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Effect of groundwater flow on remediation of dissolved-phase VOC contamination using air sparging

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Abstract

This paper presents two-dimensional laboratory experiments performed to study how groundwater flow may affect the injected air zone of influence and remedial performance, and how injected air may alter subsurface groundwater flow and contaminant migration during in situ air sparging. Tests were performed by subjecting uniform sand profiles contaminated with dissolved-phase benzene to a hydraulic gradient and two different air flow rates. The results of the tests were compared to a test subjected to a similar air flow rate but a static groundwater condition. The test results revealed that the size and shape of the zone of influence were negligibly affected by groundwater flow, and as a result, similar rates of contaminant removal were realized within the zone of influence with and without groundwater flow. The air flow, however, reduced the hydraulic conductivity within the zone of influence, reducing groundwater flow and subsequent downgradient contaminant migration. The use of a higher air flow rate further reduced the hydraulic conductivity and decreased groundwater flow and contaminant migration. Overall, this study demonstrated that air sparging may be effectively implemented to intercept and treat a migrating contaminant plume.

Keywords: In situ air sparging; VOCs; Groundwater remediation; Groundwater flow; Saturated soils

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1. Introduction

In situ air sparging has proven to be an effective means of remediating saturated soils and groundwater that have been contaminated with volatile organic compounds (VOCs). However, little is known about how site-specific subsurface variables, namely soil

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heterogeneity, contaminant type/location, and groundwater flow affect the relative contributions of the mass transfer, transport, and transformation mechanisms that are critical to the remedial performance of air sparging [1–3].

In relatively permeable soils like sands or gravels, groundwater flow can be relatively high. If dissolved-phase VOC contamination resides within such soils, groundwater flow can substantially smear the contaminant plume, greatly expanding the size of the contaminant plume beyond the original spill. When air is injected into these soils during air sparging, not only will vapor-phase partitioning of the contamination occur, the injected air during air sparging will affect the flow of the groundwater passing through the zone of influence. Additionally, the flowing groundwater may affect the air flow and therefore the size and shape of the resulting zone of influence. The interaction between the two migrating fluids (air and water) may adversely affect the performance of air sparging.

Very few studies have addressed the effects of groundwater flow on air sparging performance. Rutherford and Johnson [4] performed a laboratory study to investigate the effects of air flow and groundwater flow on oxygenation rates during the use of air sparging. It was determined that when low air injection rates were utilized ($Q_{\mathrm{air}} < 10$ l/min), the injected air had little effect on the water flow field. Increased air flow led to a larger zone of influence and a greater air channel density within the zone of influence. The increased air channel density led to an increased air/water interfacial area, increasing the rate of oxygenation of the flowing groundwater. Once an air injection rate of 20 l/min was reached, further increases in air injection rates did not increase the size of the zone of influence or the air channel density within the zone of influence. The high air injection rate, however, affected groundwater flow; the increased air saturation within the zone of influence decreased the relative permeability of water, forcing the flowing groundwater to circumvent the zone of influence. Because the water avoided the zone of influence, the rate of oxygenation of the groundwater was reduced as a result of the reduced air/water interfacial area.

Gordon [5] reported a field system where air sparging is used for the treatment of migrating contaminant plumes and prevention of off-site migration. The system included 134 air injection wells and 58 soil vapor extraction wells arranged in 15 legs. Except in the potential source areas where the legs are arranged to provide maximum coverage, the legs are oriented perpendicular to groundwater flow to serve as curtains to downgradient flow. The legs are sequentially pulsed for increased treatment. No skirting of the treatment zone was observed, and it was determined that the redundant legs provided more efficient treatment.

Under most natural groundwater flow conditions, volumetric flux through aquifer material is small. Even for thick aquifers, flow is on the order of a few liters per minute. Instead of a network of injection wells, either an open trench or a trench backfilled with cohesionless soil sparged with air was suggested as an effective method to remediate and also prevent off-site contaminant migration [6]. Based on such a concept, Marley et al. [7] reported an air sparging system used to prevent VOC migration at a site in the eastern USA. To prevent the contaminant plume from migrating into a nearby stream, a 360-ft long segmented trench was installed to intercept the VOC plume. The 1-m wide trench was backfilled with material that had a greater hydraulic conductivity than the native soil. Additionally, the air flow rate was carefully chosen to achieve target cleanup rates while limiting the reduction of relative permeability for water flow within the trench. This prevented the groundwater from circumventing the trench.

To date, a critical assessment of how injected air flow is affected by groundwater flow and vice versa has not been made. Additionally, the relative contributions of volatilization and removal and off-site advective–dispersive transport of contaminants with groundwater are unknown. This study presents the results of controlled physical model tests conducted to determine how air sparging will be affected in settings with considerable groundwater flow as well as how to optimize remediation of dissolved-phase VOC contamination under such conditions. Such an investigation is necessary because dissolved-phase VOC contamination often exists within the mobile fraction of groundwater and thus may be subjected to substantial off-site migration due to groundwater flow. It is essential to determine how air sparging can be implemented to remediate this type of contaminant condition as well as help prevent further off-site contaminant migration.

2. Objectives and scope

The objective of this investigation is to assess the interaction between injected air flow and groundwater flow and determine how this interaction affects air flow patterns and ultimately the performance of air sparging. Additionally, the contributions of contaminant removal through volatilization/vapor-phase partitioning and groundwater flow-induced advective–dispersive transport were assessed. Two-dimensional aquifer simulation tests utilizing homogeneous coarse sand soil profiles contaminated with dissolved-phase benzene subjected to a groundwater flow were conducted. Two different air injection rates were utilized to study how different air injection rates affect air sparging performance under such conditions.

3. Experimental methodology

3.1. Experimental test setup

A two-dimensional aquifer simulation test setup, shown in Fig. 1, has been developed to study spatially dependent variables that affect air sparging. The large dimensions of the setup allow for the placement of a heterogeneous soil profile, including soil layers, lenses and other localized variations. The simulator also offers additional flexibility by allowing control of contaminant placement and options related to groundwater flow. A detailed description of the test setup is provided by Reddy and Adams [8].

3.2. Testing program

Two tests were performed to study the effect of groundwater flow on the removal of a dissolved VOC plume using air sparging. Both tests used a homogeneous coarse sand soil ($D_{10} = 0.43$ mm, $D_{50} = 0.55$ mm, $k = 4.64 \times 10^{-2}$ cm/s) profile subjected to a hydraulic gradient of 0.011. One test was subjected to an air flow of 2500 ml/min, and the other test used an air flow of 4750 ml/min. An initial contaminant zone with an initial benzene concentration of 200 mg/l was formed in each soil profile. These tests were compared to a test previously performed by the authors [8] with identical soil and contaminant conditions subjected to air flow rate of 2225 ml/min under static groundwater condition in order to assess the effect of groundwater flow.

3.3. Testing procedure

When preparing a test, two stainless steel sheets were placed into the soil chamber (see Fig. 1) to create three sub-chambers. This allowed to make the middle chamber, which extends approximately 20 cm on either side of the sparge location as the initial contaminant source zone. Soil was placed into the soil chamber by maintaining a consistent drop height. A benzene solution with a concentration of 200 mg/l was then injected from the bottom port (see Fig. 1) to completely saturate the middle chamber. While the contaminant was placed in the middle chamber, the two outside sub-chambers were simultaneously saturated with clean tap water that infiltrated from the water reservoirs (see Fig. 1). Once the contaminant zone was established and saturation of the side sub-chambers was completed, the steel sheets were removed from the soil profile, the tank lid was fastened and sealed in place, and effluent air tubes fitted with activated

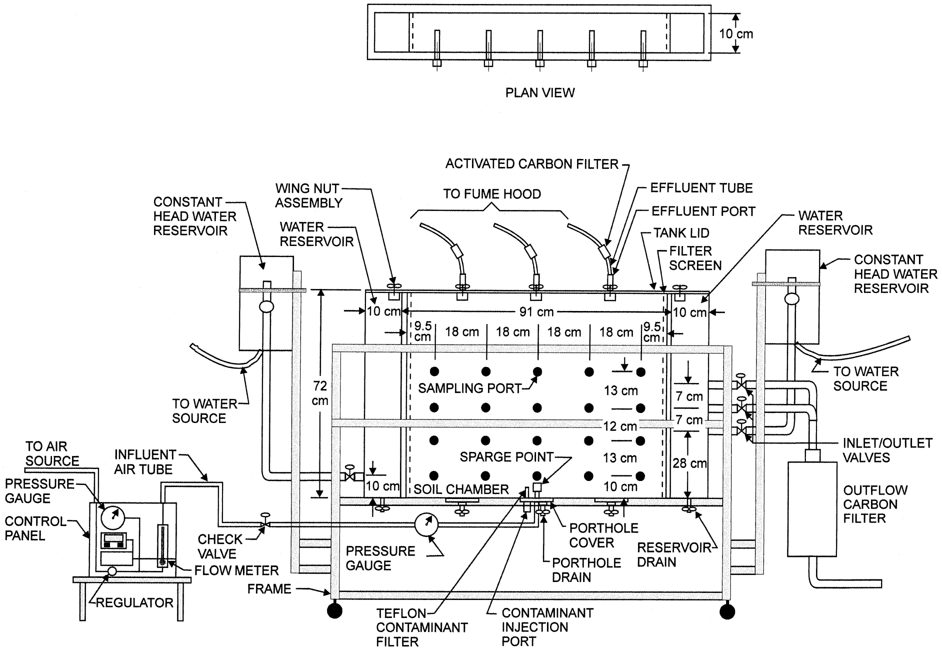


Fig. 1. 2-D aquifer simulation apparatus.

carbon filters were fastened to the tank lid effluent ports. The initial benzene concentration distribution was determined through sampling and analysis of the pore water from the sampling ports. A detailed description of the soil profile, benzene solution, and the initial contaminant zone is provided by Reddy and Adams [8].

To study the effect of groundwater flow, a groundwater gradient was established across the soil profile. The adjustable water reservoirs were adjusted to provide the desired water level within the tank reservoirs. The height difference in the water levels between the influent and effluent reservoirs was maintained at 1 cm, providing a gradient, $(\Delta h/l)$, of 0.011 over the 91-cm length of the soil profile. Once the gradient and a steady discharge flow rate were established, air injection began.

During the course of testing, air was continuously injected at a specified flow rate and injection pressure. Two air injection rates were used: 2500 ml/min (denoted as low air flow) and 4750 ml/min (denoted as high air flow). Both air flow rates were injected under a pressure of 4.5 kPa. Pore water sampling and analysis were performed in the same manner as described by Reddy and Adams [8]. Additionally, both the water within the outlet reservoir and the effluent flow from the test apparatus were analyzed for benzene regularly to determine the extent of benzene migration and/or removal as a result of the migrating groundwater. The effluent groundwater flow passed through a carbon filter to remove benzene before discharging.

4. Results and analysis

4.1. Air injection without groundwater flow

A test was performed in which a homogeneous coarse sand soil profile contaminated with dissolved-phase benzene was subjected to air sparging with an injection rate of 2225 ml/min [8]. This test was performed using a static groundwater condition. Fig. 2 shows the zone of influence of the injected air. The parabolic zone of influence intercepted a substantial portion of the initial contaminant plume, leading to vapor-phase partitioning and efficient removal of the dissolved-phase benzene. However, a sizeable portion of the contaminant plume was not traversed by the injected air flow, relying upon diffusion for contaminant removal. Diffusion is a rate-limiting process; therefore, tailing of residual contaminants occurred, leading to increased time of injection required for complete benzene removal.

4.2. Low air injection during groundwater flow

This test was performed in a homogeneous coarse sand layer subjected to an air flow of 2500 ml/min and groundwater flow under a hydraulic gradient of 0.011. Once groundwater flow was established, air injection began. The resulting air flow pattern and zone of influence were very similar to the previous test performed without groundwater flow as depicted in Fig. 2. The only exception occurred in the upper left region of the initial contaminant zone, where a slight decrease in air channel density was observed. However, this effect was slight and likely resulted from a localized effect within the soil,

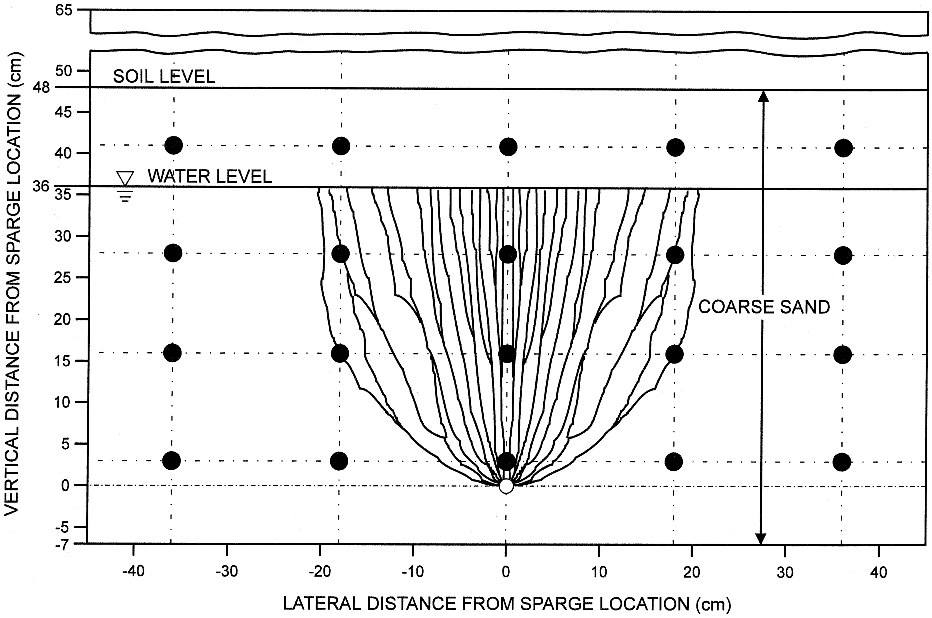


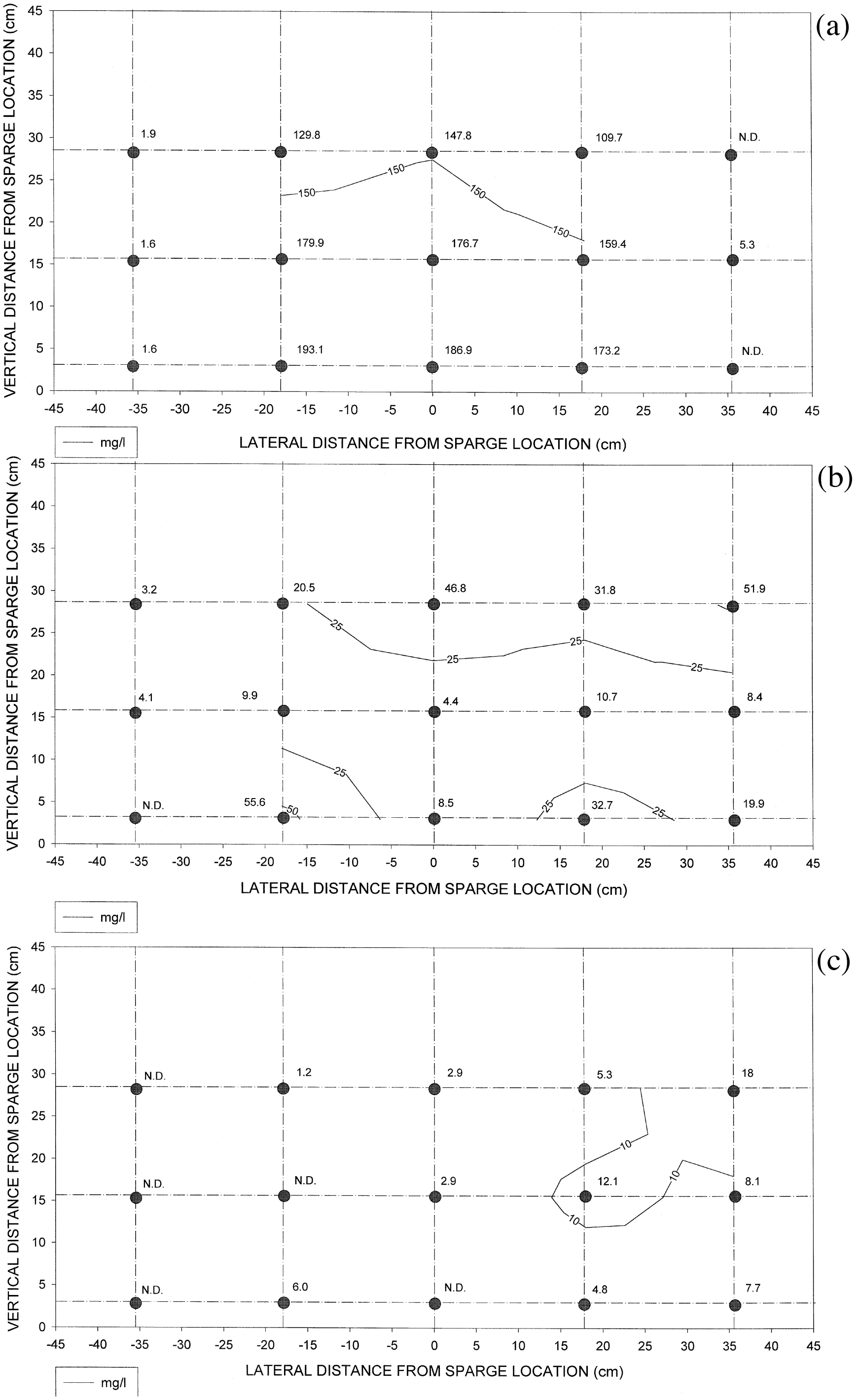
Fig. 2. Air flow pattern in saturated coarse sand: air flow arte = 2250 ml/min and static groundwater condition.

such as a lower void ratio, as opposed to migrating groundwater. It is important to note that the groundwater flow did not affect the size or shape of the zone of influence.

Fig. 3(a) shows the initial contaminant distribution within the pore water of the soil profile. The initial aqueous phase benzene concentrations ranged from 109 to 193 mg/l. After 70 min of air injection, the contaminant distribution was greatly altered by both the air flow and the groundwater flow, as shown in Fig. 3(b). As in the test performed without groundwater flow, the regions immediately surrounding and above the sparge or injection location experienced substantial contaminant removal within 70 min of air injection. The aqueous benzene concentrations in these regions ranged from 4 to 46 mg/l. The regions to the left and right of the sparge location that are outside of the zone of influence also experienced substantial contaminant removal during this time period as well. The aqueous benzene concentrations in these regions were reduced to 32 to 55 mg/l. It is important to note that a substantial increases in contaminant concentrations, with aqueous concentrations ranging from 3 to 52 mg/l, were detected in regions that were initially contaminant-free.

As shown in Fig. 3(b), the region in the immediate vicinity of the point of injection experienced a substantial reduction in benzene concentration. This region was subjected to the greatest volumetric air flow. Increased benzene concentrations were detected with

Fig. 3. Benzene distribution for test with air flow rate = 2500 ml/min and with groundwater flow: (a) time = 0 min, (b) time = 70 min, and (c) time = 160 min.


(a)
VERTICAL DISTANCE FROM SPARGE LOCATION (cm)
LATERAL DISTANCE FROM SPARGE LOCATION (cm)
mg/l
1.9
129.8
147.8
109.7
N.D.
150
150
150
150
1.6
179.9
176.7
159.4
5.3
1.6
193.1
186.9
173.2
N.D.
(b)
3.2
20.5
46.8
31.8
51.9
25
25
25
25
4.1
9.9
4.4
10.7
8.4
25
N.D.
55.6
50
8.5
25
32.7
25
19.9
(c)
N.D.
1.2
2.9
5.3
18
10
10
10
N.D.
N.D.
2.9
12.1
8.1
N.D.
6.0
N.D.
4.8
7.7
0
5
10
15
20
25
30
35
40
45
-45
-40
-35
-30
-25
-20
-15
-10
-5

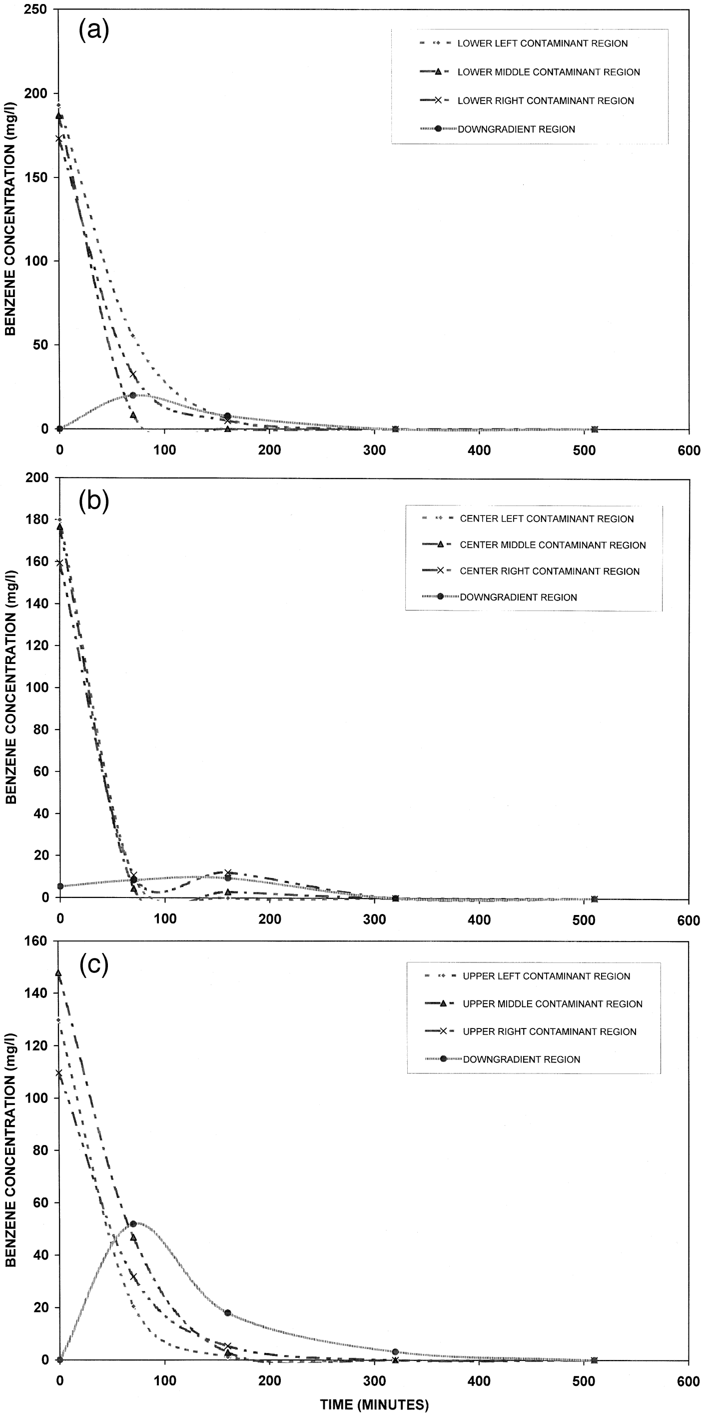
increasing height above the injection point as a result of lower air channel density, leading to less efficient benzene vapor-phase partitioning due to saturation of the migrating air. Additionally, regions in the middle and upper left and right of the initial contaminant zone experienced major benzene concentration reductions. The regions immediately to the left and right of the point of injection experienced sizable benzene concentration reductions, but the rate of removal was lower in these regions than in other initially contaminated regions. Further injection led to continued contaminant concentration reductions. As shown in Fig. 3(c), minor concentrations were detected within the zone of influence after 160 min of air injection.

The substantial removal that occurred from the initial contaminant zone is the result of two important mass transfer phenomena. First, a zone of influence with a high density of pore scale air channels created a large interfacial mass transfer area. The resulting high air saturation greatly expedited the partitioning of dissolved-phase benzene into the vapor phase through volatilization. Regions in the vicinity of the injection point experienced faster benzene removal due to higher air flow density and saturation (the lateral expansion of the zone of influence with increased elevation reduced the density of air flow and interfacial mass transfer area in the upper contaminant regions). Also, the migrating air induced vertical contaminant migration due to advective–dispersive transport by the groundwater. This migration did not produce any substantial degree of increased benzene concentration because the migrating air responsible for the contaminant migration also accounted for removal through volatilization.

Dissolved-phase benzene removal due to vapor-phase partitioning did not, however, account for total removal of benzene mass within the initial contaminant zone. Advective–dispersive transport induced by groundwater flow resulted in lateral benzene migration. In regions of high groundwater flow, advective transport controls mass transfer. This is verified by the substantial increases in benzene concentration in regions downgradient from the initial contaminant zone. As shown in Fig. 4(a), the region downgradient from the lower region of the initial contaminant zone experienced aqueous-phase benzene infiltration after 70 min of air injection. While Fig. 4(b) depicts little downgradient migration from the middle region of the initial contaminant zone, Fig. 4(c) shows that a sizable downgradient infiltration occurred from the upper region of the initial contaminant zone. Fig. 4(c) shows that after 70 min of air injection, a benzene concentration of 50 mg/l was detected downgradient from the upper region of the initial contaminant zone. Additionally, benzene was detected in both the downgradient water reservoir as well as the effluent groundwater flow from the soil profile.

The migration of groundwater also accounted for the removal of benzene from the regions to the left and the right of the injection point. The benzene in the region to the left of the injection point migrated through groundwater flow-induced advective–dispersive transport towards the injection point. Upon entering the zone of influence, the migrating benzene efficiently partitioned into the vapor phase through volatilization. Benzene initially located within the right side of the initial contaminated region,

Fig. 4. Benzene concentration vs. elapsed time for test with air flow rate = 2500 ml/min and with groundwater flow: (a) lower regions, (b) center regions, and (c) upper regions.


(a)
LOWER LEFT CONTAMINANT REGION
LOWER MIDDLE CONTAMINANT REGION
LOWER RIGHT CONTAMINANT REGION
DOWNGRADIENT REGION
BENZENE CONCENTRATION (mg/l)
250
200
150
100
50
0
0
100
200
300
400
500
600
(b)
CENTER LEFT CONTAMINANT REGION
CENTER MIDDLE CONTAMINANT REGION
CENTER RIGHT CONTAMINANT REGION
DOWNGRADIENT REGION
BENZENE CONCENTRATION (mg/l)
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
(c)
UPPER LEFT CONTAMINANT REGION
UPPER MIDDLE CONTAMINANT REGION
UPPER RIGHT CONTAMINANT REGION
DOWNGRADIENT REGION
BENZENE CONCENTRATION (mg/l)
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
TIME (MINUTES)

especially within the region immediately to the right of the injection point, never entered into the zone of influence and as a result migrated downgradient due to advective–dispersive transport. The benzene within the middle and upper regions of the initial contaminant zone also migrated through groundwater flow-induced advective–dispersive transport, but since the zone of influence encompassed these regions, off-site migration from these regions was minimized.

The high degree of air saturation within the zone of influence reduced the relative water permeability, which in turn reduced groundwater flow-induced advective–dispersive transport of contamination from regions within and upgradient from the zone of influence. Additionally, the reduced water flow rate increased the residence time of the groundwater within the zone of influence. As a result, the contribution of aqueous/vapor-phase benzene partitioning is increased. Therefore, by reducing permeability, the extent of off-site advective–dispersive transport of groundwater migration is reduced. Although not included in this study, measurement of degree of air saturation and consequent effects on the relative permeability of water and air phases will help explain the flow dynamics and contaminant removal.

Continued groundwater flow and air injection result in complete benzene removal after 510 min, as shown in Fig. 5. The initial benzene mass remaining with respect to time is plotted for tests with and without water flow, respectively. As shown in the figure, removal occurs much faster when the soil profile is subjected to groundwater flow. As previously discussed, groundwater flow induced advective–dispersive transport

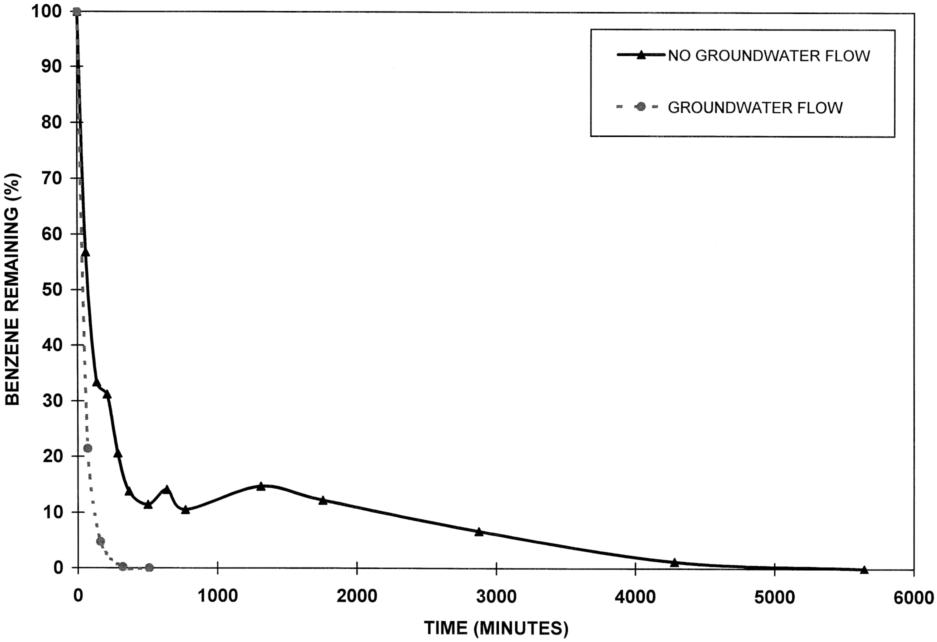


Fig. 5. Effect of groundwater flow on benzene removal under injected air flow rate of 2500 ml/min.

of dissolved-phase benzene out of the profile, accounting for a portion of the initial benzene mass. The groundwater also caused portions of the plume upgradient from the zone of influence to migrate into the zone of influence, leading to vapor-phase partitioning and removal. In the test without groundwater flow, contamination outside of the zone of influence had to migrate through diffusive transport into the zone of influence for removal. This rate-limiting process led to lengthy remedial times required for removal. Therefore, if sparging is implemented to intercept migrating contaminant plumes, the flow of groundwater will actually assist in contaminant delivery to the treatment zone and faster overall removal.

Fig. 6 shows the relative contributions of benzene removal from the soil profile due to the injected air flow as well as off-site migration due to groundwater flow-induced advective–dispersive transport. After 60 min of air injection, nearly 55% of the initial benzene mass has been removed from the soil profile through vapor phase partitioning while 20% has migrated out of the soil profile with the effluent groundwater. A small portion (less than 2%) resided within the outflow groundwater reservoir. With continued air injection, additional benzene migration with the effluent groundwater flow occurred, but the contribution of this was greatly lessened; only an additional 7% of the initial benzene mass migrated out of the soil profile due to advective–dispersive transport during the remainder of the test. Nearly 15% of the initial benzene mass, however, was additionally removed through vapor-phase partitioning with further injection. The major-

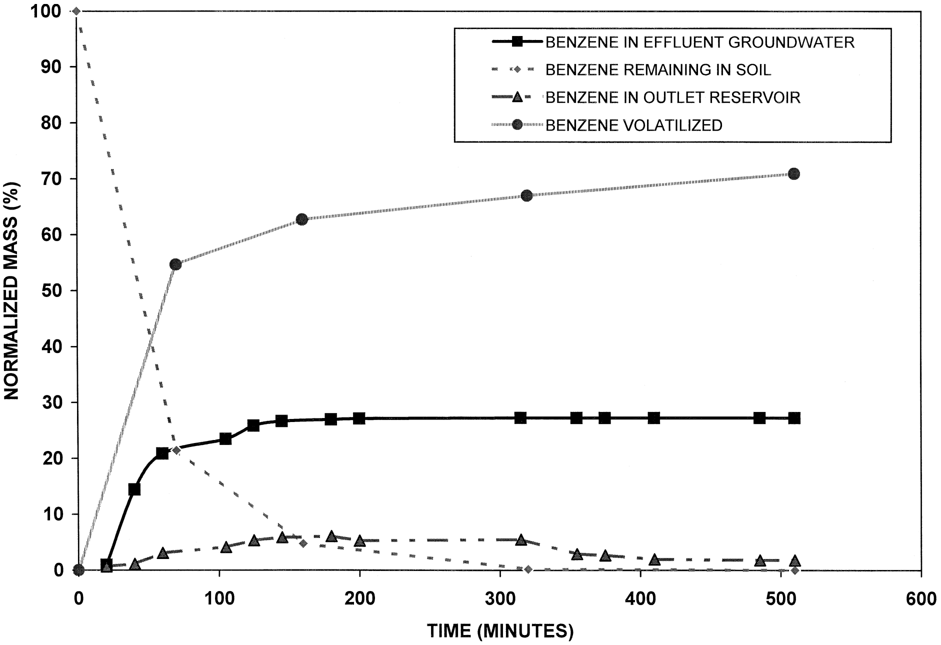


Fig. 6. Mass of benzene remaining vs. benzene removed for test with air flow rate = 2500 ml/min and with groundwater flow.

ity of the benzene mass that migrated out of the soil profile with effluent groundwater flow initially existed in regions downgradient from the zone of influence. The benzene mass initially within or upgradient from the zone of influence was removed through volatilization, although a minimal portion migrated out of the zone of influence with the groundwater flow.

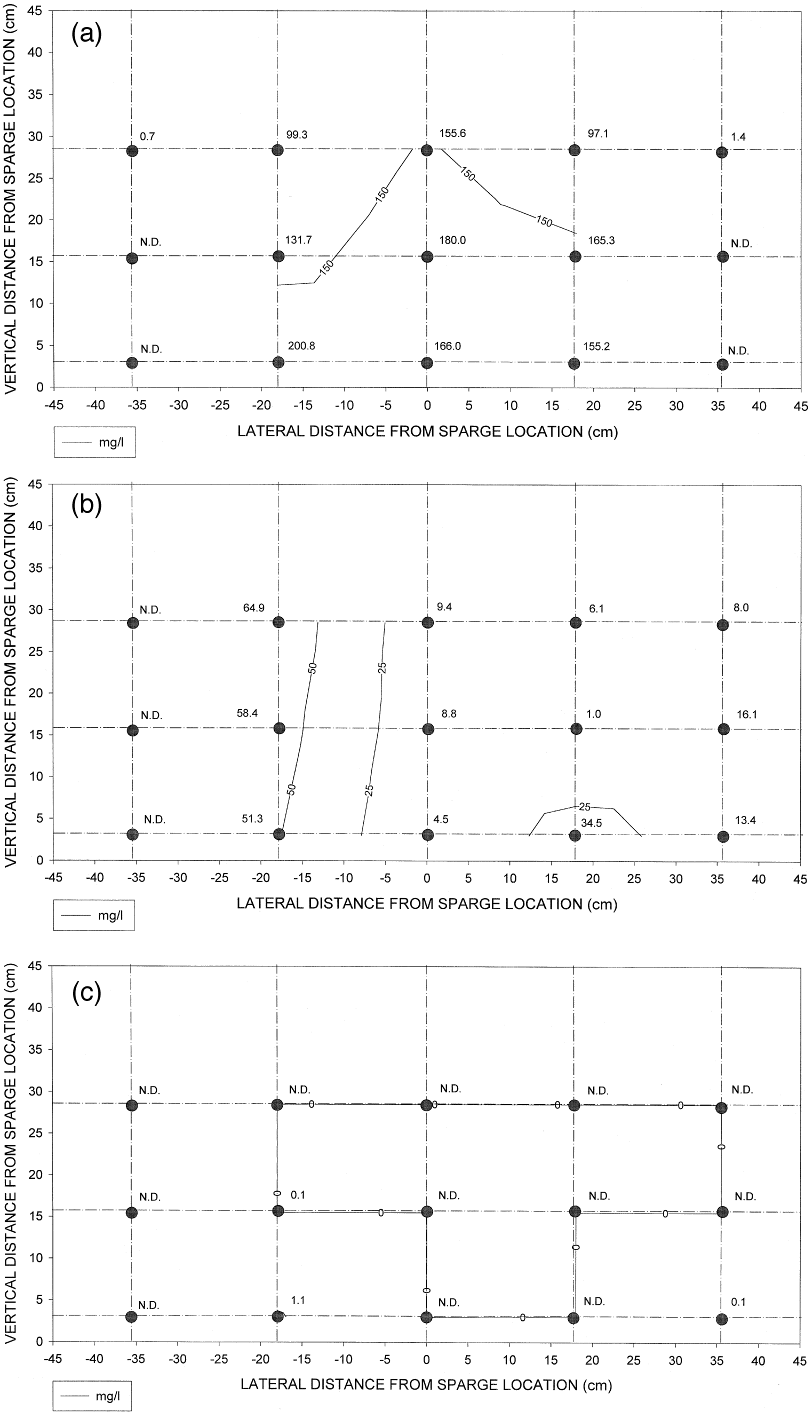
4.3. High air injection during groundwater flow

To study the effect of increased air flow on air saturation and its potential to control spreading of contaminants, an additional test was performed using an increased air injection rate of 4750 ml/min. Once groundwater flow was established, air injection began. The resulting zone of influence was very similar to that observed in the previous test. Since a higher volumetric air flow was confined to the same region of flow, a greater air saturation within the zone of influence resulted. A greater interfacial mass transfer area was developed for benzene to partition into the vapor phase as well as reduced relative permeability for groundwater flow. Rutherford and Johnson [4] determined that increased air flow increased the size of the zone of influence and air channel density; however, an enlarged zone of influence was not observed during this test; rather, a greater air channel density was observed.

The initial contaminant distribution, as shown in Fig. 7(a), is relatively uniform, but slightly reduced concentrations were detected in the upper left and upper right regions of the initial contaminant zone. As shown in Fig. 7(b), after 70 min of injection, significant reductions in benzene concentration occurred within the entire initial contaminant zone. As in the previous test, regions to the immediate left and right of the injection point also experienced significant benzene concentration reductions, but to a lesser extent when compared to other regions. It is interesting to note that the right side of the initial contaminant zone appears to experience a greater rate of benzene removal than the left side of the zone. Although a symmetric zone of influence was observed, a greater volume of air flow may have traversed the right side of the initial contaminant zone, leading to more efficient vapor-phase partitioning and subsequent removal. Nevertheless, the increased air injection utilized in this test led to efficient benzene removal. The entire soil profile was essentially contaminant-free after 265 min, as shown in Fig. 7(c).

As in the previous test, benzene concentrations are greater in the upper regions of the initial contaminant zone compared to the lower regions after an initial period of air injection. This effect is not as great as that observed in the previous test, however, it is attributed to the increased rate of air injection. Although this air flow rate would theoretically increase vertical advective–dispersive dissolved-phase benzene migration, the increased interfacial mass transfer area due to increased air saturation in the upper regions allowed for more efficient benzene partitioning from the aqueous phase into the vapor phase than in the previous test with a lower air injection rate.

Fig. 7. Benzene distribution for test with air flow rate = 4750 ml/min and with groundwater flow: (a) time = 0 min, (b) time = 70 min, and (c) time = 265 min.


(a)
0.7
99.3
155.6
97.1
1.4
N.D.
131.7
180.0
165.3
N.D.
N.D.
200.8
166.0
155.2
N.D.
150
150
150
150
(b)
N.D.
64.9
9.4
6.1
8.0
N.D.
58.4
8.8
1.0
16.1
N.D.
51.3
4.5
34.5
13.4
50
50
25
25
25
(c)
N.D.
N.D.
N.D.
N.D.
N.D.
N.D.
0.1
N.D.
N.D.
N.D.
N.D.
1.1
N.D.
N.D.
0.1
0
VERTICAL DISTANCE FROM SPARGE LOCATION (cm)
LATERAL DISTANCE FROM SPARGE LOCATION (cm)
mg/l
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
45

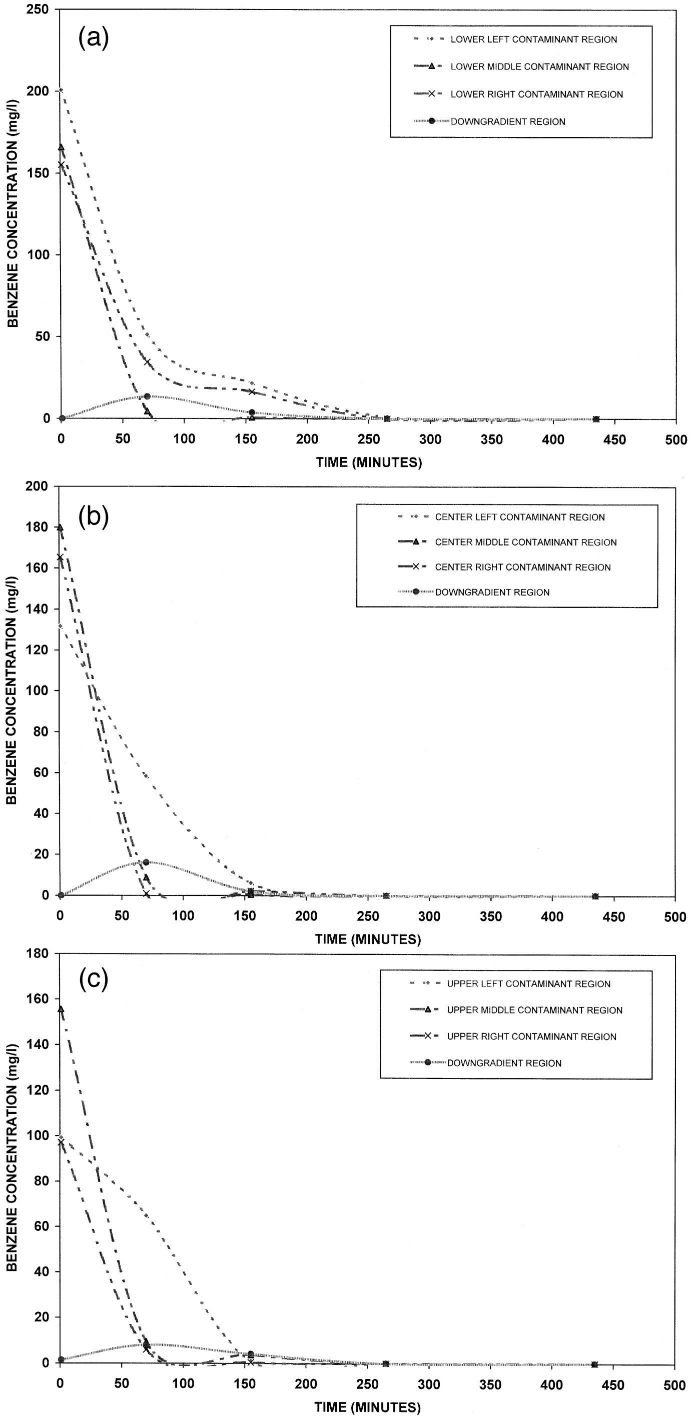
The increased air flow not only expedited removal through volatilization due to increased air saturation and mass transfer area, the increased air saturation also reduced benzene advective–dispersive transport due to groundwater flow. The increased rate of aqueous/vapor phase partitioning contributed to reduced off-site migration, but the increased air saturation also reduced the relative permeability for groundwater flow. As shown in Fig. 7(b), regions downgradient from the zone of influence that were initially free of benzene concentration experienced infiltration due to groundwater-induced advective–dispersive transport, but the extent of this effect is lessened when compared to the previous test utilizing a lower air injection rate.

Because the air flow lessened off-site migration and subsequent contamination downgradient from the zone of influence, as shown in Fig. 8(a)–(c), less benzene existed outside the zone of influence. When this smearing effect occurred in the previous test, a portion of the benzene infiltrated regions of the soil profile not directly impacted by air flow. This contamination could only be removed from the soil profile through advective–dispersive transport, a less efficient process than volatilization. Therefore, the increased air injection had a three-fold effect; increased air flow increased the mass transfer area required for greater volatilization; downgradient migration was prevented by increasing the contaminated groundwater residence time within the zone of influence; and greater air flow led to less contaminant smearing into regions unaffected by air flow, thus confining contamination to a region where more efficient removal occurred.

As shown in Fig. 8(a)–(c), concentrations within regions downgradient from the initial contaminant zone reached peak values of 10–20 mg/l after 70 min of air injection, followed by subsequent reduction and eventual removal. Additionally, advective–dispersive transport of aqueous-phase benzene from regions within the initial contaminant zone to the left and the right of the injection point were lessened due to reduced groundwater permeability. As shown in Fig. 8(a), after 155 min, benzene concentrations within these two regions were higher than in the previous test after a similar elapsed time. The reduced permeability resulting from the increased air flow lessened the advective–dispersive transport of aqueous-phase benzene from these regions.

The relative contributions of benzene volatilization and advective–dispersive transport due to injected air and groundwater flow are illustrated in Figs. 9 and 10. In Fig. 9, the percentage of initial mass remaining with respect to time is shown for the test without groundwater flow as well as the two tests subjected to groundwater flow. As shown, the rate of removal using a high air flow rate is very similar to that of the previous test subjected to lower air flow, indicating similar rates of removal. However, in Fig. 10, the relative removal contributions of volatilization and advective–dispersive transport are notably different from the previous test. After 70 min, nearly 70% of the initial benzene mass was removed through volatilization compared to 55% using a lower air injection rate. Additionally, off-site migration from the soil profile, measured based on concentrations in outlet reservoir and effluent groundwater, was reduced to 10% from

Fig. 8. Benzene concentration vs. elapsed time for test with air flow rate = 4750 ml/min and with groundwater flow: (a) lower regions, (b) center regions, and (c) upper regions.


(a)
BENZENE CONCENTRATION (mg/l)
0
50
100
150
200
250
TIME (MINUTES)
0
50
100
150
200
250
300
350
400
450
500
LOWER LEFT CONTAMINANT REGION
LOWER MIDDLE CONTAMINANT REGION
LOWER RIGHT CONTAMINANT REGION
DOWNGRADIENT REGION
(b)
BENZENE CONCENTRATION (mg/l)
0
20
40
60
80
100
120
140
160
180
200
TIME (MINUTES)
0
50
100
150
200
250
300
350
400
450
500
CENTER LEFT CONTAMINANT REGION
CENTER MIDDLE CONTAMINANT REGION
CENTER RIGHT CONTAMINANT REGION
DOWNGRADIENT REGION
(c)
BENZENE CONCENTRATION (mg/l)
0
20
40
60
80
100
120
140
160
180
TIME (MINUTES)
0
50
100
150
200
250
300
350
400
450
500
UPPER LEFT CONTAMINANT REGION
UPPER MIDDLE CONTAMINANT REGION
UPPER RIGHT CONTAMINANT REGION
DOWNGRADIENT REGION

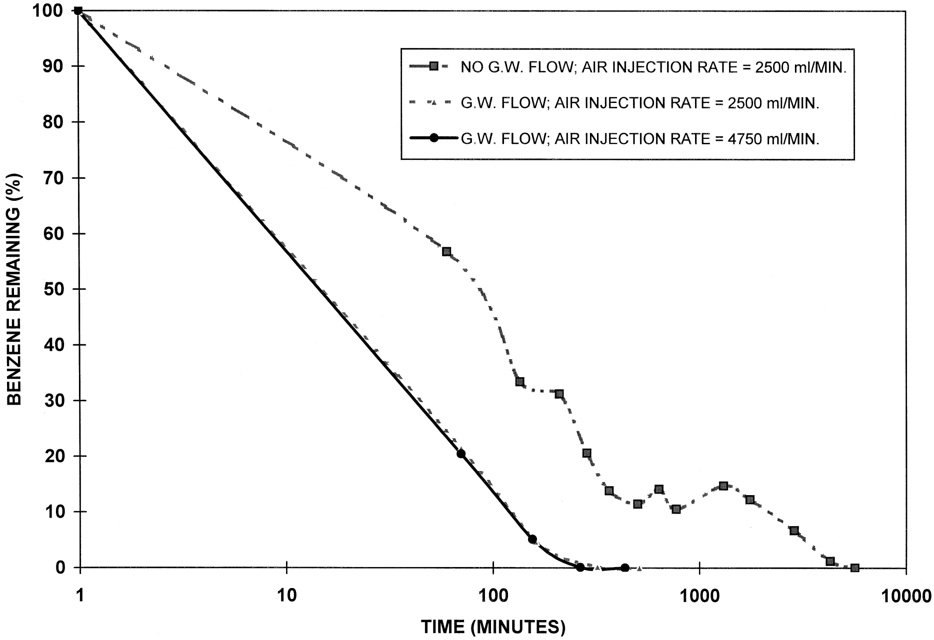


Fig. 9. Effect of air injection rate and groundwater flow on benzene removal.

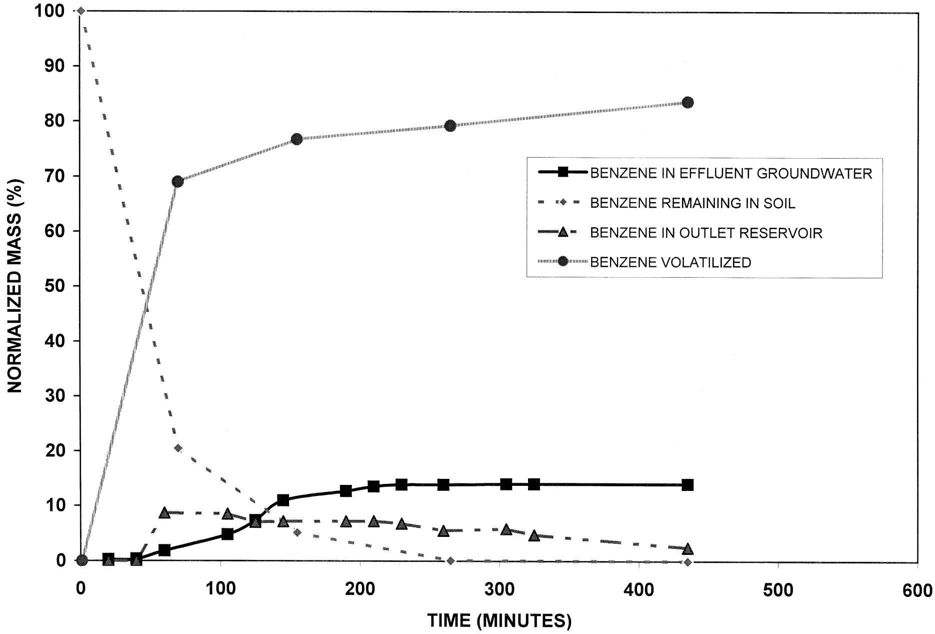


Fig. 10. Mass of benzene remaining vs. benzene removed for test with air flow rate = 4750 ml/min and with groundwater flow.

nearly 20% using a lower air injection rate. Upon completion of the test, nearly 85% of the initial benzene mass was removed from the soil profile through volatilization, thereby reducing off-site effluent benzene migration to 15% of the initial mass. Although the removal rates were similar for both air flow rates, the higher air flow rate resulted in greater volatilization contribution to contaminant removal and reduced off-site contaminant migration due to groundwater flow.

Benzene that migrated with the groundwater was initially located downgradient from the zone of influence. Benzene initially located within or upgradient from the zone of influence was effectively prevented from migrating downgradient from the zone of influence. Increased air flow lessened the contribution of advective–dispersive transport. Therefore, it demonstrates that increased air flow will lessen downgradient migration of a contaminated groundwater plume, reducing off-site contamination.

5. Practical implications

The results of this study have numerous implications for field application of air sparging. Air sparging can be used in relatively permeable soils (e.g., sands), under groundwater flow conditions. However, caution must be exercised for the potential smearing of the contaminant plume, resulting in downgradient contaminant migration under groundwater flow conditions.

Air sparging results in increased air saturation, consequently reducing the relative hydraulic conductivity. The reduced hydraulic conductivity results in reduced groundwater flow and subsequent downgradient contaminant migration. Using an increased air injection rate may further reduce hydraulic conductivity; however, too much air injection may reduce the relative hydraulic conductivity to the extent that groundwater flow may bypass the zone of influence. Therefore, a careful assessment of the changes in relative permeability of water and air phases and their effects on the groundwater flow and contaminant removal should be performed.

Under groundwater flow conditions, remedial strategy may include using air sparging as a ‘‘fence’’ to intercept the contaminant plume. If the air injection flow rate does not create preferential groundwater flow, air sparging may be used to effectively intercept and treat migrating contaminant plumes. Care must be taken to assure that the entire contaminant plume is intercepted to prevent contaminant from circumventing the treatment zone. Additionally, an air sparging system must be designed to effectively intercept the entire contaminant plume and assure that contamination does not initially reside downgradient from the zone of influence.

6. Conclusions

This study investigated the effects of groundwater flow on the performance of air sparging. Homogeneous coarse sand profiles contaminated with dissolved-phase benzene were subjected to a hydraulic gradient of 0.011 as well as a no-flow condition. Two different air injection rates were used to investigate how injected air interacts with groundwater flow. The following conclusions may be drawn from this study.

(1) The shape of the injected air zone of influence was not affected by groundwater flow when the hydraulic gradient was less than or equal to 0.011. The shape of the zone of influence was very similar to that observed without groundwater flow. In both cases, the zone of influence featured similar air channel density and air saturation, and, as a result, similar removal rates due to volatilization were realized.

(2) The injected air flow did not prevent contaminant migration into regions initially free of contamination. The relative hydraulic conductivity within the zone of influence, however, was reduced, reducing advective–dispersive transport of contamination downgradient of the initial contaminant zone due to groundwater flow. Increased air flow further decreased the relative hydraulic conductivity and led to reduced downgradient contaminant migration resulting from groundwater flow. Too high of an injection rate, however, may be problematic, as preferential groundwater flow may cause contamination to circumvent the treatment zone. It was determined that most of the off-site contaminant migration resulted from contaminant initially located downgradient from the zone of influence, illustrating the need to assure that air is injected in or downgradient from contaminated regions.

(3) When air was injected into the soil profile, aqueous-phase benzene was able to partition into the vapor phase over the mass transfer area resulting from the increased air saturation within the zone of influence. Advective–dispersive mass transport of the benzene also resulted from air injection. The air injection-induced transfer/transport processes were shown to dominate over the advective mass transport induced by groundwater flow, demonstrating that air sparging can be effectively implemented within contaminated soils subjected to groundwater flow for remediation and to help prevent downgradient migration.

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