



## Factors affecting air sparging remediation systems using field data and numerical simulations

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### Abstract

Field data from five air sparging sites were used to assess the effect of several soil, contaminant, and air sparging system factors on the removal time and associated costs required to reach specified clean-up criteria. Numerical simulations were also performed to better assess the field data and to expand the data sets beyond the five field sites. Ten factors were selected and evaluated individually over a range of values based on information from practitioners and the literature. Trends in removal time and removal cost to reach a specified clean-up criterion were analyzed to ascertain the conditions controlling contaminant removal with variations in each factors' value. A linear sensitivity equation was used to quantify system dynamics controlling the observed contaminant removal trends for each factor. Factors found most critical across all field sites in terms of removal time and/or cost were contaminant type, sparge pulsing schedule, number of wells, maximum biodecay rate, total soil porosity, and aquifer organic carbon content. Factors showing moderate to low effect included the depth of the sparge point below the water table, air injection rate/pressure, horizontal air conductivity, and anisotropy ratio. At each field site, subsurface coverage of sparged air, sparged air residence time, contaminant equilibrium in the system, contaminant phase distribution, oxygen availability to microbes, and contaminant volatility seem to control the system responses and were affected by one or more of the 10 factors evaluated.

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### 1. Introduction

In situ air sparging is a remediation technique effective in removing volatile and semi-volatile organic compound (VOC and SVOC) contamination in the saturated zone. Air

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sparging technique involves forcing air through points at or below the water table forming a zone of partial desaturation, known as the radius of influence (ROI), around each injection point. Through a process known as air stripping, solubilized and sorbed VOCs within the ROI volatilize and migrate to the vadose zone where they can be captured by a soil vapor extraction (SVE) system, commonly used with air sparging. Air sparging also induces microbial degradation of contaminants by enhancing aerobic subsurface conditions. Under such conditions, microbes can utilize the organic chemicals as a substrate for growth and energy [1].

Air sparging has been shown to be effective in removing several types of contaminants with relatively high Henry's Law constants ( $K_H > 10^{-5}$ ) such as the lighter petroleum compounds (C<sub>3</sub>–C<sub>10</sub>) and chlorinated solvents [2–5]. Also, contaminants with larger aqueous solubilities and high  $K_H$  will be more readily removed because of their propensity to desorb from soil particles into the aqueous phase and subsequently diffuse to sparging air channels [6]. High soil organic carbon content results in increased sorption of organic contaminants, thus reducing contaminant concentrations in the groundwater and retarding aqueous phase transport down gradient [7].

Characteristics of the porous medium have significant effects on contaminant removal and system design factors. In air sparging, airflow distributions are directly impacted by air permeability, which is a function of particle size and distribution. Air channels, likely only a few grain sizes in diameter and formed by the injected air, make up the extent of the ROI [2,8–10]. These air channels take the path of least resistance (lowest capillary pressure) through the porous media, avoiding areas of lower permeability [11]. To impact the lower permeability regions, higher air entry pressures are needed [8]. Therefore, in highly anisotropic media, the geometry of the ROI can be highly variable [12].

For contaminant vapor movement, increases in porosity and moisture content decrease the gas movement rate [13]. VOC vapor movement will be greatest through dry, highly permeable sand or gravel and slowest through clay and wet soils, as water may reduce the contact area between the VOC and air [13,14]. Furthermore, lower permeability soils tend to have a greater capacity to adsorb contaminants because of the higher surface area to volume ratio and greater amounts of organic carbon content usually associated with such soils [15,16]. Therefore, in a heterogeneous aquifer, there can be a tendency for the majority of VOCs to be located in the areas with the least permeability [15,16], which are also least touched by sparging induced air channels [11], thus the most difficult to remediate.

During air sparging, mass transport is the primary mechanism controlling contaminant removal [17]. At the onset of sparging, contaminant mass removed is mostly from the evacuation of vapors in the soil pore space on the unsaturated zone in equilibrium with the surrounding organic contaminant [2] followed by advective and dispersive/diffusive transport of contaminant from the surrounding aqueous phase to the ROI [14]. Diffusive transport can be limited by slow mass-transfer from immobile non-aqueous phase liquids (NAPLs) to the advecting aqueous and gas phases, as well as from areas of low permeability within the aquifer [18]. Contaminant removal through air-sparging induced biodegradation is secondary to mass transport, but becomes increasingly more significant in long-term operations [19].

Braida and Ong [20] investigated the mass transfer of VOCs and showed that it occurs within a thin layer of saturated porous media next to air channels. The size of the mass

transfer zone was found to be affected by the mean particle size and the aqueous diffusivity of the VOC.

Harvey et al. [21] studied the impact of pulsed sparging on contaminant removal and reported that for the conditions they studied pulsed sparging did not improve the total removal nor the rate at which contaminants being removed.

In designing an effective remediation system for a given site, there are several factors to consider. For example, the layout of the sparging well network is highly important for contaminant removal [22]. Increases in the air injection rate and number of wells have been shown to lead to enhanced contaminant removal although the effects of increased injection rate on biodegradation are not well understood [4,6,9,18,23]. In addition, using a cyclic or pulsed sparging operation may increase VOC removal by causing agitation and mixing of the groundwater although some evidence suggests continuous sparging may be optimal [11,24–26].

To advance the evolution of air sparging systems, a better understanding of the processes that occur and their interactions during an air sparging remediation is essential. Most laboratory research has been conducted on systems that are far removed from field conditions, thus not well suited for application to air sparging at the field scale. Analysis of critical factors that focuses on practitioner-oriented results will be more applicable for field situations. In this study, field data from five air sparging sites and numerical simulations were used to assess the effect of several soil, contaminant, and air sparging system factors on the removal time and associated costs required to reach specified clean-up criteria.

## 2. Methods

Numerical modeling has proven to be a valuable tool in analyzing physical and chemical processes occurring during air sparging. A number of models have been developed in the last decade to describe multiphase flow of multiple components, contaminant removal, and microbial degradation of organic contaminants, each with their own advantages and limitations for field scale applications [4,10,13,18,27–34].

In order to identify the system dynamics affecting contaminant removal during air sparging and sensitivity to several air sparging-related factors, data from five air sparging remediation sites were analyzed with the aid of a commercially available Windows<sup>®</sup>-based numerical modeling program, BIOVENTING<sup>plus</sup> developed by Environmental Systems & Technologies [33,34]. BIOVENTING<sup>plus</sup> allows evaluation of in situ air injection or extraction system designs for the removal of organic contaminants from soil and groundwater. This modeling tool considers a number of fundamentally important processes that govern the effectiveness of a specific technology in contaminant removal. Processes considered include: horizontal and vertical airflow; multicomponent, multiphase chemical partitioning, velocity-dependent vapor stripping efficiency, oxygen-limited, nutrient-limited, or mass transfer-limited biodecay, and vacuum enhanced free product recovery [33,34]. This model was chosen for this analysis following careful field testing and consistency verification. Model selection was based on several specific criteria deemed necessary in the modeling of field remediation sites and the evaluation of several soil, contaminant, and air sparging system design factors pertinent to each site. These criteria include: (1) suitability of

describing the physical–chemical interactions taking place during air sparging remediation; (2) suitability in describing multiphase, multicomponent flow; (3) accuracy in simulating contaminant removal at field air sparging remediation sites; (4) incorporation of many of the important soil, contaminant, and system design factors in a format advantageous to their evaluation; (5) ability to describe the removal of organic contaminants over time; (6) flexibility in describing a wide range of subsurface conditions and air sparging system designs; (7) availability and ease of use. The field data from the five sites provided the base scenarios for field evaluation of the model. Additional data were generated based on these scenarios to provide a wider range of feasible cases, which were used for the additional model evaluation and comprehensive sensitivity analysis.

### 2.1. Field site descriptions

*Site 1* [5,35]: Site 1 is located in Burlington County, New Jersey. Groundwater investigations indicated the presence of a mixture of chlorinated solvents, primarily 1,1,1-trichloroethane (TCA) and trichloroethylene (TCE) in the subsurface. Affected soils extended to approximately 181 m<sup>2</sup> (1950 ft<sup>2</sup>) around a depressional area where pooled dense non-aqueous phase liquid (DNAPL) was observed. Contaminated soils extended between 1.5 and 4.6 m (5–15 ft) below the ground surface (bgs) throughout a continuous layer of medium to coarse sand and gravelly sand underlain by a hydraulically restrictive clay layer. A water table at the site was observed to range between 0.15 and 2.7 m (0.5–9 ft) bgs. The remediation system at the site consists of 134 air sparging wells and 58 SVE wells creating 15 legs operated in a 0.5 h on and 1 h off cycle. The system was started on 21 June 1995 and continues to operate at the present time.

*Site 2* [36]: Site 2 is located in Pawtucket, Rhode Island. Site soils consisted of fine to coarse sand and fine to medium gravel layers, with a water table observed at a depth of approximately 4.7 m (15.5 ft). Contamination was observed to extend between 4.6 and 7.6 m (15–25 ft) bgs. Initial remediation consisted of free product recovery, groundwater pump and treat and SVE. However, site assessment following initial remediation measures indicated that approximately 1.8–3.2 kg (4–7 lb) of residual weathered gasoline remained in the saturated zone. The subsequent remediation system consisted of 13 air sparging wells and the previously installed SVE system. Of the 13 air sparging wells, 7 were advanced to a depth of 3.7 m (12 ft) and operated on a pulsed cycle of 6 h on and 6 h off at an air injection rate of 82–245 m<sup>3</sup> per day (2–6 cfm). The remaining six wells were advanced to a depth of 1.5 m (5 ft) and operated on a pulsed cycle of 3 h on and 9 h off at an injection rate of 122–245 m<sup>3</sup> per day (3–6 cfm). Sparging was initiated at the site on 21 May 1990 and concluded 60 days later.

*Site 3* [19,37]: Site 3 is located in Porter County, Indiana. Contaminated soil and groundwater was found to contain spent non-halogenated solvents including substituted benzenes, alkanes, polyaromatic hydrocarbons (PAHs), and cycloalkanes generated from the manufacturing of tin-plate containers. The contaminant mass was estimated at 4600 kg (10,140 lb) with a maximum vertical extent of 7 m (23 ft) and horizontal extent of 400 m<sup>2</sup> (4300 ft<sup>2</sup>). Site soils were characterized as fine aeolian sands, relatively homogeneous in nature interspersed with layers of peat and marl. The water table observed at the site existed at approximately 1.5 m (5 ft) bgs. The remediation system consisted of a soil vapor collection

system and 10 equally spaced air sparging wells operated continuously at an air injection rate between 50 and 73 m<sup>3</sup> per day (1.2–1.8 cfm). System operation started in October 1992 and concluded in October 1995.

*Site 4 [38–40]:* Site 4 is a gasoline contaminated site located in Chesterton, Indiana. Gasoline contamination of site soils was limited in horizontal extent and extended from 2.74 to 3.96 m (9–13 ft) below the ground surface. However, groundwater contamination was further reaching in both vertical and horizontal extent, reaching 7.6 m (25 ft) bgs in depth and covering an area of approximately 2415 m<sup>2</sup> (26,000 ft<sup>2</sup>). Site soils consisted of surface level clay followed by fine to coarse sand with an intermediate thin clay layer creating a perched water table at 3.7 m (12 ft) in depth. A true water table was present at 4.9–5.5 m (16–18 ft). The remediation system consisted of 33 air sparging wells and four vertically drilled SVE wells. The sparging wells were operated on a pulsed cycle of 8 h on and 16 h off at an air injection rate of 20.4 m<sup>3</sup> per day (0.5 cfm). System operation started on 4 September 1996 and continues to operate at the present time.

*Site 5 [41]:* Site 5 is located in Highland, Indiana. Site investigations indicated a release of approximately 19,050 kg (42,000 lb) of gasoline or weathered gasoline affecting an area of approximately 855 m<sup>2</sup> (9200 ft<sup>2</sup>) with a vertical extent no deeper than 4.9 m (16 ft). Site soils were seen to consist of fine to medium sands with interspersed silt and clay layers underlain by a hydraulically restrictive layer of silt loam and silty clay. The water table at the site was observed to exist at approximately 2.1 m (7 ft) bgs. A total of 53 air sparging wells were used at the site with a cycles operating at approximately 5 h on and 19 h off with an injection pressure of 121 kPa (17.5 psi). Sparging at the site lasted a total of 60 days.

## 2.2. Numerical simulations

A total of 25 inputs are needed for BIOVENTING<sup>plus</sup> to perform airflow, mass recovery, and cost computation calculations. These inputs include some that are intrinsic to the site and others that need to be measured or estimated based upon site characterizations or pilot tests. Details of site properties and air sparging system design specifications required as inputs in the model are presented in Table 1 for each of the five field sites evaluated. When possible, values were determined directly from reported field investigations, otherwise literature obtained values were used.

Output generated from airflow calculations includes air pressure, pore volume turnover rate, and local efficiency at radial distances from each air sparging well. Output from mass removal calculations includes species mass remaining, and average soil, aqueous and gas phase species concentrations at specific time intervals during the duration of sparging.

BIOVENTING<sup>plus</sup> operates by calculating the airflow and air pressure distribution around each sparging well in a system using the DeGlee–Hantush–Jacob solution with adjustments considered for soil capillary head pressure and water saturation. Mass removal is then calculated using a finite difference approach that solves a mole balance equation for each species within a specified soil volume as follows:

$$\frac{-dM_i}{dt} = J_{Vi} + J_{Bi} + J_{Fi} \quad (1)$$

Table 1  
Field site details related to BIOVENTING<sup>plus</sup> model input values

Input parameter	Site 1	Site 2	Site 3	Site 4	Site 5
Horizontal air conductivity (m per day)	130 <sup>a</sup>	190 <sup>a</sup>	129.6 <sup>a</sup>	100 <sup>a</sup>	120 <sup>a</sup>
Anisotropy ratio	1.5 <sup>a</sup>	1.5 <sup>a</sup>	2.6 <sup>a</sup>	7 <sup>a</sup>	3.1 <sup>a</sup>
Total porosity	0.35 <sup>b</sup>	0.3 <sup>c</sup>	0.3 <sup>d</sup>	0.3 <sup>c</sup>	0.3 <sup>d</sup>
Pore size distribution coefficient	1.7 <sup>e</sup>	2.4 <sup>e</sup>	2.3 <sup>e</sup>	2 <sup>e</sup>	1.5 <sup>e</sup>
Organic carbon content (fraction)	0.001 <sup>b</sup>	0.002 <sup>b</sup>	0.006 <sup>d</sup>	0.006 <sup>b</sup>	0.005 <sup>d</sup>
Maximum biodecay rate (mg/kg per day)	0 <sup>b</sup>	0 <sup>d</sup>	0.34 <sup>b</sup>	0.001 <sup>b</sup>	0 <sup>b</sup>
Aquifer temperature (C)	15 <sup>e</sup>	15 <sup>e</sup>	15 <sup>e</sup>	15 <sup>e</sup>	15 <sup>e</sup>
Depth from water table to sparge point (m)	0.86 <sup>d</sup>	3.05 <sup>d</sup>	3.96 <sup>d</sup>	5.18 <sup>d</sup>	3.96 <sup>d</sup>
Well diameter including filter pack (m)	0.102 <sup>d</sup>	0.102 <sup>d</sup>	0.108 <sup>d</sup>	0.108 <sup>d</sup>	0.0508 <sup>d</sup>
Air injection rate per well (m <sup>3</sup> per day)	327 <sup>d</sup>	163 <sup>d</sup>	63.2 <sup>d</sup>	20.4 <sup>d</sup>	–
Air injection pressure per well (atm)	–	–	–	–	1.19 <sup>d</sup>
Duration of on-cycle (h)	0.5 <sup>d</sup>	6 <sup>d</sup>	Continuous <sup>d</sup>	8 <sup>d</sup>	5 <sup>d</sup>
Duration of off-cycle (h)	1 <sup>d</sup>	6 <sup>d</sup>	0 <sup>d</sup>	16 <sup>d</sup>	19 <sup>d</sup>
OCT for 2X efficiency (days) <sup>f</sup>	30 <sup>a</sup>	5 <sup>a</sup>	5 <sup>a</sup>	5 <sup>a</sup>	5 <sup>a</sup>
Number of sparging wells	134 <sup>d</sup>	6 <sup>d</sup>	10 <sup>d</sup>	33 <sup>d</sup>	53 <sup>d</sup>
Total simulation time (days)	624 <sup>d</sup>	60 <sup>d</sup>	1113 <sup>d</sup>	888 <sup>d</sup>	56 <sup>d</sup>
Spill composition	Chlorinated solvent <sup>d</sup>	Weathered gas <sup>d</sup>	Non-halo solvent <sup>d</sup>	Gasoline <sup>d</sup>	xWeathered gas <sup>d</sup>
Contaminated soil area (m <sup>2</sup> )	3902 <sup>b</sup>	36 <sup>b</sup>	408 <sup>d</sup>	3159 <sup>b</sup>	855 <sup>b</sup>
Total contaminant mass (kg)	1588 <sup>b</sup>	6.8 <sup>b</sup>	4600 <sup>d</sup>	95 <sup>b</sup>	10070 <sup>b</sup>
Contaminated soil volume (m <sup>3</sup> )	6244 <sup>b</sup>	110 <sup>b</sup>	883 <sup>b</sup>	6739 <sup>b</sup>	1812 <sup>b</sup>
TPH clean-up criteria-aq (mg/l) <sup>g</sup>	200	5	50	0.5	25
TPH clean-up criteria-soil (mg/kg) <sup>h</sup>	125	10	1500	2.5	1500
Fixed cost per well (mu)	2000 <sup>e</sup>	2000 <sup>e</sup>	2500 <sup>e</sup>	2000 <sup>e</sup>	1600 <sup>d</sup>
Other fixed costs (mu)	62000 <sup>e</sup>	62000 <sup>e</sup>	10000 <sup>e</sup>	62000 <sup>e</sup>	75000 <sup>d</sup>
Cost per unit airflow (mu/m <sup>3</sup> )	0.015 <sup>e</sup>	0.015 <sup>e</sup>	0.015 <sup>e</sup>	0.015 <sup>e</sup>	0.015 <sup>e</sup>
Other operating costs (mu per year)	20000 <sup>e</sup>	20000 <sup>e</sup>	24000 <sup>e</sup>	20000 <sup>e</sup>	360000 <sup>d</sup>
Inflation rate (% per year)	5 <sup>e</sup>	5 <sup>e</sup>	5 <sup>e</sup>	5 <sup>e</sup>	5 <sup>e</sup>

<sup>a</sup> Calibrated/adjusted value.

<sup>b</sup> Estimated from field data.

<sup>c</sup> [46].

<sup>d</sup> Field measurement.

<sup>e</sup> [33,34].

<sup>f</sup> Time required after pump shut-off to achieve 50% of the equilibrium solution concentration.

<sup>g</sup> Used for analysis of all parameters except contaminant type.

<sup>h</sup> Used for analysis of contaminant type parameter.

where  $M_i$  is the total moles of species  $i$ ;  $t$  time, and  $J_{Vi}$ ,  $J_{Bi}$  and  $J_{Fi}$  are component loss rates (moles per time) due to vapor recovery, biodecay and free product removal within the contaminated soil volume, respectively. Eq. (1) is solved using an implicit time marching scheme and the total moles of contaminant and the molar composition are updated for each time step. [33,34].

The vapor removal rate per well term,  $J_{Vi}$  in Eq. (1) is computed using the following equation:

$$J_{Vi} = EQC_{ai}^{eq} \quad (2)$$

where  $E$  is an efficiency factor corresponding to the ratio of average off-gas concentration to the equilibrium vapor concentration,  $Q$  is the total airflow rate for all wells averaged over time considering any off-cycle time for pulsed flow systems,  $C_{ai}^{eq}$  is the equilibrium vapor concentration of species  $i$ .

In BIOVENTING<sup>plus</sup>, Eq. (2) is solved using the mass balance equation described by Johnson et al. (1990) in which contaminant in the aqueous, vapor, NAPL, and adsorbed phases is defined under equilibrium conditions:

$$M_i = x_i \left\{ \frac{\theta_a p_i V}{RT} + M_T^{NAPL} + \frac{\rho_w \theta_w V}{\gamma_i W_w} + \frac{K_i \rho_b V \rho_w}{\gamma_i W_w} \right\} \quad (3)$$

where  $M_i$  is the moles of species  $i$  in all phases,  $x_i$  the mole fraction of species  $i$  in the NAPL,  $\theta_a$  the air-filled porosity,  $p_i$  the absolute total gas phase pressure of species  $i$ ,  $V$  the volume of contaminated soil,  $R$  the ideal gas constant,  $T$  the absolute temperature in the soil-water system,  $M_T^{NAPL}$  the moles of all species in the NAPL,  $\rho_w$  the density of water,  $\theta_w$  the volumetric water content,  $\gamma_i$  the aqueous phase activity coefficient,  $W_w$  the molecular weight of water,  $K_i$  the soil sorption coefficient for species  $i$ , and  $\rho_b$  is the soil dry bulk density.

To determine the efficiency factor in Eq. (2) the following mass balance equation was used:

$$d(Q_R \bar{C}_R) = k_R(1 - \bar{C}_R) dV_R \quad (4)$$

where  $Q_R$  is the horizontal airflow rate at distance  $R$  from the well,  $\bar{C}_R$  the ratio of vapor concentration to equilibrium concentration at distance  $R$ ,  $k_R$  the mass transfer coefficient at distance  $R$  (which is a parameter that is calibrated using site-specific data), and  $V_R$  is the volume of contaminated soil within distance  $R$  from the well. This equation is solved subject to the condition  $\bar{C}_R = 0$  at  $R$  is the minimum of the well half spacing or the average contaminant distance from the well, to yield  $\bar{C}_R = E_s$  at  $R = 0$ , where  $E_s$  is the steady-state efficiency. For steady-state airflow,  $E = E_s$ . If airflow is periodically cycled on and off, the efficiency factor will increase due to partial recovery of equilibrium vapor concentrations during the off cycles. The pulsed efficiency is computed as the flow weighted average value of the average concentration over the on-cycle for the flow path to the well [33,34].

The removal rate by biodecay will be limited by either: (1) oxygen availability, (2) rate of mass transfer into the aqueous phase, or (3) nutrient availability or other intrinsic limitations. The oxygen-limited decay rate is computed assuming oxygen is supplied by mass flow. The efficiency for oxygen delivery with the air stream is assumed to be the same as the venting efficiency. BIOVENTING<sup>plus</sup> has defined relationships for each of these cases as detailed in [33,34]. In addition, BIOVENTING<sup>plus</sup> incorporates the use of a preference factor for each contaminant related to the preferential utilization of a given contaminant by a microbial population. Biodegradation effects on an estimated time to reach a specified remediation goal can be significant for a particular system design [34,42].

Remediation cost is calculated in the model using the following equation:

$$\text{Cost} = C_0 + C_1NT + FP_1Q_wNT + FP_2Q_aNT + FP_3T \quad (5)$$

where  $C_0$  is the fixed cost,  $C_1$  the capital cost per well,  $N$  the number of wells,  $F$  a time discount factor (based on inflation rate),  $P_1$  the cost per unit volume of water flow,  $P_2$  the cost per volume of airflow,  $P_3$  the cost per unit time for operating costs not related to flow rates,  $Q_w$  the water flow rate per well,  $Q_a$  the airflow rate per well, and  $T$  is the remediation time.

Although BIOVENTING<sup>plus</sup> is able to consider a wide range of remediation scenarios, it is not without limitations. Due to the complex nature of airflow and contaminant partitioning, a number of assumptions were incorporated into the model to allow for its ease of use. The following is a list of such assumptions and limitations associated with the model:

- assumes steady state, radial airflow to and from injection/extraction wells;
- uses an analytical solution (DeGlee–Hantush–Jacob solution) to solve for airflow in the saturated and unsaturated zones;
- cannot perform simultaneous air sparging and soil vapor extraction computations;
- all wells are assumed to be equally distributed, screened the same length, and located the same distance below the soil surface, limiting the model's ability to simulate more complex sparging systems;
- assumes system is radially symmetric around each sparging well;
- assumes system equilibrium has been reached at the beginning of each time step;
- site soil is assumed to be relatively homogeneous with no spatial variability;
- contamination is assumed to be uniformly distributed (i.e. complete mixing) throughout the contaminated soil volume.

### 2.3. Analysis of factors affecting remediation

Investigations began by verifying the model's contaminant removal prediction ability. A consistency test, involving approximately 250 hypothetical simulations, was performed by varying the values of several model input parameters, to determine whether results from factor variations were comparable to those expected under similar field situations. A field test of each of the five sites was also performed to test the model's predictive capability by determining a value for each model input based on available site information (Table 1), calibrating the model, and running an air sparging simulation for the reported duration of sparging at the site. Model calibration involved adjusting the anisotropy ratio, horizontal air conductivity, field mass transfer rate coefficient and off-cycle time required to achieve 50% of the equilibrium solution concentration of a contaminant (OCT) until model calculations of the radial sphere of influence, sparging point air pressure, and total amount of contaminant remediated matched those reported at the site. Contaminant removal results, reported as total petroleum hydrocarbons (TPH) mass remaining versus time, were statistically compared to those recorded in the field to determine the accuracy of the model predictions.

Following successful completion of the model evaluation, sparging-related system dynamics and sensitivities were analyzed using the BIOVENTING<sup>plus</sup> model. Several contaminant types, site characteristics, and air sparging system design factors were defined and



Table 2  
Ranges for each parameter used in the parameter analysis

Input parameter	Site 1	Site 2	Site 3	Site 4	Site 5
Horizontal air conductivity (m per day)	33–130	47.5–950	32.4–259	25–500	30–1080
Anisotropy ratio	1.5–6	0.38–6	1.95–7.8	4–11	0.78–9.3
Total porosity	0.1–0.6	0.1–0.6	0.15–0.6	0.1–0.6	0.08–0.6
Organic carbon content (fraction)	0–0.01	0–0.02	0–0.012	0–0.012	0–0.01
Maximum biodecay rate (mg/kg per day)	0–10	0–10	0–10	0–1	0–10
Depth from water table to sparge point (m)	0.86–1.72	0.76–6.1	3.08–8.23	3.11–10.4	0.99–7.92
Air injection rate per well (m <sup>3</sup> per day)	327–654	40.8–326	31.7–569	10.2–122	–
Air injection pressure per well (atm)	–	–	–	–	0.3–2.38
Pulsed operation (h on/off)	0.5/23.5, continuous	0.5/23.5, continuous	0.5/23.5, continuous	0.5/23.5, continuous	0.5/23.5, continuous
Number of sparging wells	134–536	2–18	8–20	20–99	13–159
Spill composition	See below for all sites <sup>a</sup>				

<sup>a</sup> The spill compositions tested for each site consisted of gasoline, weathered gasoline, chlorinated solvent, JP-4 and JP-8 jet fuels, container by-product, kerosene, diesel, and no. 2 fuel oil.

evaluated at each site in terms of their effect on overall clean-up cost and time needed to reach a specified clean-up criteria. These factors, italicized in Table 1, were selected due to their importance noted in the literature and that they can be inputs in BIOVENTING<sup>plus</sup>. For each factor a range of values was chosen above and below the original base value reported at the site, as summarized in Table 2. In the case of contaminant types, a range of available contaminant composition files associated with a wide variety of contaminant types were selected for the analysis. Model simulations were performed to assess the effects of both TPH and contaminant-specific (e.g. toluene, total xylenes, or TCA) aqueous and soil phase clean-up criteria on removal *t* time and removal cost at each field site. For each factor at each of the five field sites, simulations were performed for every value in the range of values while holding the value of all other factors constant. Results for removal time, removal cost, average efficiency, and average pore volume turnover rate (PVTR) were recorded for each simulation. For each site, the aforementioned results were used directly to identify system dynamics controlling the observed contaminant removal trends.

### 3. Results and discussion

Analyses were performed for the 10 sparging-related factors at each field site to identify system dynamics controlling contaminant removal trends and to obtain results concerning relative levels of sensitivity for each factor. The sensitivity data were compared across all sites and conclusions were made concerning the sensitivity of each factor on assessing and optimizing air sparging remediation on a site-specific basis. Results concerning both the factors controlling system dynamics and the individual sensitivities are described concurrently.

### 3.1. Application of the model to remediation sites

To ensure the applicability of the BIOVENTING<sup>plus</sup> model for the purposes of assessing factors impacting the remediation at the five sites, model evaluation were conducted. Despite the model limitations described earlier, test results showed that the model adequately predicts contaminant removal over time. Consistency test results for evaluated factors agreed well with expected trends for both contaminant removal time and contaminant mass remaining versus time. Supporting the statement of field test results also indicated good agreement between field and model results. When compared to reported field measurements, simulation results for TPH mass remaining or mass removed versus time showed close agreement, as shown in Fig. 1A–C for a representative sample of the five sites.  $R^2$  values for each site ranged from 0.806 to 0.976. Based on the results of the consistency and field tests, BIOVENTING<sup>plus</sup> was concluded to provide reasonably accurate modeling of the field sites and is believed to generate reasonable factor analysis of these sites.

### 3.2. Analysis of factors affecting removal time

#### 3.2.1. Design factors

*3.2.1.1. Sparging depth and number of sparging wells.* Changes in sparging depth and well density were observed to have similar, yet minor, effects on contaminant removal at each of the five sites evaluated (Fig. 2A and B). Results indicated that subsurface coverage (referring to the combined ROIs of all sparging wells) was a controlling factor affecting contaminant removal. In cases where subsurface coverage was dramatically affected by sparging depth or well density, as with Site 1, contaminant removal time was reduced by enhancing coverage through increased depth or well density. This reduction in removal time was caused by a minimization of non-sparging influenced dead zones. Additionally, in cases where sparging depth did not considerably affect coverage, such as with Sites 2–4, sparged air residence time (referring to the time sparged air remains in the system) effects dominated contaminant removal. Results in these cases showed minor increases or decreases in removal time, depending on the benefit or detriment caused by the increased residence time and its effects on system equilibrium. On the other hand, the large increase in removal time observed with Site 5 occurred because, unlike the other four sites, a constant injection pressure was utilized, causing injection rates to decrease substantially with increased depth.

Based on these results, well density and sparging depth should be chosen such that a basic, yet effective subsurface coverage is provided for the system. Sparging depth should also be placed near or equal to the vertical extent of contamination to allow for sparged air to reach the entirety of the contaminated soil volume. The number of wells chosen for the system becomes more critical with the remediation of smaller contaminated areas where the addition or removal of even one well, could substantially affect coverage. Under these conditions, well density should be carefully chosen based on ROI measurements obtained from a pre-sparging pilot test taking into consideration the effects of depth. At sites with larger contaminated areas, where the addition or reduction of a larger number of wells will not affect coverage as greatly, the specification of the minimum number of wells does not need to be as carefully considered.

3.2.1.2. *Air injection rate/pressure.* Increases in air injection rate or pressure were observed to decrease contaminant removal time to a point where, at higher rates or pressures, removal times became fairly constant. The effect on removal time was small to moderate and was most sensitive when pressure, not injection rate, was varied (Fig. 2C). As air injection rate increased at a site, injection pressure also increased producing enhanced subsurface coverage and decreased sparged air residence time. For Sites 1, 2, and 4, a coupling of

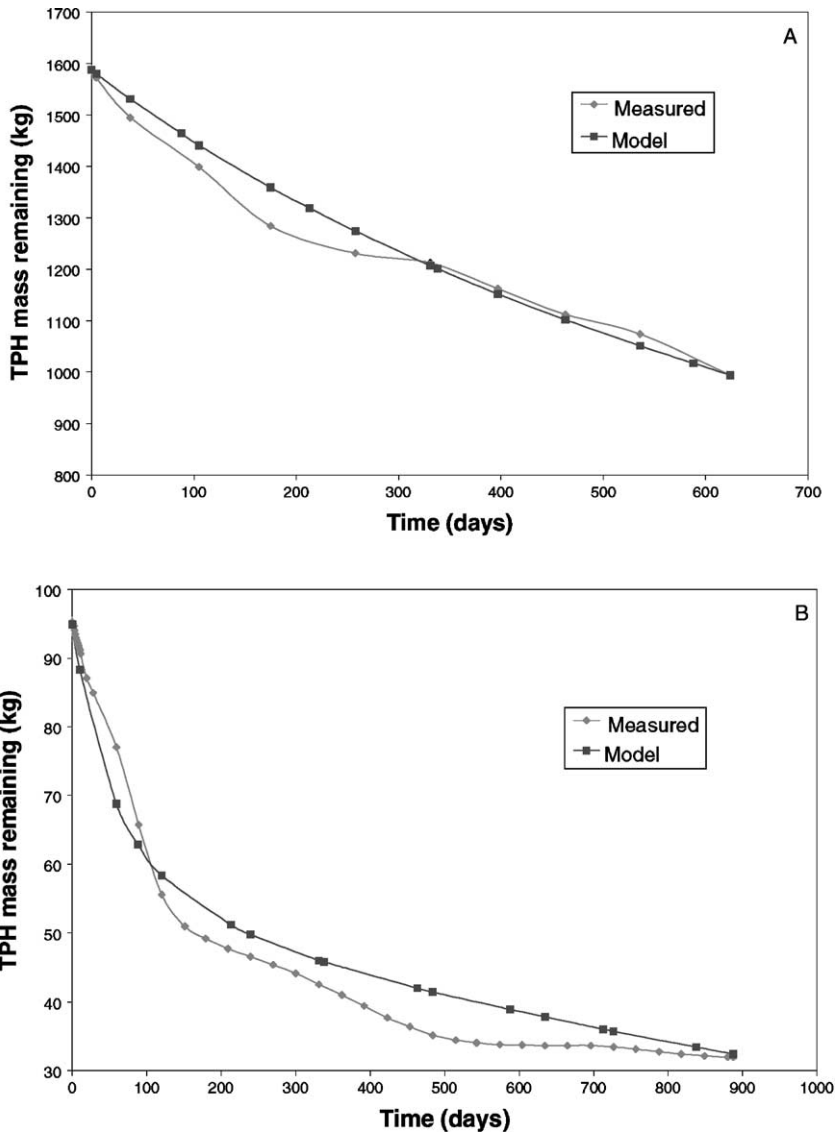


Fig. 1. Field test comparison results for: (A) Site 1; (B) Site 4; (C) Site 5.

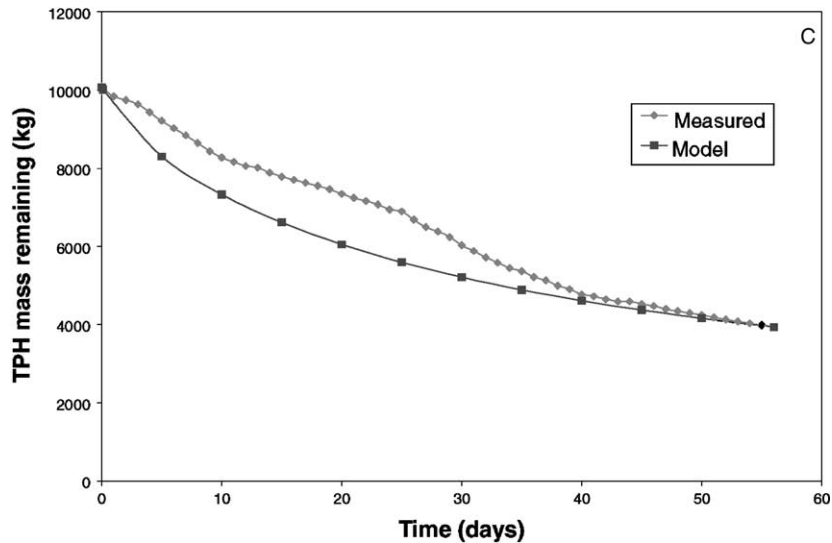


Fig. 1. (Continued).

residence time and coverage effects enhanced contaminant removal producing decreased removal time with increasing injection rate (Fig. 2C). For Site 3, where microbial decay rates were high relative to the other sites (Table 1), microbial degradation was the key removal mechanism, therefore changes in injection rate did not significantly reduce removal times. If oxygen availability had been limiting, increases in airflow rates may have enhanced contaminant removal.

These results indicate that an air injection rate should be chosen which maximizes the effect of the dominant removal mechanism at the site, i.e. volatilization or microbial degradation. As noted in the literature, higher air injection rates/pressures might enhance volatilization at the expense of reduced removal through degradation as the relative percentage of removal that is due to degradation is decreased when injection centers are increased, while lower injection rates may favor microbial degradation depending on oxygen availability in the system. The optimality of either mechanism can be further estimated based on the contaminant spill and soil type present at the site. More permeable soils and contaminants with higher volatilities and solubilities will favor volatilization while less permeable soils and less volatile and soluble contaminants will favor microbial degradation, as long as oxygen availability is not limiting, assuming that the contaminant is aerobically biodegradable. The performance of volatilization in a system can be estimated from a pilot test while the performance of microbial degradation can be estimated using an in situ respiration test [43].

**3.2.1.3. Sparging operation.** The degree of pulsed (or continuous) sparging tested at each field site produced large changes in contaminant removal time. For Site 1, where the large injection rate caused sparged air residence time to fall below its most efficient level, i.e.

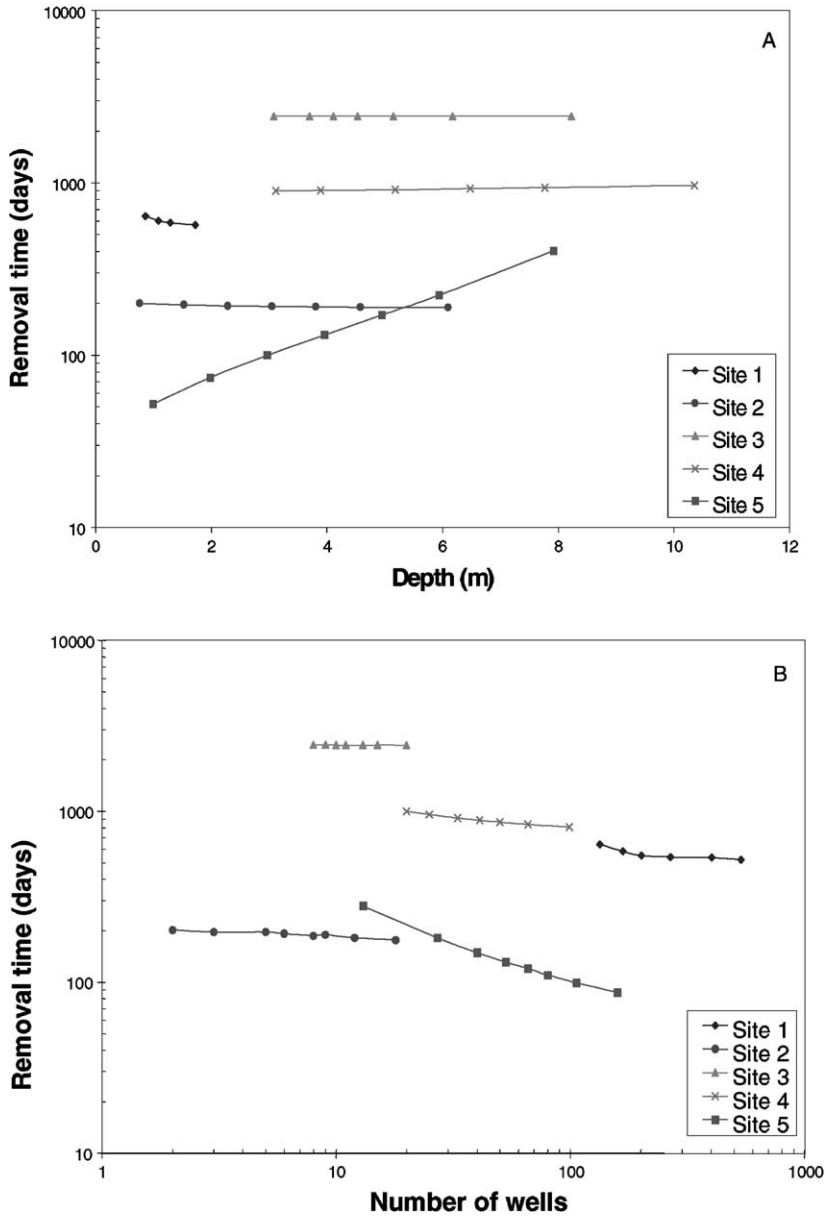


Fig. 2. Removal time results for system design parameters: (A) depth of the sparge point below the water table; (B) air injection rate; (C) number of wells; (D) pulsed sparging operation.

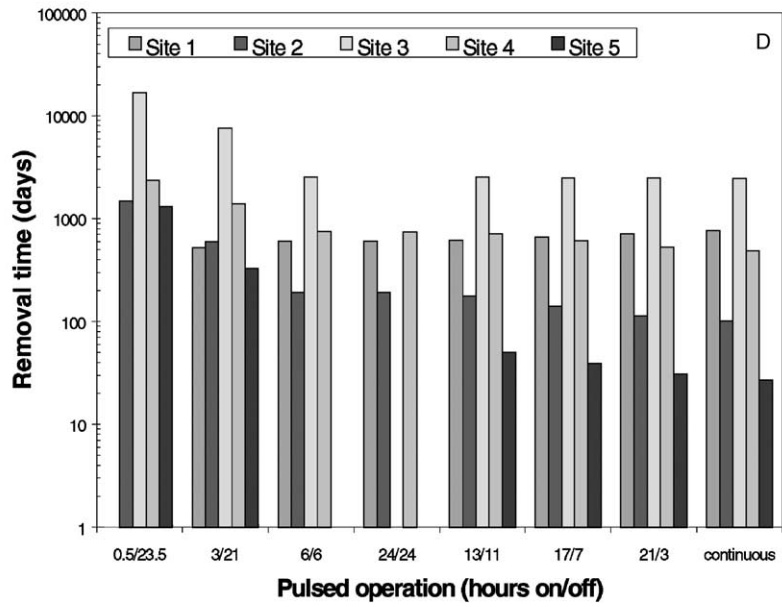
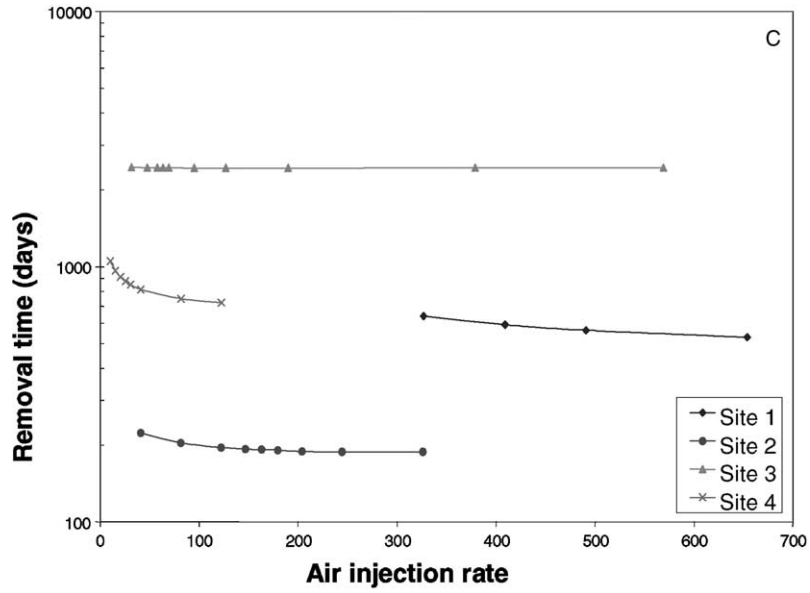


Fig. 2. (Continued).

where a high degree of non-equilibrium exists, pulsed operation was observed to produce the lowest removal times (Fig. 2D). Under continuous flow conditions, the sparged air will strip contaminant at a rate faster than it can diffuse to areas of sparging induced airflow. During the off-cycle time of pulsed sparging, the contaminant will have time to diffuse to areas of sparging induced airflow where it can be quickly stripped by the next sparging on-cycle. Conversely, for Sites 2–5, where the specified injection rates were slow enough to produce sparged air residence times above the most efficient, continuous operation was observed to produce the lowest contaminant removal times (Fig. 2D). During continuous operation, contaminant movement to areas of sparging influence will likely be equal to or greater than the rate of contaminant volatilization and evacuation from soil pore spaces, thus maintaining the system near equilibrium.

Results indicate that under near equilibrium conditions, continuous sparging yields the most efficient contaminant removal as also supported by Elder et al. [25], and Girolimon [26]. However, if conditions are such that non-equilibrium may prevail, pulsed sparging would likely provide the most effective contaminant removal. Such conditions could be induced by very high air injection rates/pressures, moderate to low volatile/soluble contaminants, and/or non-permeable soils where contaminant movement would be restricted, the latter of which is supported by Reddy and Adams [44]. Conversely, if the contaminant was of a high to moderate volatility/solubility, low air injection rates/pressures were utilized, and/or the soil was moderately to highly permeable, as with many field sites, equilibrium conditions would likely prevail and continuous operation would be most effective.

### 3.2.2. Site-specific factors

**3.2.2.1. Contaminant types.** At all sites, changes in the contaminant type produced a high level of variability in removal time results and was dominated by contaminant volatility. As seen in Fig. 3, for all field sites, either fresh gasoline or the chlorinated solvent produced the lowest removal times while kerosene, diesel, and no. 2 fuel oil produced the largest removal times. Note that the simulations assumes complete mixing in the system, therefore, in the case of dense non-aqueous phase liquid (e.g. chlorinated solvents), air sparging will only be effective if sparging depths can be placed within or below the DNAPL pools. These trends indicate that air sparging is best suited for the remediation of gasoline and chlorinated solvents and least suited for the remediation of kerosene, diesel, and no. 2 fuel oil. Air sparging also appears to be moderately effective in removing jet fuels and substituted benzene contaminants. These results are supported by Brown et al. [2], Gordon [35], Marley et al. [3], and Reddy et al. [4].

**3.2.2.2. Horizontal air conductivity.** Changes in horizontal air conductivity did not affect removal time significantly for any of the sites except for Site 5. Horizontal air conductivity represents the relative ease of horizontal vapor movement through the soil subsurface. Larger air conductivities represent coarser grained soils with easier movement of air, such as gravel or sand, while smaller air conductivities represent finer grained soils, such as silt or clay. When air injection rates were held constant over the range of conductivities tested, as with Sites 1–4, increasing horizontal air conductivity decreased subsurface

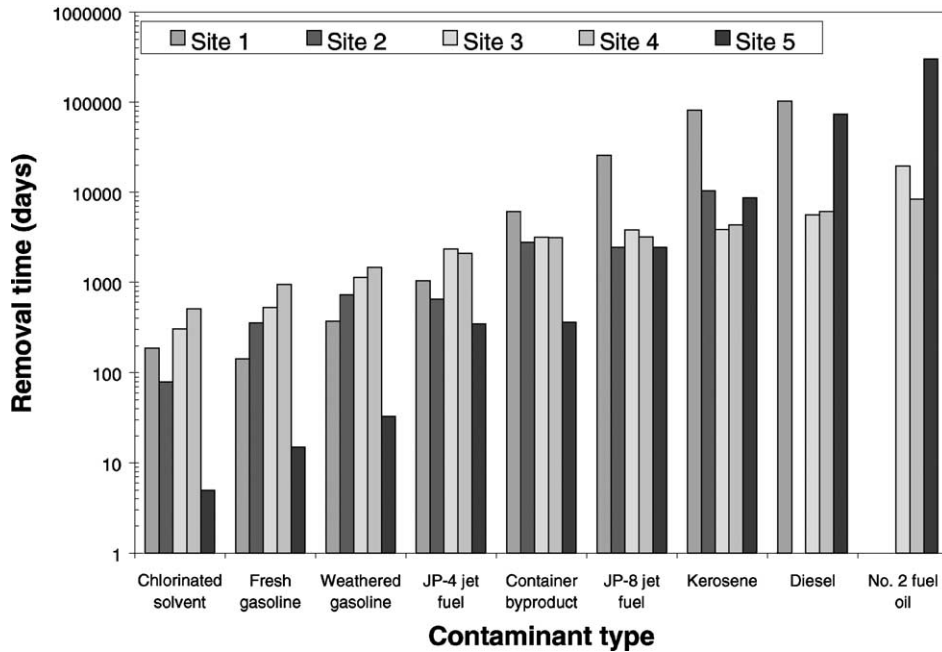


Fig. 3. Removal time results for contaminant types. Used soil phase clean-up criteria specified in Table 1.

coverage and air saturation, the controlling factors (due to possible short circuit flows), thus producing minor increases in removal time (Fig. 4A). Conversely, at Site 5, where air injection rates varied (a constant air injection pressure was used), increases in horizontal air conductivity caused subsurface coverage to increase and residence time to decrease producing fairly substantial decreases in removal time. With the constant air injection pressure specified at the site, airflow rates were substantially higher in soils with larger horizontal air conductivities (2.92 cfm for a conductivity of 120 m per day to 27.2 cfm for a conductivity of 1080 m per day). Despite this result, the general effect on contaminant removal appears small and is dependent on the degree to which coverage, air saturation, and residence time change. Consequently, only basic field estimates appear needed for this factor since even large errors in its estimation would not significantly affect removal time.

**3.2.2.3. Anisotropy.** Variations in anisotropy were observed to produce very little effect on removal time at all but one site. The anisotropy ratio represents the relationship between horizontal to vertical air conductivity in soil and simulations show it has a significant effect on the ROI size. As long as the air injection rate is held constant, increasingly anisotropic soils have greater subsurface coverage due to increasing sparge point air injection pressure. With Sites 2–4, where subsurface coverage was fairly complete at all anisotropy values, changes in anisotropy produced negligible reductions in removal time (Fig. 4B). Conversely, in situations where subsurface coverage changed significantly, as with Site 1,



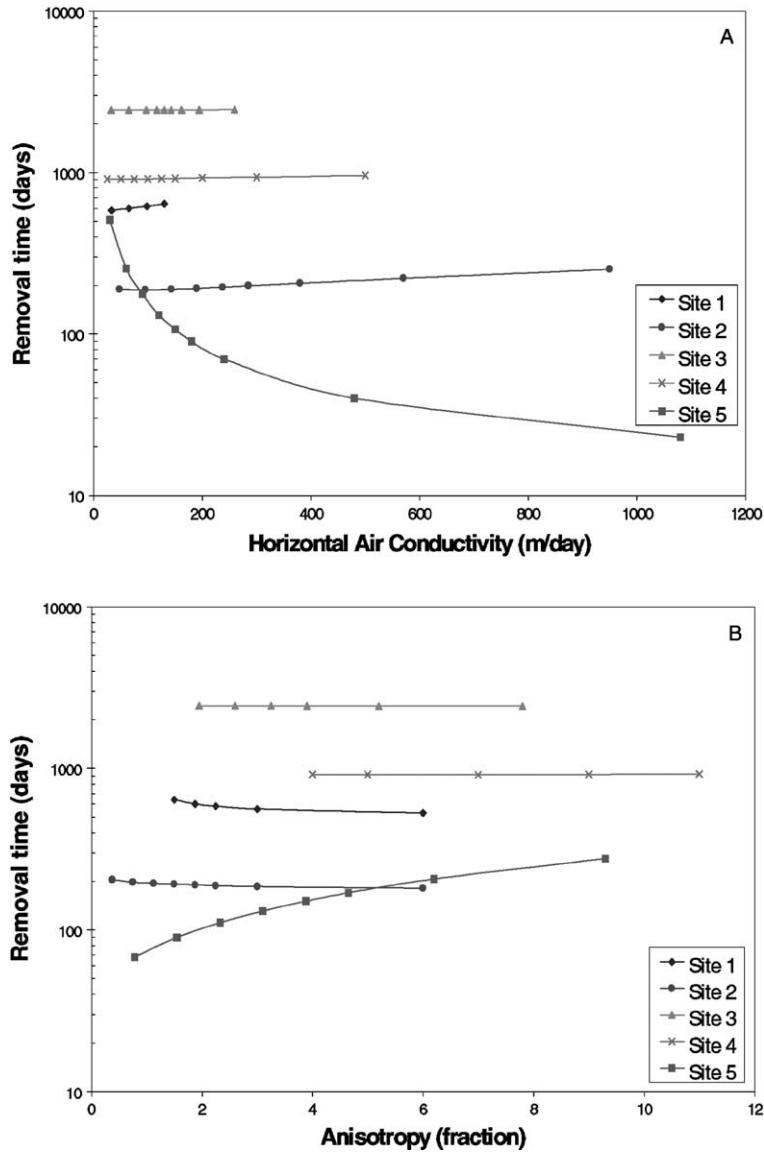


Fig. 4. Removal time results for site characteristic parameters: (A) horizontal air conductivity; (B) anisotropy ratio; (C) total soil porosity; (D) organic carbon content; (E) maximum biodecay rate. Used aqueous phase clean-up criteria specified in Table 1.

more substantial, yet still minor, reductions were seen. For Site 5, increases in anisotropy decreased subsurface coverage due to the constant injection pressure that was specified. In general, though, the effects of this factor on contaminant removal appear small and are dependent on the level of change induced to subsurface coverage.

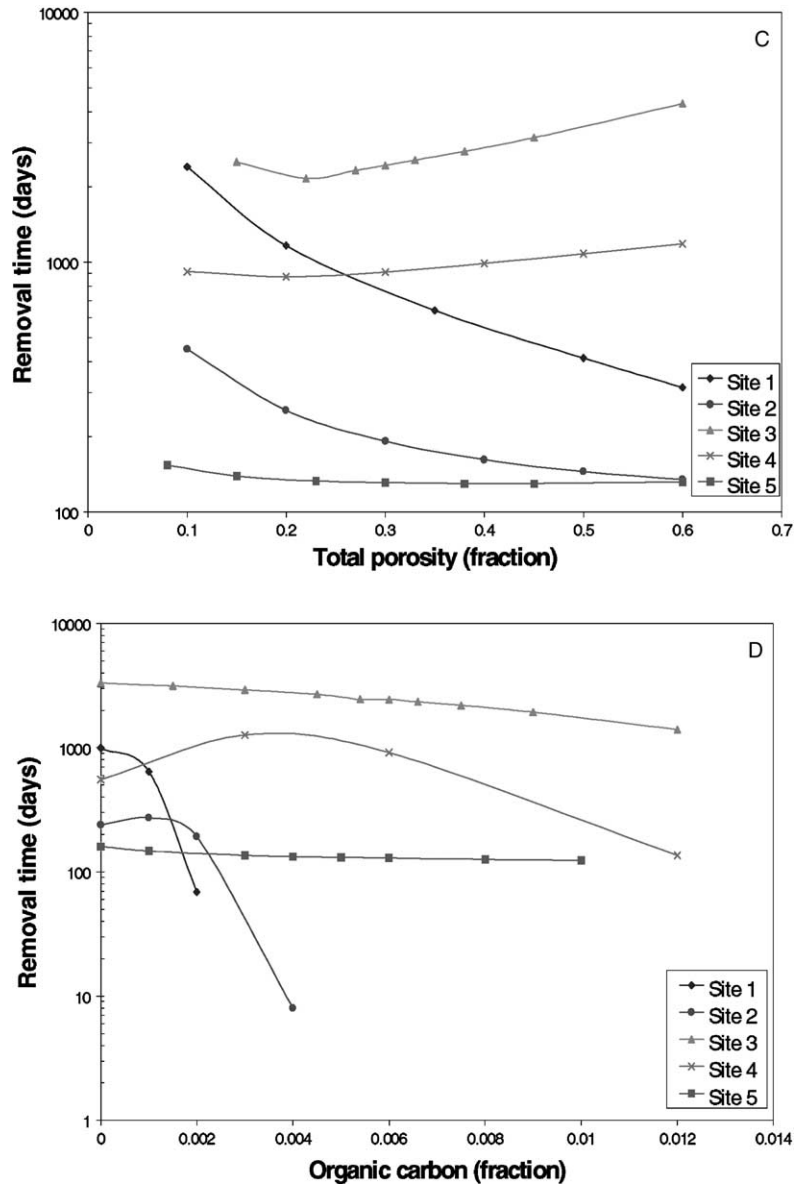


Fig. 4. (Continued).

**3.2.2.4. Total porosity.** With Sites 1, 2, and 5, where volatilization was the key removal mechanism, the balancing of residence time and air saturation effects produced a general decrease in removal time with higher porosity soils (Fig. 4C). Such conditions can be found with a high volatility contaminant type or a high air injection rate. Sites 3 and 4,

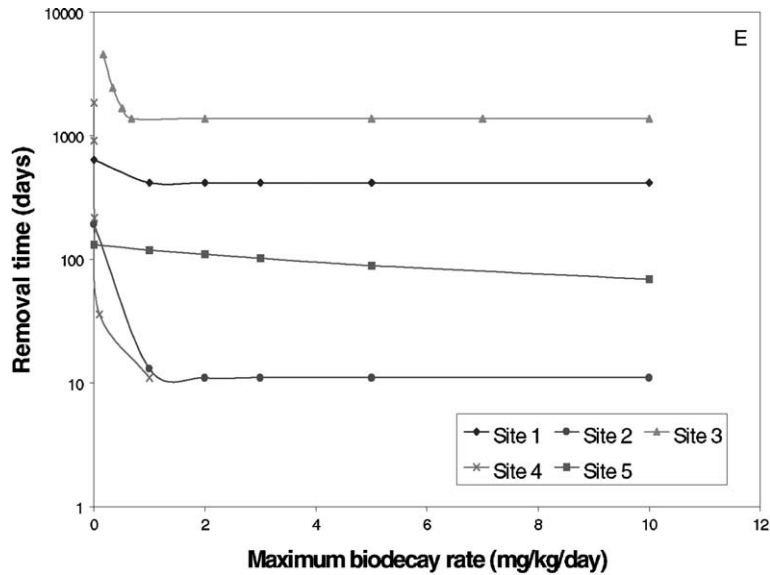


Fig. 4. (Continued).

where both volatilization and microbial degradation were significant removal mechanisms, the effects of air saturation and contaminant availability for microbes became increasingly important, acting to increase removal time in soils with increasing porosity. This seems to be surprising for Site 3, which included PAHs (which should be relatively slow degrading) which might be due to the fact that one degradation rate is used for all contaminants, leading to unexpected results. These trends indicate that the effects of total porosity are removal mechanism dependent and have a substantial effect on contaminant removal in a system. On a practical scale, air sparging is seldom used in soils other than coarse sand and gravel or fine to medium sand. In soils with lower porosities, the effectiveness of air sparging is reduced due to non-beneficial bubble formation and highly preferential vertical airflow. In soils with higher porosities, high air injection rates/pressures (above a practical level) are required and air sparging's effectiveness is reduced due to restrictions in airflow resulting from the associated lower permeability of the soil. With this small window of total porosity where air sparging is practical, total porosity is not as critical as it appears to be.

**3.2.2.5. Organic carbon content.** The presence of increasingly larger amounts of aquifer organic carbon in the system were observed to produce substantial decreases in removal time results based on clean-up criteria specified in terms of aqueous phase concentrations (Fig. 4D). With a larger organic carbon content, contaminant sorption increases, thus decreasing aqueous phase concentrations. If clean-up criteria were based on soil phase concentration, the increase in sorbed phase concentrations associated with larger organic carbon contents would have resulted in longer removal times. Although organic carbon content affects removal times, site-specific assessment of organic carbon is subject to a

large degree of spatial variability. However, site-specific estimates of organic carbon could aid in predicting when a specified soil phase criteria would be met or if a practitioner was concerned with long-term aqueous phase contaminant rebound. For aqueous phase based clean-up criteria, aqueous phase contaminant concentrations can be measured directly and used to predict removal times.

*3.2.2.6. Maximum biodecay rate.* For all field sites, contaminant removal times decreased substantially with increasing biodecay rate in the system. When volatilization was limited by the contaminant volatility, contaminant mass, or airflow at the site, such as with Sites 2–4, increases in the maximum biodecay rate produced very large reductions in removal time (Fig. 4E). At Sites 1 and 5, where volatilization was not hindered under any circumstances, changes in the maximum biodecay rate produced only moderate effects on removal time.

Accurate field measurement of the maximum biodecay rate appears to be important due to the effect of this removal mechanism on overall contaminant removal at a site. Information pertaining to the level of biodecay occurring during air sparging remediation, obtained from an in situ respiration test, can aid in the design of an appropriate air injection rate/pressure and sparging operation. Furthermore, accurate knowledge of the biodecay rate can provide useful insight for predicting the daily amount of contaminant removed by this mechanism.

### 3.3. Analysis of factors affecting removal cost

As shown in Eq. (5), removal costs (denoted as generic monetary units,  $\mu$ ) are comprised of both fixed and operating costs. For the factors tested, fixed costs change only with the number of wells while operating costs change with both removal time and airflow volume. Consequently, in situations where remediation requires long times, operating costs will dominate the removal costs at the site. Conversely, in situations where removal times are short, capital costs will most likely dominate the removal cost.

For all factors but the number of wells, removal costs follow the same general trends observed in the removal time results. This arises as a result of removal cost being a function of either removal time or both removal time and airflow volume for these factors. For the number of wells, removal costs increase fairly linearly with an increasing number of wells at all but Site 5 (Fig. 5). For Sites 1–4, the large capital cost of a single well is greater than the reduction in operating cost produced by the associated decrease in removal time, therefore, removal costs increase with increasing the number of wells. For Site 5, initial decreases in removal cost arise because the reduction in operating costs produced from decreases in removal time outweigh the capital cost associated with each well.

### 3.4. Sensitivities of factors affecting remediation at the sites

A quantitative measure of each factor's effect on contaminant removal cost and time was calculated for each site using a linear sensitivity index equation similar to that employed by Nearing et al. [45]:

$$S = \frac{(b_2 - b_1)/((b_2 + b_1)/2)}{(p_2 - p_1)/((p_2 + p_1)/2)} \quad (6)$$

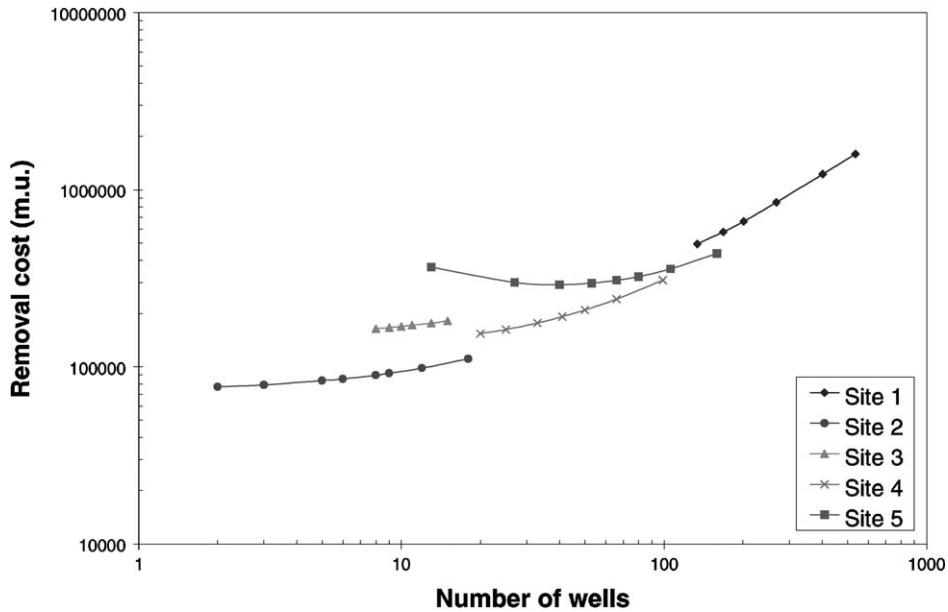


Fig. 5. Removal cost results for number of wells.

where,  $b_1$  and  $b_2$  are the maximum and minimum result values associated with input factor values  $p_1$  and  $p_2$ , respectively. An  $S$  value of zero indicates that a factor has no sensitivity or effect on the outcome being assessed. Negative sensitivity values indicate a decrease in removal time or cost with an increase in the value of the factor, while positive values indicate the opposite. Results are presented in Tables 3 and 4 for removal time and removal cost, respectively, and depict not only the actual sensitivity values but also the slope of the removal time and cost curves associated with each factor. Results from these sensitivities confirm the results discussed in the previous section. The depth of the sparge point below the water

Table 3

Sensitivity indices within 0.05 index units of factors affecting removal time with a value of zero indicating no sensitivity

Parameters	Site 1	Site 2	Site 3	Site 4	Site 5
Depth below water table	-0.2	0	0	0.1	1.0
Air injection rate/pressure	-0.3	-0.1	0	-0.2	-1.4 <sup>a</sup>
Number of wells	-0.2	-0.1	0	-0.2	-0.6
Pulsed sparging	0.4	-1.7	-1.5	-1.3	-1.9
Contaminant type	2.0	2.0	1.9	1.8	2.0
Horizontal air conductivity	0.1	0.2	0	0	-1.0
Anisotropy ratio	-0.2	-0.1	0	0	0.7
Porosity	-1.1	-0.7	0.7	0.3	-0.1
Organic carbon content	-1.0	-1.4	-0.4	-1.3	-0.1
Maximum biodecay rate	-0.2	-0.9	-1.0	-1.0	-0.3

<sup>a</sup> Air injection pressure was specified as an input parameter.

Table 4  
Sensitivity indices within 0.05 index units of factors affecting removal cost with zero indicating no sensitivity

Parameters	Site 1	Site 2	Site 3	Site 4	Site 5
Depth below water table	-0.1	0	0	0	0.6
Air injection rate/pressure	0.2	0	0	0	-0.9 <sup>a</sup>
Number of wells	0.9	0.2	0.2	0.5	0.3
Pulsed sparging	0.8	-0.6	-1.0	-0.4	-1.5
Contaminant type	1.4	1.4	1.4	0.9	1.9
Horizontal air conductivity	0	0	0	0	-0.5
Anisotropy ratio	-0.0	0	0	0	0.4
Porosity	-0.5	-0.1	0.5	0.1	-0.1
Organic carbon content	-0.3	-0.1	-0.3	-0.3	-0.1
Maximum biodecay rate	-0.1	-0.8	-0.6	-0.3	-0.1

<sup>a</sup> Air injection pressure was specified as an input parameter.

table, air injection rate/pressure, number of wells (in terms of removal time), horizontal air conductivity, and anisotropy ratio factors were all observed to exhibit relatively low to medium sensitivity values across all sites for both removal time and cost. The only variation to this trend arose with Site 5 where removal time and, consequently, cost, is affected in different ways due to the constant air injection pressure specified at this site. Across all sites, the number of wells (in terms of removal cost), pulsed sparging operation, contaminant type, total porosity, aquifer organic carbon content, and maximum biodecay rate factors exhibit medium to high sensitivity values for both removal time and cost results. Of these factors, the contaminant type and pulsed sparging operation exhibit the largest sensitivity values in terms of both removal time and cost. The number of wells factor displays a much larger sensitivity to removal cost than to removal time due to the large capital costs associated with each additional well.

#### 4. Summary

Field data from five air sparging sites and numerical simulations were used to analyze several soil, contaminant, and air sparging system design factors for their effect on contaminant removal time and overall remediation cost. Results of this research indicated that the factors most significantly affecting contaminant removal (in terms of removal time and cost) were the contaminant type, pulsed sparging operation, number of wells (removal cost only), maximum biodecay rate, total porosity, and aquifer organic carbon content. Factors having little to moderate effect on contaminant removal consisted of depth of the sparge point below the water table, air injection rate/pressure, horizontal air conductivity, and anisotropy ratio. Trends observed during factor analyses were inferred to result from a number of physical factors controlling contaminant removal at each site. These factors appear to consist of subsurface coverage of the sparged air, sparged air residence time, system contaminant equilibrium, contaminant phase distributions, oxygen availability for microbes, and contaminant volatility. One or a number of these factors controlled contaminant removal characteristics resulting from changes in each individual factor.

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