Delta P_{max}$, (d) $\Delta t\mathrm{DO}_{max}$.

Differences in ΔP_{max} during the nine trials between Level 3, and Levels 4 and 5 (Fig. 6a) and between Radii a and c (Fig. 6b) are due to the facts that the IAS well screen was at the same depth as the Level 5 MPs and Radius a is closer to the IAS well (0.9 m) than Radius c (3.4 m). Similarly, $t\Delta P_{max}$ was shorter for the Level 3 and Level 4 MPs than for the Level 5 MPs (Fig. 6c). The pressure in the shallower MPs is released as soon as the air finds a pathway to the water table and the Level 3 points are located very close to the water table while the Level 5 points are located at least 3 m below it. The $\Delta t\mathrm{DO}_{max}$ is shorter for the Level 4 MPs than for the Level 5 MPs (Fig. 6d) because, for many trials, air reached MP 4a2 immediately upon turning on the blower.

Table 2
IAS sensor data ANOVA results

Parameter	Level	Radius
ΔP_{max} (m of water)	L3 < L4, L5	Rc < Ra
$t\Delta P_{max}$ (min)	L3, L4 < L5	NSD
$t\mathrm{DO}_{max}$ (h)	L4 < L3, L5	no test (Ra > Rb, Rc)
$\Delta t\mathrm{DO}_{max}$ (h)	NSD	no test (Ra > Rb, Rc)

NSD = no significant difference at $\alpha = 0.05$.

No statistical test for significance was possible for comparing tDO_{max} and ΔtDO_{max} as a function of radius, as neither subset of data was balanced. However, the physical explanation for the ''missing data'' is useful. Except for MP 5b2, only Radius a probes recorded a change in DO during the trials, so the time until the DO reached a maximum was less in Radius a than at any other point in the grid. If the blank entries for tDO_{max} and ΔtDO_{max} in the other MPs were replaced with very large values (indicating an infinite period of time before air reached the MP) and zero, respectively, there would be a significant difference between the Radius a MPs and the other MPs in the monitoring grid.

There was no change in the oxygen concentration ($[O_2]$) in any of the 16 vadose zone MPs during or following any of the nine trials. Oxygen concentration in the vadose zone was between 8% and 14% by volume throughout the study, and there was no indication that injected air was moving into the vadose zone MPs. Based on the preferential pathways that developed in the saturated zone and the relatively small volume of air that was injected in each trial, this result is not surprising.

3.3. Air travel to monitoring points

A DO increase to an ''out-of-range'' value, as shown in Fig. 5, occurred in at least four of seven different MPs during each trial except Trial 2-1, indicating that air moved directly from the IAS well to the MP. All of those MPs were in Radii a and b (within 1.5 m of the IAS well), but the same MPs were not affected during every trial. The order of air arrival may indicate the order of subsurface channel formation. An analysis using the coefficient of concordance [30] indicated that the order of air arrival was not ''the same'' among all nine trials; i.e., channels which developed during one trial did not necessarily develop during the next.

A sequential order analysis was conducted to find trials that had ''the same'' order of air arrival in the MPs. That is, Trials 1-1 and 1-2 were compared and found to be similar using a Spearman rho procedure [31], and then Trials 1-1, 1-2, and 1-3 were compared using the coefficient of concordance analysis. This process was repeated until adding a trial resulted in the order no longer being similar for the group. The last trial was dropped and an ''average'' order for the group was determined using a weighted ranking.

The results of this analysis of similarity in the ''average'' order of groups of trials are included in Table 3, which indicates there is a 99.99% chance that five MPs received air flow in ''the same'' order in Trials 1-1 through 1-3. The orders for Trials 2-1 and 2-2 are not similar to each other nor to any other trials. Five MPs received air flow in ''the same'' order in Trials 2-3 through 3-3.

These results are illustrated in Figs. 7 and 8 and provide new insight into the mechanics and benefits of pulsed operation of IAS systems and groundwater mixing [32,33]. Figs. 7 and 8 show that once preferential pathways were established in the tight, stratified soil, those ''channels'', though not identical, did not change much with successive injection pulses, as there was little restriction of air flow to force the injected air into other areas.

Table 3
Order significance for air arrival in monitoring points

Comparison	Procedure	*m*	n	Calculated	ZZ table	*P*	rho	rho Table	Similar?
Trials 1-1, 1-2	Spearman rho		5				1.0000	0.786	Y
Trials 1-1 thru 1-3	Coefficient of Concordance	3	5		0.9999	0.0001			Y
Trials 1-1 thru 2-1	Coefficient of Concordance	4	7	0.54	0.7054	0.2946			N
Trials 1-2, 1-3	Spearman rho		7				1.0000	0.786	Y
Trials 1-2, 1-3, 2-1	Coefficient of Concordance	3	7	0.57	0.7157	0.2843			N
Trials 1-3, 2-1	Spearman rho		5				0.7500	1	N
Trials 2-1, 2-2	Spearman rho		5				0.7500	1	N
Trials 2-2, 2-3	Spearman rho		6				0.8571	0.886	N
Trials 3-1 thru 3-3	Coefficient of Concordance	3	6	1.69	0.9545	0.0455			Y
Trials 2-3 thru 3-3	Coefficient of Concordance	4	6	1.65	0.9505	0.0495			Y
All 9 Trials	Coefficient of Concordance	9	7	1.26	0.8962	0.1038			N

The ''average'' time it took for air to arrive at each MP is listed in Table 4. Nearly immediate (less than 2 min) short circuiting of air flow between the IAS well and MPs 4a2 and 5a2 occurred in every trial, while air arrived at other MPs sometime thereafter. The rapid short circuiting to MPs 4a2 and 5a2 may have been due to their intersecting an air pocket that formed under a confining layer above the IAS well screen, or to cracking of the native fine silty loam soil by vibration during the installation of the driven well points, or to some combination of both.

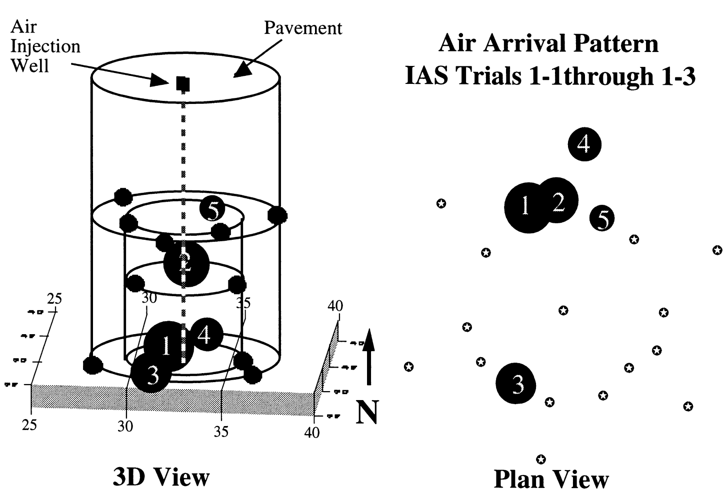

Fig. 7. Average order of air arrival: IAS Trials 1-1 through 1-3.

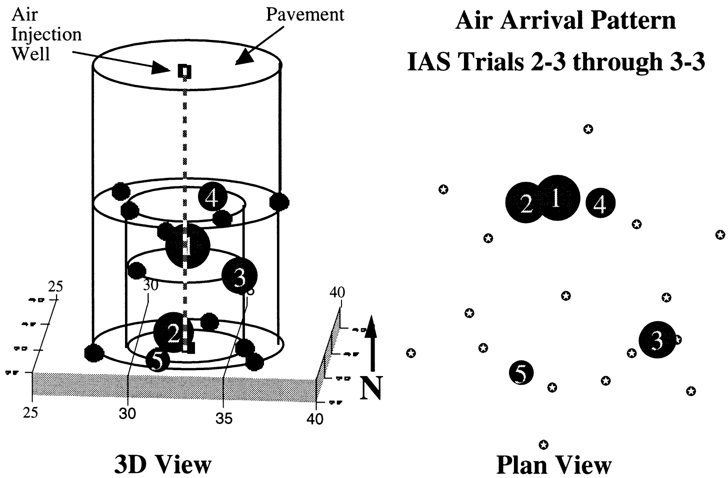

Fig. 8. Average order of air arrival: IAS Trials 2-3 through 3-3.

Air arrival times of more than 5 min might indicate travel through small-diameter, newly forming channels. However, a more likely scenario, and one supported by the proximity of the affected MPs to one another, is that air flow out of MPs 4a2 and 5a2 could not accommodate the 5.1 m^3/h air injection rate. Therefore, as the channels leading to 4a2 and 5a2 were pressurized, preferential pathways were eventually established to other close, Radius a MPs.

A series of nine additional tests was conducted to further investigate how air was moving among the MPs. Air was injected for 10 min with all MPs containing instrumentation bundles as in the original nine trials. After a rest period, the bundle was removed from MP 4a2 and/or MP 5a2 and it was sealed at the surface with a rubber cap and hose clamp. Then air was injected for 10 more minutes. When MP 4a2 was sealed at the surface there was little change in head in MP 3a2, but when 4a2 was sealed with the bundle, the DO probe in 3a2 responded as if the water was bubbling rapidly and the total head increased by 0.6 m. This response was repeated in successive open and sealed trials leading to the conclusion that air moved to MP 3a2 through MP 4a2.

Table 4
Elapsed time for air arrival at each well during IAS trials

1-1 through 1-3		2-3 through 3-3	
Well Point	Average time (min)	Well Point	Average time (min)
5a2	0.2	4a2	0.1
4a2	1.7	5a2	1.5
5a3	5.0	4a1	4.4
5b2	7.3	3a2	5.7
3a2	30.3	5a3	16.1

Another interesting observation from these sealing tests is that, even though there was a rest period of at least 20 min between each pulse, some spaces that were filled with air during an injection remained filled until the next injection. As reported by others [34–36], one explanation for this observation is that an air bubble formed under a confining layer in the saturated zone and that air was more rapidly released from the bubble at MPs that penetrated this confining layer. This supports the explanation of the short-circuiting to MPs 4a2 and 5a2 presented previously.

As illustrated in Table 3, the order of air arrival for Trials 2-1 and 2-2 were not similar to each other nor to the other trials. It seems likely that conditions in the subsurface were altered during these two trials and preferential pathways were established that did not change during the remainder of the study. Although the currently popular idea of change of air travel due to the collapse and reformation of channels is one possibility, the explanation probably is simpler.

Following these IAS trials, the same MPs were used to investigate an in-well aeration (IWA) system at the site [24]. During installation of the IWA well, the IAS well was pulled from the ground and a through-wall, circumferential crack in the casing was discovered at approximately 4.9 m, which is the depth of the bottom of the Level 4 well screens. The crack appeared oxidized, indicating that it had been exposed to corrosion for some time prior to its removal from the ground. A combination of events (stress during installation, vibration during air injection, etc.) may have caused the casing to crack through after Trial 1-3 and before Trial 2-3 (personal communication with Caryn Bacon, Metallurgical Engineer, P.E., April 10, 1998). Once this crack developed, air no longer left the IAS well exclusively from the screen, and a large portion of air may have moved directly from the casing to MP 4a2 (only 90 cm away) and escaped out of it. The channel between the IAS well and MP 4a2 that was established during the first three trials was reinforced from this new opening in the casing and did not collapse during the remaining trials. While this cracking of the injection well may have reinforced the channel directly from the well to MP 4a2, the data from Trials 1-1, 1-2, and 1-3 were not compromised by the cracking. The data collected during the first three trials indicate that short-circuiting was occurring and support conclusions drawn from all nine trials.

3.4. Contaminant response

The effect of IAS on HC distribution below the site was determined by collecting one set of groundwater samples prior to injection and one set 2 weeks after each series of injection trials. The HC data were then divided into the five balanced groups, and the ANOVA model was run for each of these subsets. As mentioned, subsets of the data had to be analyzed to account for the unbalanced design because of missing MPs on Radius b. If a significant difference was indicated in either Level or Radius for several of the subsets, an HSD was calculated for each subset and the largest HSD was used to compare the means.

There was no change in the average concentration of any compound analyzed across all MPs at each Level in the monitoring grid through the injection trials. This result is not surprising, as the volume of air introduced during any 30-min trial (2550 l) was inadequate to strip or to stimulate aerobic decomposition of a significant mass of the contaminant.

Prior evaluation of the contaminant plume [23], using traditional MWs screened over approximately 3 m of soil, indicated that higher water table elevations (i.e., shallower) tend to result in higher HC concentrations (for MW 1, $R^2 = 0.89$ and 0.92 for correlation between depth to water and benzene and xylene concentrations, respectively). A significant mass of residual HC appears to be trapped in the capillary fringe just above the water table, which is not always saturated. This hypothesis is supported by the results of this study, as the concentrations of TPH and most analyzed constituents were significantly greater at Level 3 than at either Level 4 or 5, as illustrated for benzene in Fig. 9. Also, no difference in the concentration of any constituents was evident across the four radii, as illustrated for benzene in Fig. 9, indicating that the ‘‘source’’ zone for this plume extends beyond the boundaries of the 12-m diameter monitoring grid.

For some of the compounds within several of the subsets, the ANOVA results indicated that the concentrations were different at some Level–Radius combinations than at others. Review of interaction plots for all subset analyses indicated that the cause was the extreme difference in Level 3 concentrations from those at Levels 4 and 5. Most compounds had higher concentrations closer to the center of the grid on Level 3 but not on Level 4 or 5. For cases in which the interaction term was significant, the interaction plots were analyzed to determine if there was a true effect due to radius. For all subsets and all compounds, the Level 3 concentrations were different from the Levels 4 and 5 values by at least the HSD, but the difference among radii was not significant; thus, the radius effect was negated. This typical interaction is illustrated for benzene in Fig. 10.

Continual mass reduction over time is a good indicator of contaminant removal, and changes in the center of mass (CoM) location can identify plume migration or uneven oxygen distribution. The total mass of contaminant and the CoM location for constituents based on the dissolved phase concentration at each MP were estimated using a Thiessen area procedure [24,37]. As with the concentration, the total mass did not change between sampling events. As illustrated for benzene (Fig. 11), the CoM location changed only by 0.5 m and did not move in a consistent direction. The biggest change occurred between the pre-IAS sample and the three post-IAS samples, and is due to the difference in the number of MPs that were sampled (pre-IAS = 25 of 33; Post 1 = 30; Post 2 = 29; and Post 3 = 30). This small movement of the CoM is consistent for all compounds analyzed.

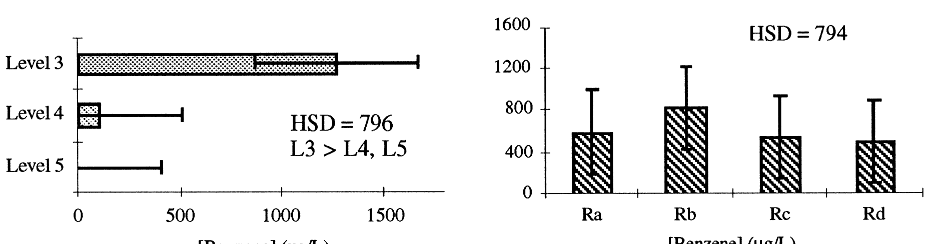

Fig. 9. Concentration of benzene at Layton site by Level and Radius.

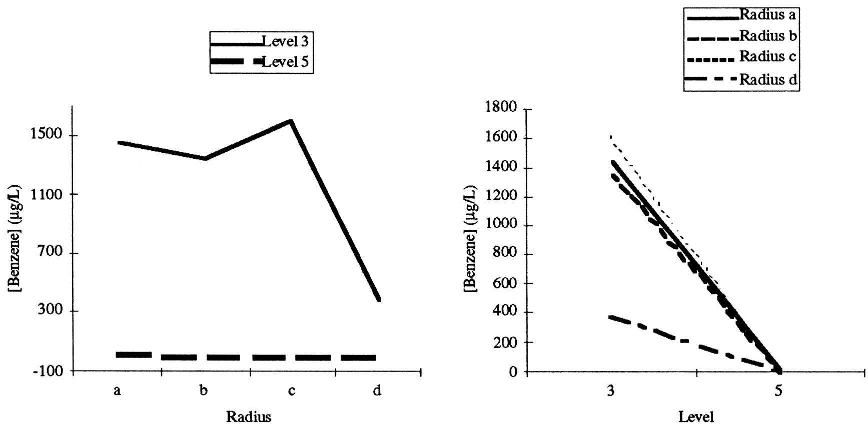

Fig. 10. Interaction plots for D subset of benzene data.

As in the saturated zone, no changes in the HC constituent concentrations were measured in the vadose zone MPs during the four sampling events. In fact, only samples from MP 1d1, which was located in the area where the USTs were removed and very near a sewer drainline trench (see Fig. 2), had concentrations that exceeded detection limits. This area had the highest HC concentrations both prior to and after operation of the IAS system. The HC data, along with the $[O_2]$ sensor responses, indicate that very little transfer of gases or vapors occurs through the vadose zone at the site except in the higher permeability corridor along the drainline trench and excavation pit. This conclusion was confirmed after completing the IAS trials by injecting helium into the IAS well at a flow rate close to the 5.1 m^3/h used for the trials. Measurable concentrations of helium were present during the test in the gases released from MP 4a2 (46% by volume), and in MP 1d1 (0.5 mg/l of air) within 25 h after injection was terminated [6].

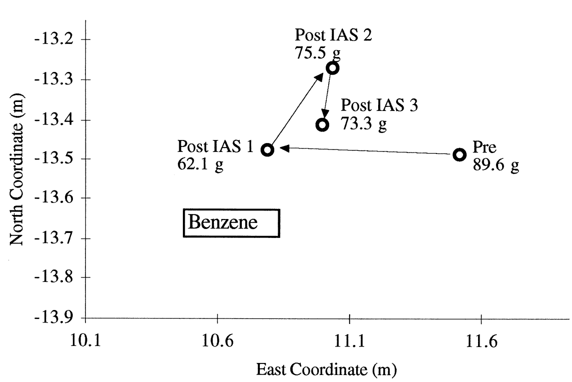

Fig. 11. Center of mass trajectory of benzene in the monitoring grid during IAS trials.

3.5. Oxygen consumption

Because of the almost immediate leak of air from MPs 4a2 and 5a2, it was not possible to conduct traditional shut-down tests (as described by Hinchee and Ong [38]) to determine oxygen uptake rates in either the saturated or vadose zones. However, because continuous DO data have not been readily available to investigate oxygen consumption and to predict oxygen requirements for saturated zone, aerobic remediation, oxygen consumption rates were estimated for this IAS system.

Fig. 12 illustrates the DO data for MP 4a2 during each successive IAS injection. Trial 3-3 is not included, as data during 20 to 70 h elapsed time (the period of DO decline) were lost. As described previously, DO increases almost immediately to an ''out-of-range'' value followed by a period when the water was either pushed completely out of the MP or was bubbling rapidly. Except for Trials 2-2 and 2-3, the DO decreased rapidly to 4 to 6 mg/l 2 to 3 h after injection stopped, and then gradually decreased further to below the detection limit of 0.8 mg/l. The period during the gradual decline was used to estimate an oxygen uptake rate constant for each trial for each MP in which DO increased during injection.

The procedure used for the groundwater DO data reduction was similar to that used for shut-down data for bioventing and soil vapor extraction systems so the results could be compared with vadose zone oxygen uptake rates. Zero- and first-order rate constants were calculated for each trial using only data falling within the calibrated range of the DO probes. Based on an evaluation of the rates calculated by Hall [24], although some MPs fit a zero-order model better, the rates tended to be first-order. When both zero- and first-order regression relationships were significant (i.e., the 95% confidence intervals did not overlap zero), which was true for most calculations, residual plots were reviewed to identify the relationship resulting in the most random plot of residuals. None of the residual plots were shown to be truly random, however, suggesting that neither the zero- nor first-order reaction rate models accounted for all of the variability in oxygen consumption observed over time at this site.

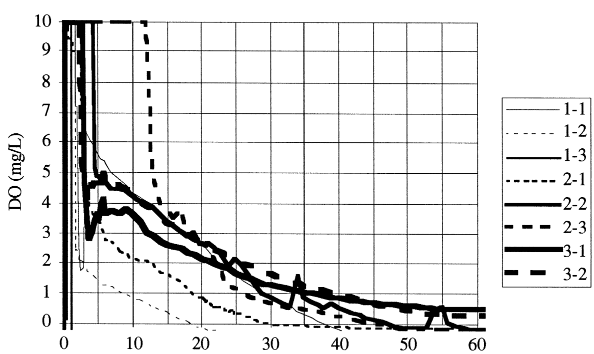

Fig. 12. DO for MP 4a2 for all trials.

The oxygen uptake rates during the IAS field trials were estimated at 2 to 6 mg DO/day. The oxygen uptake rate of the Technalithics Laboratory polarographic probe was estimated at 0.2 to 0.5 mg DO/day in a series of laboratory tests [24]; thus, the decline shown in Fig. 12 was not entirely due to oxygen depletion by the probe. Because of the short duration of the tests, changes in HC mass could not be detected to corroborate the use of 1.5 to 5.5 mg DO/day for biodegradation of contaminants. Other possible causes of the rapid oxygen decrease are diffusion, reaction with inorganic oxygen sinks, and advection of non-aerated groundwater into the monitoring point. However, the low sulfide and iron species' concentrations at the site [23], the expected slow oxygen diffusion rate, and estimated radial groundwater velocities of less than 0.07 to 0.14 ft/day [6] suggest that most of the oxygen was consumed in the aerobic respiration of hydrocarbon contaminants. Changes in hydrocarbon concentration, as a result of these air injections, was not measurable because of the huge reservoir represented by residual HC saturation at the site (Fig. 1).

4. Conclusions

Although IAS has been used for soil and groundwater remediation since the mid-1980s, review of the published literature revealed only a limited number of field investigations at sites that were adequately instrumented, indicating a need for a full-scale study to assess the applicability of IAS at any given site. A cylindrical monitoring grid comprised of 49 MPs was installed at a gasoline-contaminated site, and a single IAS well was operated for nine 30-min injection trials separated by at least 5 days. In situ instrumentation bundles containing a DO probe, a pressure transducer, a thermocouple, and a sampling tube were sealed in each MP and the responses of the sensors were recorded with a Campbell Scientific, 21X DataLogger.

Short-circuiting of air to two MPs 0.9 m from the IAS well occurred within 2 min after injection began. Air eventually arrived at least two other MPs during eight of the nine trials. Even with this short-circuiting, pressure increased rapidly when the blower was turned on, followed by a steady, more gradual decline. As expected, the pressure increase was greater in MPs deeper and closer to the IAS well than in MPs near the water table or the edge of the monitoring grid. The monitoring system was able to describe the asymmetry of air flow in the saturated zone and evaluate the effectiveness of IAS at the site, even though it may have provided an air migration pathway from the IAS well to the vadose zone. This demonstrates the importance of having an adequate monitoring system for evaluating the effectiveness (or ineffectiveness) of IAS at any site.

Because air pathways developed so quickly and because the distribution of affected MPs was asymmetrical, the injected air probably moved through the subsurface in channels and there was not a ''volume'' of soil that was oxygenated. However, the order of air arrival at the MPs changed during the trials. The order was the same for the first three trials, but was significantly different for the next two. Finally, an order was established that remained relatively unchanged for the last four trials. It appears that during the fourth and/or fifth trials a large, preferential pathway was established which did not collapse between trials.

Oxygen uptake rates estimated for MPs that received air during any trial tended to be first-order and exceeded the consumption rates of the DO probes. However, as there were no contemporaneous HC data, the portion of the 1.5 to 5.5 mg DO/day used for biodegradation of contaminants could not be determined. Because low concentrations of sulfide and iron species that might consume oxygen have been measured at the site [23] and groundwater velocities are too low to support advection of non-aerated groundwater into the MPs, the majority of the oxygen probably was consumed in aerobic respiration. In any case, the Technalithics Laboratory probes can measure in situ DO over short time periods, and could be used to estimate oxygen transfer during system operation, or oxygen uptake during shutdown tests.

Short-term trials indicated that IAS technology is ‘‘infeasible’’ [8] for remediation of soil and groundwater at the gasoline-contaminated WTS site. It was apparent after one 30-min trial that air was short-circuiting to at least one MP. Had the system been operating effectively, a longer-term test might have allowed the volume of influence of the IAS well or the oxygen transfer rates to be estimated. With the data available from the monitoring system, had the first trial been a pilot test conducted prior to installing a system of IAS wells at the site, the technology would have been deemed inappropriate based on the short-circuiting due to the low horizontal hydraulic conductivity of the soil. For this reason, it is recommended that effectively monitored pilot tests be conducted at sites with lower conductivity soils.

Acknowledgements

The U.S. Environmental Protection Agency, through the Regions VII and VIII Hazardous Substance Research Center, funded this work. In-kind contributors include Campbell Scientific, Technalithics Laboratory, Wasatch Environmental, and Wasatch Trailer Sales.

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