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Numerical investigations of optimal well spacing and the effect of screen length and surface sealing on gas flow toward an extraction well

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ABSTRACT

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Interest in the use of vapor extraction to remove volatile and semi-volatile organic compounds (VOC's) from unsaturated soils has been growing recently. To quantify the lateral extent of the zone of effective influence of a vapor extraction well, a new term, distance of effective sweep (R_e) is introduced. This distance can be used to characterize the flow pattern, and it provides a guideline for determining the number and location of extraction wells needed at a contaminated site. In the present work, R_e represents the distance of effective sweep from a line of wells (line sink). Analysis was performed to examine the role of the screen length, l, the extension of soil-surface sealing, r, and the vadose zone thickness, H, on R_e, in a case of an array of wells where the flow is two-dimensional in the vertical plane. A regression equation was found to describe the relationships between R_e and the ratio of l/H. Additional analysis shows that vapor extraction treatment without soil-surface sealing may be most effective when the contaminant plume lateral dimension is smaller than one-half of the vadose zone height. Simulations with different r reveal that R_e increases linearly with r. Simulations of transient scenarios indicate that the concept of distance of effective sweep is limited to permeable soils because the velocities developed in clay soils at the "distance of effective sweep" may be too low to be considered effective, and the time needed for the development of steady-state flow is very significant when compared to the duration of the vapor extraction operation.

Additional analysis was performed on the distance of influence, R_i, which is the conventional parameter used to characterize the flow. The analysis suggests that R_i has linear relationship with l/H, and that for the transient phase, $R_i(t)$, may depend on the permeability, K, in a

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logarithmic manner of the form:

$R_i(t) = a(t) + b(t) \ln K$

INTRODUCTION

Volatile and semi-volatile organic compounds (VOC's) and petroleum hydrocarbons form a group of contaminants commonly found at polluted soil and groundwater sites. A frequent source of such contaminants is leaking underground storage tanks (UST's). Porter (1989) estimated that $\sim 2 \cdot 10^6$ UST's in the U.S.A. may be leaking. Because UST's are typically located above the water table, leaks or surface spills usually cause significant retention of the product as it spreads through regions of the unsaturated zone. VOC's trapped in the unsaturated zone could provide a long-term source of contamination to the underlying groundwater zone as they become dissolved in percolating precipitation. The problem is exacerbated as the VOC's volatilize into the soil gas and spread farther through the unsaturated zone under the influence of changes in the water-table position and in atmospheric pressure (Schwille, 1967; Abdul et al., 1989). Several methods have been used to clean unsaturated soils that were contaminated with VOC's. These methods include excavation and treatment or disposal and in situ methods such as biodegradation and vapor extraction. Interest in the use of vapor extraction to remove VOC's from unsaturated soils has been growing because of the favorable performance and economic advantages of that clean-up method when compared to other methods (Marley et al., 1990). In this study, a mathematical model was developed and used to evaluate the effect of the screen length of the extraction well and the extent of surface cover on air flow toward an extraction well.

An example of gasoline distribution through the subsurface, sometime after the leak from an UST has stopped, is shown in Fig. 1. The product spreads vertically through the unsaturated zone under the influence of gravity and capillary suction and migrates laterally under the influence of capillary forces (Bear, 1972; Corey, 1977). As the leak continues, the product will start to pond in the region of the capillary fringe, and lateral spread through the capillary fringe will dominate over the vertical spread, which will be impeded by the large weight of product needed to displace the water table into the groundwater zone. After the leak is stopped, product from the unsaturated zone will continue to drain, but residual retention of the product could result in a high degree of pore volume saturation (up to 60%) remaining trapped in the unsaturated zone (Hoag and Marley, 1986; Kia and Abdul, 1990). After the free product is pumped from the system, or with time after the product has spread through the region of water-table fluctuation, the main sources of contamination to the groundwater system will be the product trapped as

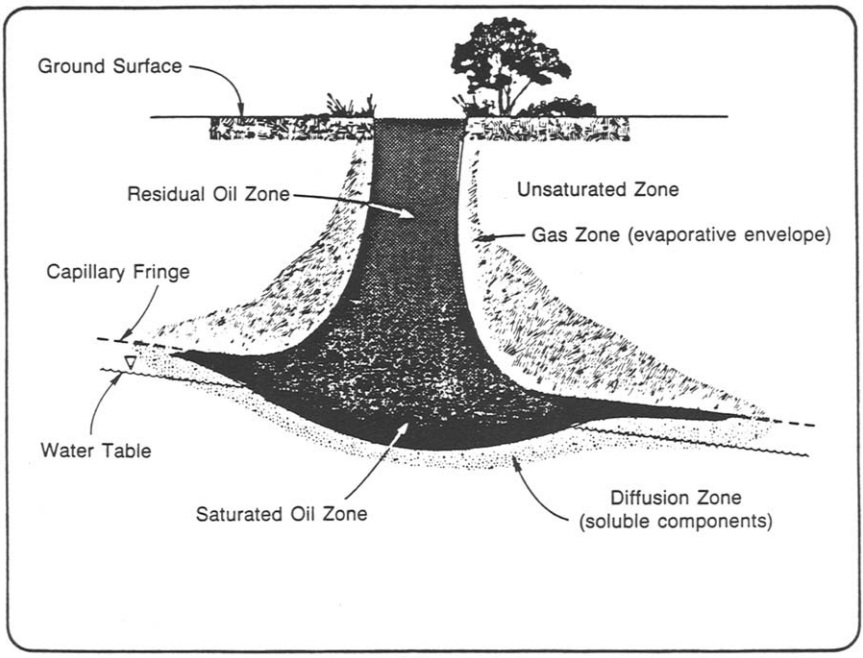

Fig. 1. A schematic view of oil seepage and distribution through a uniform soil and groundwater system (after Abriola and Pinder, 1985).

residual retention and the plume of vapor-phase constituents in the unsaturated zone.

From theoretical considerations, contaminants with high vapor pressures that are trapped in the unsaturated zone can be vaporized and removed from the subsurface by applying a vacuum on a well installed through the contaminated zone (Sleep and Sykes, 1989). Recent experimental findings (Mendoza and Frind, 1990) and performance of vapor-extraction systems in the field (Burgdorf and Lambert, 1989) have corroborated the expected performance of the vapor-extraction method.

Several mathematical models have been developed and used to simulate the vapor-extraction process in an attempt to identify the important parameters and to evaluate the sensitivity of the vapor-extraction method to those parameters. Krishnayya et al. (1988) analyzed the performance of vapor-extraction wells based on the radius of influence, R_i, which is the radius within which there is a pressure change in the soil caused by applying a vacuum on the extraction well. Their numerical simulations reveal that R_i increases linearly as the thickness of the vadose zone increases, and it monotonically grows with the suction head to an asymptotic limit. Those simulations were conducted under the assumptions of no air compressibility (steady state) and

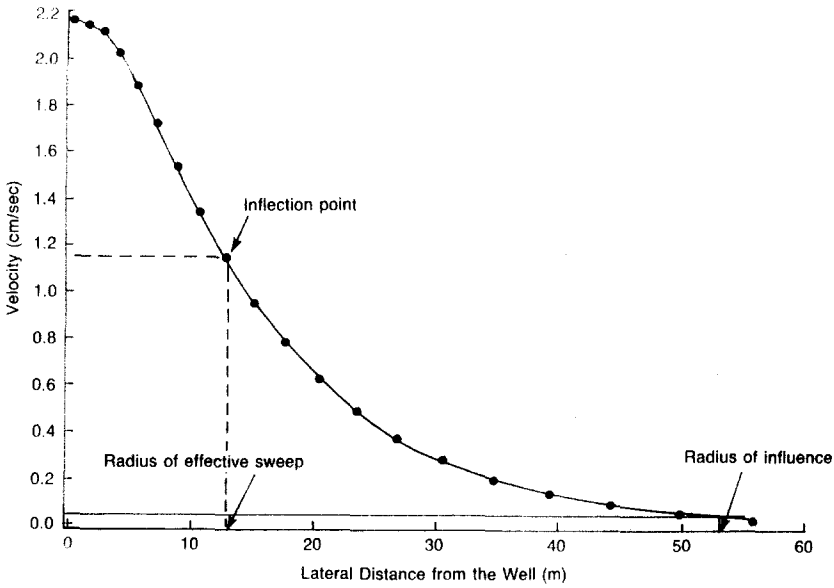

Fig. 2. An example of the velocity distribution along the base of the unsaturated zone.

suction pressure of <2.5 atm. Krishnayya et al. showed that the error in underestimation of the pressure distribution by neglecting air compressibility is $< \pm 1\%$. Johnson and Colthart (1990) estimated that the vapor pressure of VOC's may increase up to one order of magnitude by increasing the temperature from 0° to 25°C and that the performance of the vapor extraction system will increase as temperature increases. In addition, the rate of gas flow is known to be highly dependent on the relative gas permeability of the medium, and vapor contaminant transport is strongly influenced by the airflow field (Bear, 1972; Johnson and Colthart, 1990).

This work uses computer-simulation results to determine the distance of effective sweep, R_e, induced by an applied vacuum on a line of extraction wells (line sink). R_e is considered here as the distance of the zone with gas velocities of at least 0.5 of the velocity at the middle of the extraction well (line sink). The 0.5 break point is selected because it coincides with the inflection point in the distribution of the velocity along the lateral distance from the well (Fig. 2).

In this work, R_e is estimated as a function of: (a) the ratio of the length of the well screen to the thickness of the unsaturated zone (vadose zone); and (b) the ratio of the extent of surface cover to the thickness of the unsaturated zone. The effect of screen length or surface sealing is given in dimensionless quantities proportional to the thickness of the porous medium. This dimensionless representation facilitates the application of the analysis to relevant problems. The distance of effective sweep is determined in order to estimate

an optimized space between extraction wells from the velocity distribution point of view. Computer simulations were also used to investigate the rate of development of the cone of depression in sand, silt and clay soils and the dependency of R_i on soil permeability.

GOVERNING EQUATIONS

The governing equations used to described gas flow in porous media in this study are the gas flow equation coupled with equations of state. This set of equations is developed under the assumptions that the gas is a continuous phase, the effect of water flow on the gas mass balance may be neglected and there are no temporal changes in gas saturation. Neglecting the flow of water may be justified in the case of vapor extraction operations, where the soil surface is sealed and water saturation is relatively low. Note also that water saturation should be below 0.5 in order to have a continuous gaseous phase (Tung and Dhir, 1988). Temporal changes in gas saturation are due to evaporation processes and flow of water and organic liquid phases. These processes are not considered and are beyond the scope of the present research. This is because the focus of this research is primarily on optimal well spacing and the effect of screen length and surface sealing on flow toward an extraction well.

The flow equation (eq. 1) describes the distribution of the gas pressure and velocity in the porous medium for a given set of initial and boundary conditions. The equations of state (eqs. 2–5) describe functional relationships for the state parameters of the gas. These relationships are needed to solve for the coefficients in flow equation. These gas-state parameters are the gas specific density, viscosity, specific storage and relative permeability. The flow equation and the functional relationships presented by Mendoza and Frind (1990) are included in the present model.

The flow equation presented below is the gas mass balance equation in which the velocity is described by the momentum law of Darcy. This mass balance–momentum equation was developed under the following assumptions: (a) continuous gas phase; (b) constant gas saturation; (c) no mass transfer between the fluid phases; (d) no flow of the liquid phases (water or non-aqueous organic liquid); (e) alignment of the principal direction of the permeability with the Cartesian coordinate system; and (f) Darcy's law may be employed to describe the gas velocity. This equation, in horizontal (x) and vertical (z) dimensions is:

$$\frac{\partial}{\partial x}\left[K_x{}^*\mathrm{kr}_g\frac{\rho_0 g}{\mu}\left(\frac{\partial\phi}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[K_z{}^*\mathrm{kr}_g\frac{\rho_0 g}{\mu}\left(\frac{\partial\phi}{\partial z}+\frac{\rho}{\rho_0}\right)\right] = \mathrm{Ss}_g\frac{\partial\phi}{\partial t} \tag{1}$$

where g is the gravitational acceleration; K^* is the permeability at saturation of the porous medium; kr_g is the relative permeability of the gas mixture (air

and VOC); Ss_g is the specific storage of the gas mixture; t is the time; x is the length along the horizontal axis; z is the length along the vertical axis; μ is the dynamic viscosity of the gas mixture; ρ is the density of the gas mixture; ρ_0 is the density of air at a specified set of constant reference conditions; and ϕ is the pressure head of the gas mixture in terms of air head [ϕ = (pressure)/$\rho_0 g$]. Note that the term ρ/ρ_0 in eq. 1 measures the density potential of the gas mixture with respect to air.

The equation of state used to estimate the specific density of the gas was adapted from Schwille (1988) and is described by the following equation:

$$\rho = \rho_0 \frac{X_c M_c + (1 - X_c) M_a}{M_a} \tag{2}$$

where M and X are molecular weight and molar fraction, respectively; and the subscripts a and c denote fresh air and pure contaminant vapor, respectively. This equation estimates the specific density of the gas mixture, ρ, as a function of the weighted linear combination of the air and the vapor contaminant, and it is based on the assumption that the molar concentration of the contaminant is low.

A weighted expression for the viscosity of the gas mixture was presented by Reid et al. (1987) and is described by the following equation:

$$\mu = \frac{X_c \mu_c}{X_c + (1 - X_c)\Phi_{ca}} + \frac{(1 - X_c)\mu_a}{\{X_c \Phi_{ac} + (1 - X_c)} \tag{3a}$$

where Φ_{ij} is a function of the ratios of the molecular weights and the viscosities of the fresh air and pure contaminant gas as described in the following equation:

$$\Phi_{ij} = \frac{1}{\sqrt{8}}\left(1 + \frac{M_i}{M_j}\right)^{-1/2}\left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2}\left(\frac{M_i}{M_j}\right)^{1/4}\right]^2 \tag{3b}$$

The relative permeability for gas, kr_g, is a function of the gas saturation in the porous medium. The expression developed by Brooks and Corey (1964) is incorporated in our model, and is described by the following equation:

$$kr_g + (1 - Se_w)2(1 - Se_w^{(2+\lambda)/\lambda}) \tag{4}$$

where λ is the pore size distribution index; and Se_w is the effective water saturation. The effective water saturation is defined as:

$$(S_w - Sr_w)/(1 - Sr_w)$$

where S_w and Sr_w are saturation and residual saturation of the water, respectively.

The storage coefficient of the gas may follow the definition of Bear (1972)

as:

$$Ss_g = \theta_g \rho_g g \beta_g \tag{5}$$

where β_g and θ_g are the gas compressibility and the fraction of the porous medium filled by gas, respectively.

Initial and boundary conditions are needed to solve eq. 1. The boundary conditions are either first type (Dirichlet) or second type (Neumann). First-type conditions may be applied for constant or oscillating pressure at the boundaries with the atmosphere, and at sink/source locations (pumping or recharging wells). Second-type conditions of constant gas flux may be applied at impervious boundaries, such as the water table, sealed soil surface, liquid-saturated soil lenses and sink/source points.

Note that the governing equations described above are a complex nonlinear system of equations. The coefficients in eq. 1 are kr_g, Ss_g, μ and ρ. The value of these coefficients can be estimated by applying eqs. 2–5. Further complexity arises from the nonlinear dependency of Se_w (eq. 4) and θ_g (eq. 5) on ϕ (van Genuchten, 1980).

NUMERICAL SCHEME

The numerical algorithm developed for this study is an extension of the algorighm developed by Abdul (1985), which simulates saturated/unsaturated flow of water in porous media. That scheme is based on the standard Galerkin finite-element method (FEM). The FEM scheme incorporates linear triangular basis functions, and the temporal derivative of the right-hand side of eq. 1 is approximated by the implicit, backward-difference method. Successive iterations are used to overcome the nonlinear nature of eq. 1. The current form of the model only accounts for advective gas flow and does not include contaminant transport. Triangular elements are chosen because they can be used to represent arbitrarily shaped domains.

The numerical scheme converts eq. 1 into a time-marching set of ordinary differential equations (ODS's). These ODS's can be written in the following matrix form:

$$\left([\text{STIFF}] + \frac{[\text{MASS}]}{\Delta t}\right)\{\phi^{t+\Delta t}\} = \frac{[\text{MASS}]}{\Delta t}\{\phi^t\} - \{f\} \tag{6}$$

where [STIFF] and [MASS] are the stiffness and the mass matrices, respectively, resulting from the numerical approximation of the flux and accumulation terms; and $\{f\}$ is a loading vector resulting from the approximation of the boundary and vertical acceleration fluxes. The set of equations (6) forms a symmetric matrix for a problem of flow in homogeneous porous media with respect to the gas hydraulic conductivity K_g ($K_g = K^* kr_g \rho_0 g/\mu$) and to Ss_g.

$$\begin{Bmatrix} K_1 \\ K_2 \\ K_3 \end{Bmatrix} \begin{bmatrix} a_1 a_1 & a_1 a_2 & a_1 a_3 \\ a_2 a_1 & a_2 a_2 & a_2 a_3 \\ a_3 a_1 & a_3 a_2 & a_3 a_3 \end{bmatrix} \tag{7}$$

$$\begin{Bmatrix} Ss_{g1} \\ Ss_{g2} \\ Ss_{g3} \end{Bmatrix} \begin{bmatrix} 2 & 1 & 1 \\ 1 & 2 & 1 \\ 1 & 1 & 2 \end{bmatrix} \tag{8}$$

In terms (7) and (8), the subscripts 1, 2 and 3 denote indices of the triangular element; and a_i is the derivative of the basis function with respect to the x- and z-coordinate. For many field scenarios, the porous media may be considered as homogeneous, and a symmetric matrix solver may be employed. This is because contamination plumes are commonly small relative to the vadose zone dimensions, and data from the sites are not usually sufficient to adequately describe the heterogeneity of the soil in mathematical models.

SIMULATIONS AND ANALYSIS

Numerical simulations are conducted with the developed computer program to determine the role of screen length, soil-surface sealing and soil parameters in vapor extraction for a hypothetical cross-section. The roles of these factors are expressed in terms of the distance of effective sweep (R_e) and the distance of influence (R_i) for the case of a line sink. Functional relationships have been developed to identify the interdependence of the factors listed above. These relationships are obtained from statistical regression analysis of the steady-state simulation results for the hypothetical domain, shown in Fig. 3.

The simulated domain is 60 m long and 20 m high. A boundary condition of constant atmospheric pressure is assumed at the unsealed surface of the soil domain. A constant pressure (0.9 atm) with hydrostatic distribution is applied along the length of the well screen. Zero inflow/outflow conditions are imposed along the bottom of the domain, the sealed portion of the soil surface and along the unscreened portion of the well from the top of the screen to the soil surface (Fig. 3). A zero inflow/outflow condition is also prescribed along the right-hand boundary of the domain for simulations when there is no surface sealing. For surface sealing, the latter condition is changed to constant pressure with hydrostatic distribution to eliminate any boundary effect of vertical flow on the solution. The domain height of 20 m was chosen arbitrarily, and the lateral extent of 60 m is chosen as a minimal dimension to give simulation results necessary for the analysis without the influence of the pre-set conditions at the right-hand boundary on the solution. The domain

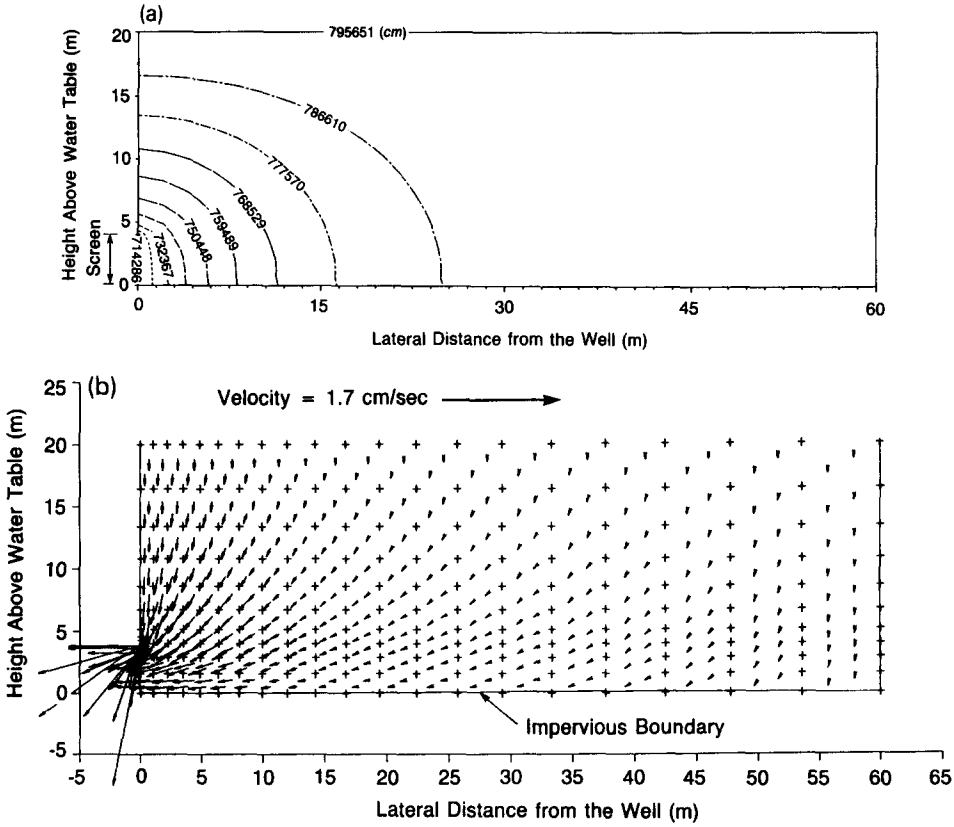

Fig. 3. Simulation results for well screen = 0.2 × the vadose zone thickness: (a) equipotential contour map (in cm of gas pressure head); and (b) flow diagram (*vectors* shows flow direction and relative velocity).

pre-set conditions at the right-hand boundary on the solution. The domain was divided into 416 triangular elements having 241 nodes for the simulations without soil-surface sealing, and divided into 496 triangular elements having 285 nodes for the simulations with surface sealing. The location of the nodes is designated by the + signs in the figures. The soil and gas-flow parameters for the simulations are given in Table 1. These parameters represent those expected for a typical sandy porous medium, and the gas parameters are taken from Weast (1982).

Steady-state results are presented as pressure-head contours and as velocity-vector diagrams (Figs. 3–5). The steady-state results are achieved with minimal computation effort by setting the gas-specific storage term (Ss_g) in eq. 1 to zero. In the contour diagram, the values on the contour lines are for the gas pressure head in cm of gas. In the velocity diagram, the bases of the vectors are located at the center of the elements, their lengths represent the velocity

TABLE 1

Soil and fluid properties

Property	Symbol	Numerical value
Soil and water:		
Void space	θ	0.3
Permeability at saturation	K^*	10^{-7} cm^2
Residual water saturation	Sr_w	0.25
Pore size distribution index	λ	2.2
Gas:		
Fresh air specific density	ρ_0	$1.28 \cdot 10^{-5}$ g cm^{-3}
Fresh air dynamic viscosity	μ_a	$1.8 \cdot 10^{-6}$ g cm^{-1} s^{-1}
Fresh air compressibility	β_a	10^{-6} cm^2 dyn^{-1}
Contaminant molar fraction	X_c	0.0
Fresh air molar fraction	X_a	1.0
Other:		
Water saturation	S_w	0.3
Gravitational acceleration	g	980.6 cm s^{-2}

magnitude and their directions show the direction of the flow at the center of the elements.

One immediate implication that can be seen from the figures is that high velocities are developed at the top of the well screen due to the concentration of stream lines. These large velocities imply that soil erosion could occur at the soil–well interface.

Effect of screen length on vapor extraction

The role of the screen length, l, is analyzed from the simulation results such as those presented in Figs. 3–5. These results are summarized in Figs. 6 and 7. In Fig. 6, the ratio of R_e to the vadose zone thickness, H, is plotted against the ratio of l to H, and in Fig. 7, R_i is plotted against the ratio of l to H. Those figures show that R_e and R_i extend farther from the well along the lower boundary of the partially saturated zone as the length of the well screen (l) increases. This observation implies that a vapor contaminant molecule is swept through the porous medium in a shorter time when l is increased. Fig. 6 also shows that R_e increases more slowly as the length of the screen increases. In addition, Figs. 3–5 show that as the value of l increases a greater fraction of the air sweeps through the medium adjacent to the upper part of the well. This decreases the time needed for decontamination of just a relatively small part of the contaminated area, thus decreasing the performance of the vapor-extraction system. This decrease is due to the significant

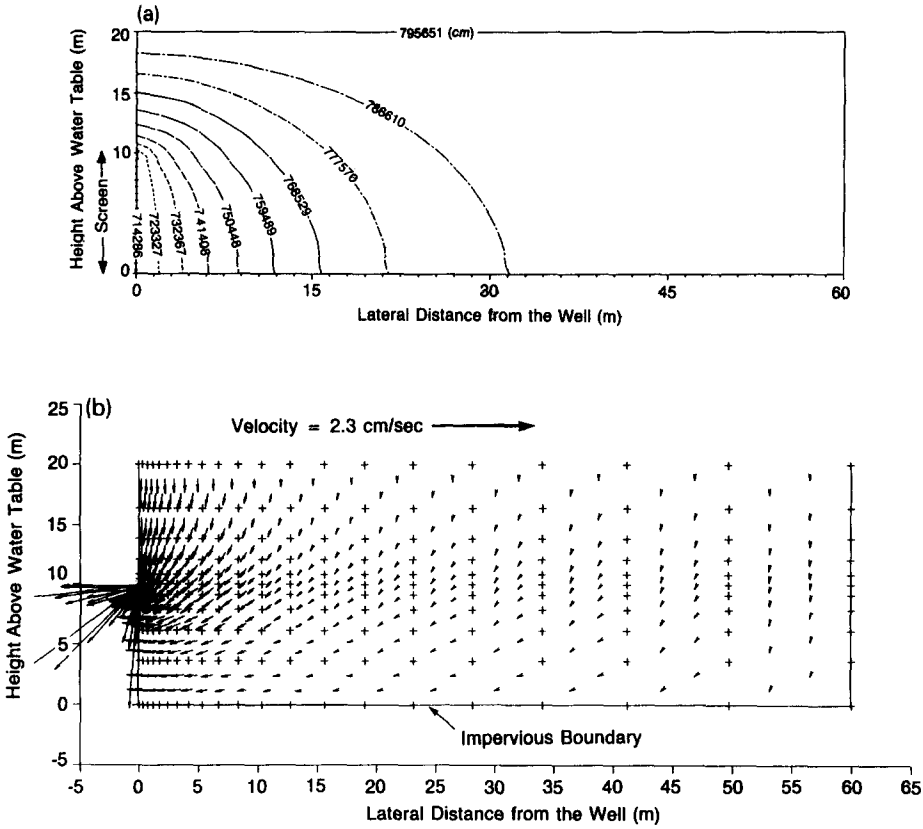

Fig. 4. Simulation results for well screen = 0.5 × the vadose zone theckness: (a) equipotential contour map (in cm of gas pressure head); and (b) flow diagram (*vectors* shows flow direction and relative velocity).

fraction of the air that will be sweeping through a clean zone. Thus, enhancement of l alone may not significantly increase the performance of decontamination operations by vapor extraction.

Regression analysis was performed on the simulation results presented in Fig. 6 to find an expression for the relationship between R_e, l and H. The regression shows the following relation between the dimensionless ratios R_e/H and l/H:

$$\frac{R_e}{H} = -0.0225 + 1.560\frac{l}{H} - 0.955\left(\frac{l}{H}\right)^2 \tag{9}$$

For this regression equation, $R^2 = 99.90\%$ and the standard deviation = ± 0.005. Fig. 6 and the regression analysis reveal that the contribution of l to the rate of increase of R_e decreases as the screen length increases. This implies that vapor-extraction treatment without soil-surface sealing may be effective only when the lateral dimension of the contamination plume is relatively small

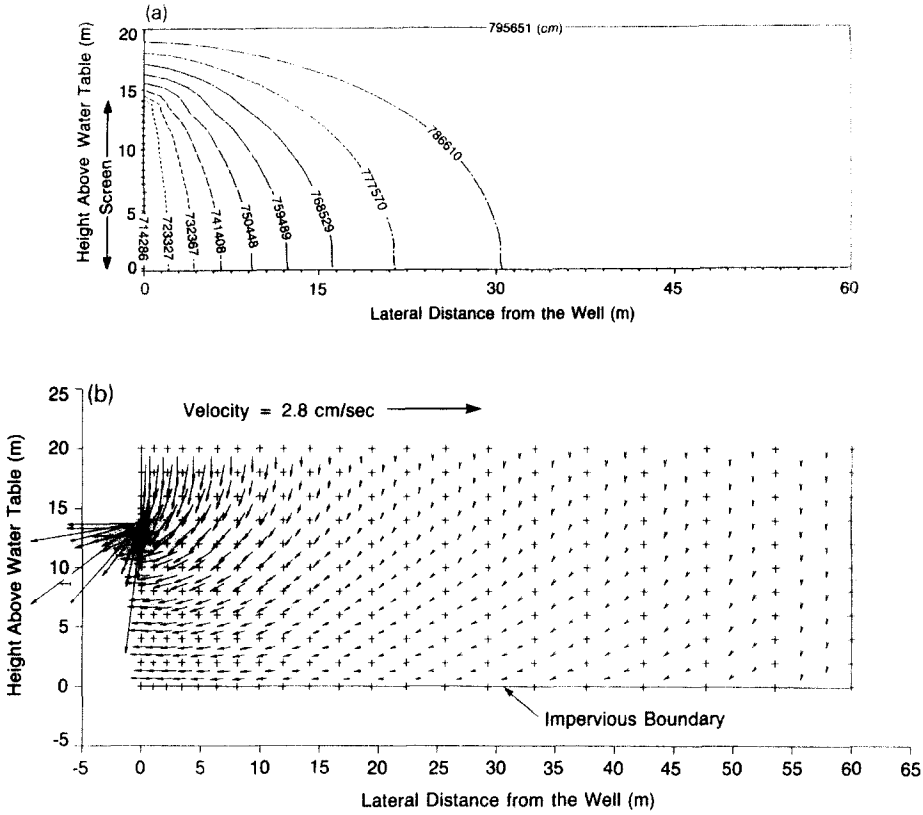

Fig. 5. Simulation results for well screen = 0.7 × the vadose zone theckness: (a) equipotential contour map (in cm of gas pressure head); and (b) flow diagram (*vectors* shows flow direction and relative velocity.

(less than one-half of the vadose zone height). This observation is based on the distribution of the velocity in the domain. It was found that increasing l/H beyond 0.5 gives values for the ratio of flux through the bottom 2 m of the screen to flux through the top 2 m of the screen of less than one-third (Fig. 8).

Fig. 7 shows a linear relationship between R_i and l/H. R_i is defined as the distance from the well to the point along the base of the vadose zone where the gas-pressure head is reduced by 25 mm from the initial-pressure head. This operational definition of R_i was previously used by Krishnayya et al. (1988).

For nonsteady-state problems, Fig. 9 summarizes simulation results for the development of R_i in different soil systems during pumping at the extraction well. These simulations were conducted for the case where $l/H = 0.5$. In this figure, the ratio of R_i at a given time to the steady-state value of R_i is plotted against time for different soil intrinsic permeabilities (K^*). Fig. 9 shows, for example, that after 10 days of pumping, R_i is fully developed for soils having values of K^* larger than 10^{-10} cm^2, but during that same time, only 55% and

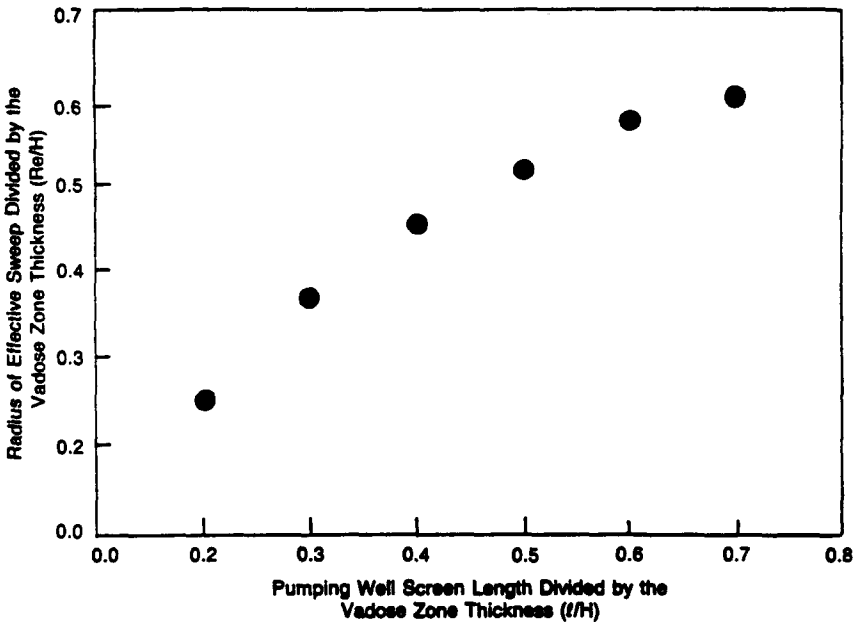

Fig. 6. Effect of screen length on the distance of effective sweep without surface sealing).

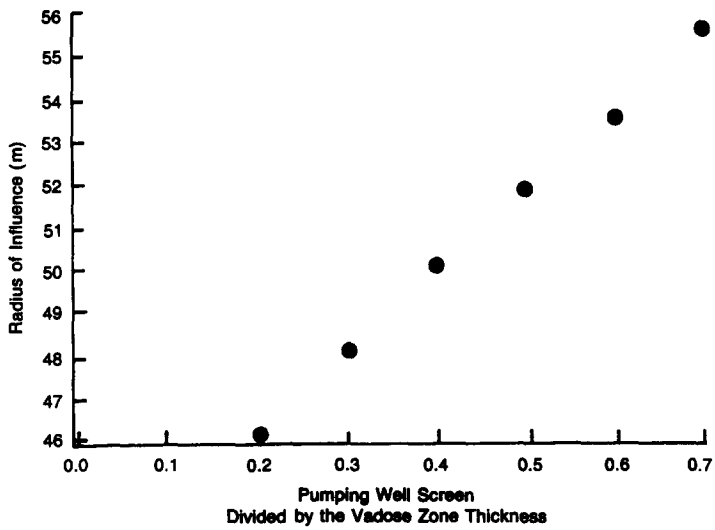

Fig. 7. Effect of screen length on the distance of influence under steady-state conditions (without surface sealing).

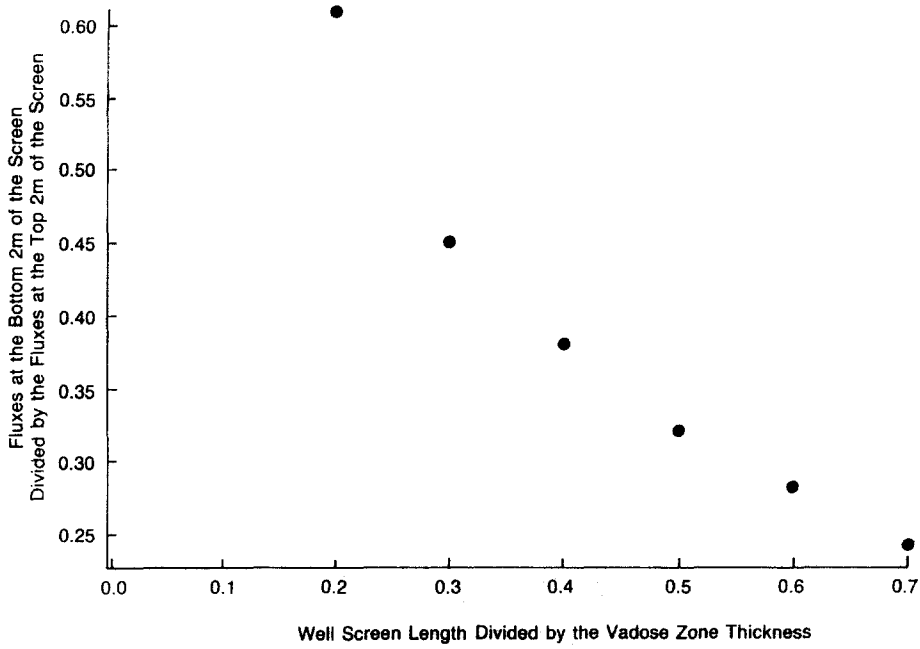

Fig. 8. Ratio of fluxes from the bottom 2 m of the screen to the top 2 m of the screen against the ratio o the well screen length to the vadose zone thickness.

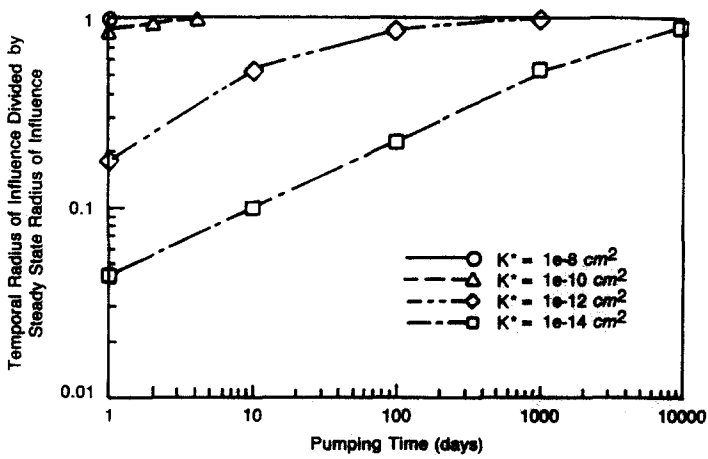

Fig. 9. Effect of screen length on the distance of influence under nonsteady-state conditions for different soil permeabilities.

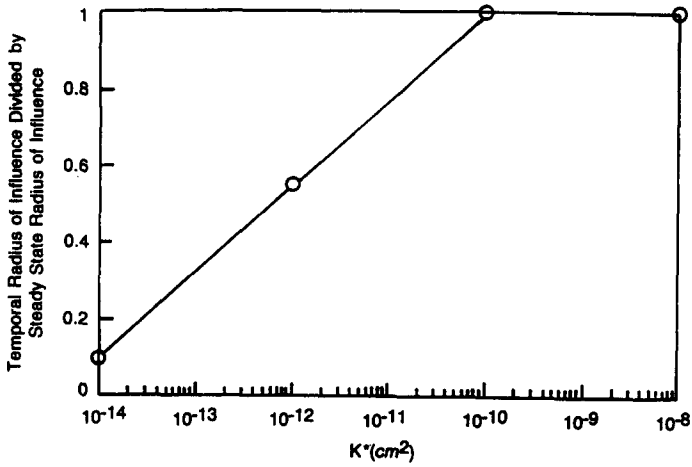

Fig. 10. Effect of permeability on the distance of influence(a snap shot at t = 10 days).

10% of R_i is developed for soils with values of $K^* = 10^{-12}$ cm^2 and $K^* = 10^{-14}$ cm^2, respectively. This observation reveals that the development of the cone of influence in the gas pressure is delayed with the reduction of the soil permeability. Fig. 9 also indicates that the development of the zone of influence for sandy to silty–sandy soils (intrinsic permeability of 10^{-10}–10^{-7} cm^2) could take up to 5 days. This time is insignificant when compared to the expected duration of the vapor extraction operation which can take several months. Thus, for sandy soils, analysis of steady-state scenarios should be sufficient for design purposes. In addition, Fig. 10, which shows the magnitude of $R_i(t)$ as a function of the permeability (K) at time = 10 days, illustrates that for the transient phase, $R_i(t)$ may depend upon K in a polynomial manner of the form:

$$\frac{R_i(t)}{R_{i(\text{steady state})}} = a_1(t) + b_1(t)\log K \tag{10}$$

or

$$R_i(t) = a(t) + b(t)\log K \tag{11}$$

where a is the intercept; and b is the slope of the curve. For the results shown in Fig. 10, $a_1 = 3.25$ and $b_1 = 0.225\,\text{s}\,\text{cm}^{-1}$ ($a = 16802.5$ cm and $b = 1163.25$ s).

Effect of surface sealing on vapor extraction

The role of surface sealing is analyzed from simulation results such as those presented in Figs. 11–13. These results show that by increasing the extent of the surface cover: (a) the pressure-head equipotentials and measurable

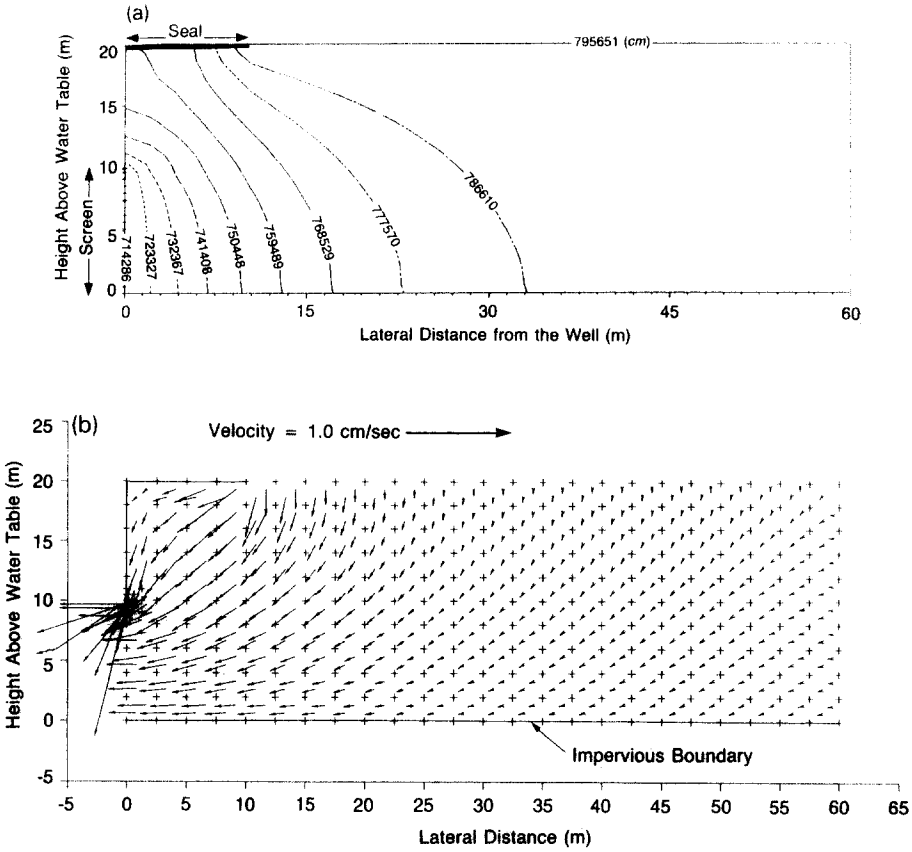

Fig. 11. Simulation results for surface sealing and well screen = 0.5 × the vadose zone thickness: (a) equipotential contour map (in cm of gas pressure head); and (b) flow diagram (*vectors* shows flow direction and relative velocity).

velocities are extended farther from the extraction well; and (b) the zone of prevailing horizontal velocity is extended. These observations imply that a vapor contaminant molecule is swept from the contaminated zone in a shorter time when the dimension of the surface seal is increasing, even without increasing the volume of the air pumped at the well.

Fig. 14 presents simulation calculations involving the length of R_e in terms of its ratio to the vadose zone thickness, H, versus the ratio of the length of the surface seal, r, to H. This figure displays that R_e increases equally with r for cases when the length of the seal is greater than the thickness of the unsaturated zone. This dependence of R_e on r implies that surface seal should be extended to cover the entire plume.

The observed dependency of R_e on screen length and on surface sealing and the linear dependency of R_i on l/H should be valid for any soil. This generality is expected to be valid because the analysis is based on the steady-state

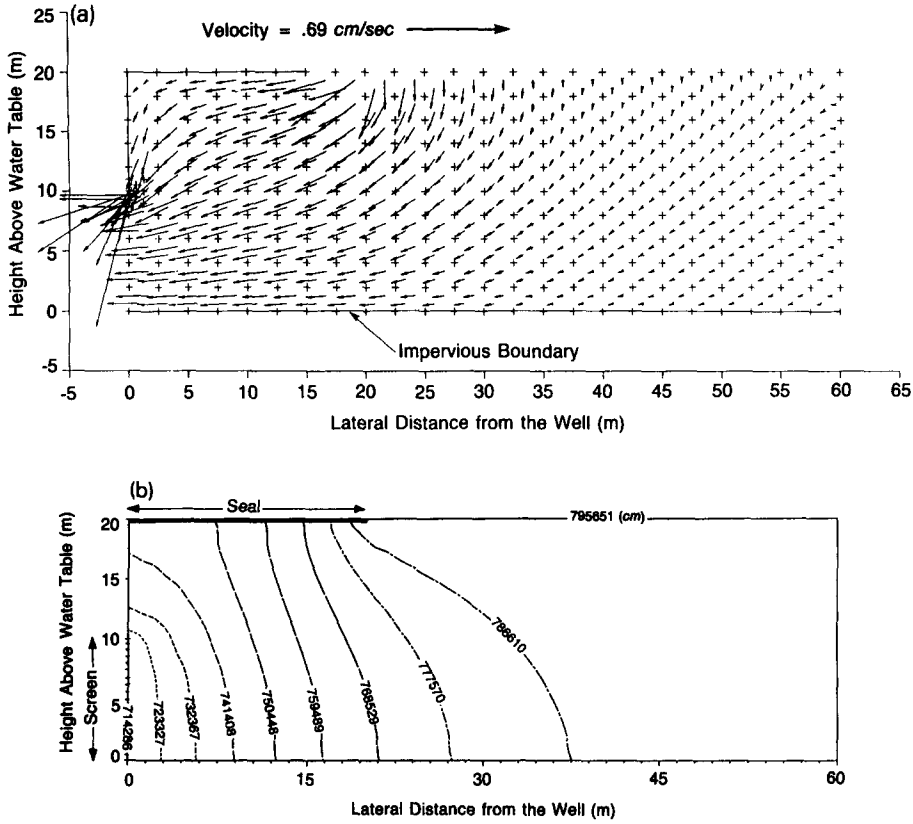

Fig. 12. Simulation results for surface sealing = 1.0 ×, and well screen = 0.5 × the vadose zone thickness: (a) equipotential contour map (in cm of gas pressure head); and (b) flow diagram (*vectors* shows flow direction and relative velocity).

solution for the flow problem in a homogeneous domain. For this case, eq. 1 simplifies into a linear partial differential equation which, in fact, is identical to the well-known Laplace potential problem, and the solution depends linearly on the boundary conditions (Bear, 1979). This linear dependency of the solution on the boundary conditions implies that for steady-state conditions: (a) the ratio between the velocity at an arbitrary point to the velocity at the middle of the extraction well is the same for any suction head; and (b) the magnitude of the velocity at an arbitrary point is linearly dependent on the magnitude of the suction pressure at the well and on the effective permeability. Thus, the extent of R_e is the same distance from the well in any homogeneous soil. Note that the concept of distance of effective sweep is limited to permeable soils ($K^* > 10^{-12}$ cm^2). This is because the suction pressure may not be higher than 2.5 atm (Krishnayya et al., 1988) and the

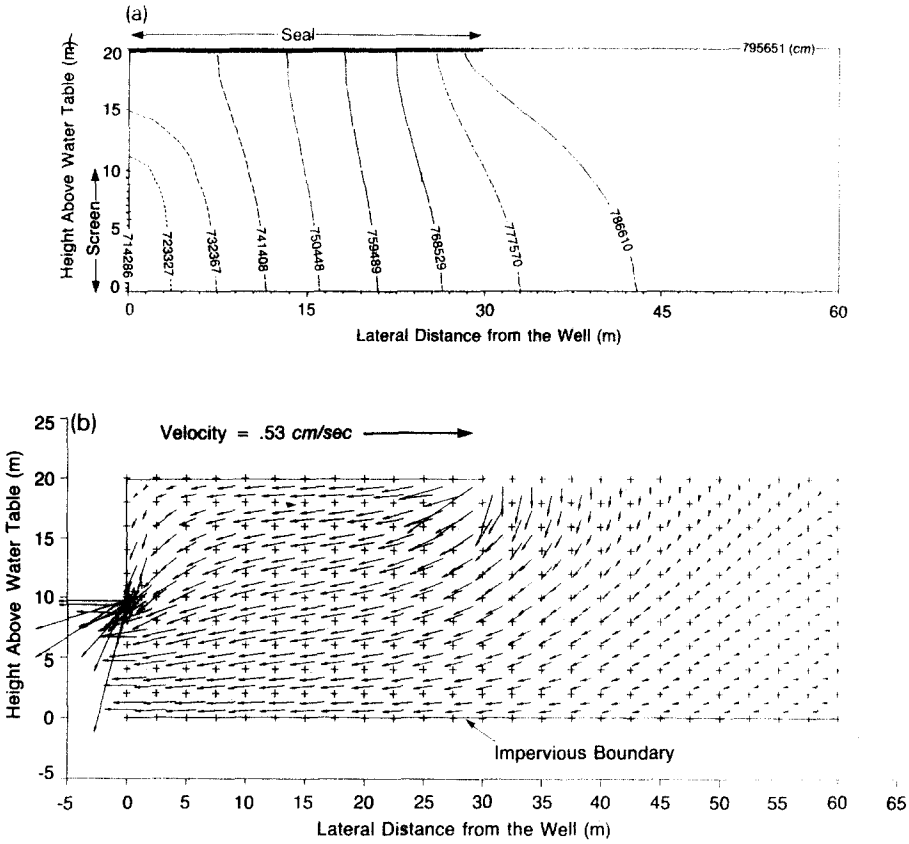

Fig. 13. Simulation results for surface sealing = 1.5 ×, and well screen = 0.5 × the vadose zone thickness: (a) equipotential contour map (in cm of gas pressure head); and (b) flow diagram (*vectors* shows flow direction and relative velocity).

velocities developed in clay soils at the "distance of effective sweep" may be too low to be considered effective.

FUTURE PLANS AND RECOMMENDATIONS

The numerical model should be extended further to obtain the concentration distribution of the contaminant by solving the advection–dispersion transport equation coupled with the solution of the continuity–momentum equation. This extension will allow estimation of the quantity of the contaminant pumped from the soil and the time required to complete the decontamination operation.

The numerical model should be further extended to solve three-dimensional problems. The extension into three dimensions could be useful to analyze the optimal configuration of pumping and injection of gas in the vadose zone

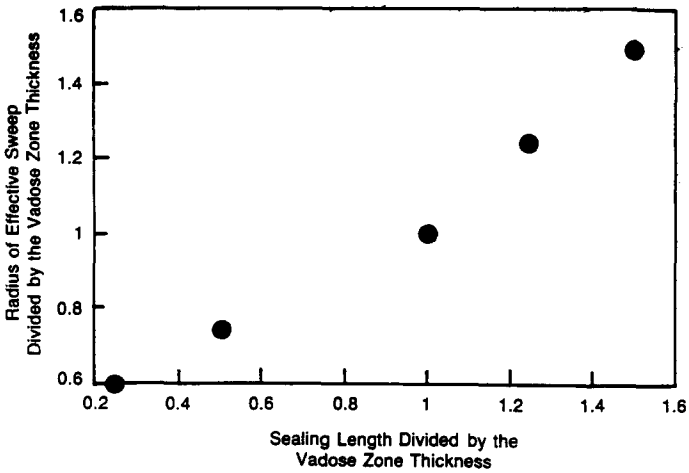

Fig. 14. Effect of top sealing on the distance of effective sweep.

domain. This extension will also produce a better analysis of the optimal configuration scheme for pumping and recharging wells.

It is also recommended to explore the application of Darcy's law for gas flow in porous media. This law is widely assumed, but has never been validated for gas flow through the vadose zone. The validation can be done by a simple laboratory experiment. This step is especially important because Darcy's equation was originally developed for a very slow flow of water in porous media, i.e. with Reynold's numbers below 1.0. However, for the same velocity, the Reynold's number for gas is ~ 10 times higher than that for the water, because of the ratios of the viscosities and specific densities of the two fluids.

CONCLUDING REMARKS

A concept of distance of effective sweep is introduced in order to estimate the zone in which VOC's may be swept effectively through a contaminated unsaturated porous medium by a vapor-extraction well. The distance is estimated as a function of the dimensionless ratios of the length of the well screen to the vadose zone thickness, and of the soil sealing length to the vadoze zone thickness. The distance is determined in order to find an approximately optimized pumping configuration for subsurface decontamination by vapor extraction. The relationships in dimensionless parameters make the functional forms applicable to any cross-section configuration of vadose zone thickness, screen length and surface sealing. These relationships should be valid for any homogeneous soil because the analysis is based on the steady-state solution of the flow problem. The analysis of the distance of effective sweep clearly shows that vapor extraction without soil-surface sealing is

limited to treating small plumes with radii smaller than one-half of the vadose zone thickness. Otherwise, it is recommended to extend the sealing to the plume dimensions.

Other findings in this work show that the distance of influence depends linearly on the screen length. The model results indicate that for sandy to silt–sandy soils the distance is fully developed within a few days and within a few years for impermeable clays. For transient flow, this distance may be related to soil permeability by the functional form $a + b \log K$ (for a line sink scenario). The relatively short duration for the development of the radius of influence in high-permeable soils justifies neglecting gas compressibility in the simulation of gas flow in such media.

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