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Jose M. Rodriguez-maroto[a]; Cesar Gomez-lahoz[a]; David J. Wilson[b]
[a] Departamento De Ingenieria, Quimica Universidad De Malaga, Malaga, Spain [b] Departments of Chemistry and of Environmental and Civil Engineering, Vanderbilt University, Nashville, Tennessee

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Soil Clean Up by *in-situ* Aeration. VIII. Effects of System Geometry on Vapor Extraction Efficiency

JOSE M. RODRIGUEZ-MAROTO and CESAR GOMEZ-LAHOZ
DEPARTAMENTO DE INGENIERIA QUIMICA
UNIVERSIDAD DE MALAGA
29071 MALAGA, SPAIN

DAVID J. WILSON
DEPARTMENTS OF CHEMISTRY AND OF ENVIRONMENTAL AND CIVIL ENGINEERING
VANDERBILT UNIVERSITY
NASHVILLE, TENNESSEE 37235

Abstract

A mathematical model for soil vapor extraction by means of a buried horizontal slotted pipe was used to examine the effects of a number of geometrical system parameters on the efficiency of soil vapor extraction. Parameters investigated include depth of pipe relative to the water table, size of impermeable overlying cap, and presence or absence of passive horizontal vent pipes. The results demonstrate the utility of mathematical modeling for exploring cheaply and rapidly the effects of variations in soil vapor extraction system design.

INTRODUCTION

Soil vapor extraction (SVE, soil vacuum extraction, soil vapor stripping, soil venting) is now a well-established technique for removing volatile organic compounds (VOCs) from the vadose zone at hazardous waste sites, leaks, spills, etc. EPA has discussed the technology in a number of reports (*1–4*, for example), and a number of models and schemes for the design of SVE facilities have been published (*5–9*, for example).

Models for field-scale SVE operation generally focus on a vertical well which is screened along part of its length near the bottom. At some sites, however, buried lateral screened pipes have been used for SVE; this was done, for instance, with excavated contaminated soil at Hill Air Force Base, Utah (*10*, *11*). This mode of operation would appear to be particularly well adapted to sites having a relatively high water table, so that the number of wells which would have to be drilled would be excessive. We developed a model for this geometry (horizontal slotted pipe) in a previous paper and used it to explore the effects of variable pneumatic permeabilities on the efficiency of SVE (*12*). In the present paper we use this model to investigate the dependence of SVE rate of clean up on geometrical factors (depth of well relative to the water table, width of impermeable cap, presence or absence of passive horizontal slotted vent pipes along the edges of the domain of influence of the vacuum pipe). One has control over these factors, unlike some of the other parameters which appear in the models (effective Henry's constant, pneumatic permeability function, etc.). Information on their impacts, singly and in combination, on rate of clean up by SVE should provide useful insight into design optimization. For the details of the model, the reader is referred to our earlier paper (*12*).

RESULTS

All runs were made in TurboBASIC on microcomputers running MS-DOS. The SVE system consists of an array of long parallel horizontal screened pipes, of which the domain of influence of one pipe is modeled. A no-flow boundary condition is assumed between adjacent domains. This permits modeling to be done in two dimensions (vertical and horizontal normal to the pipe) and in a domain of finite volume. A sketch of the geometry is given in Fig. 1. All runs were made with the standard parameter set given in Table 1 except as indicated in the captions to the figures.

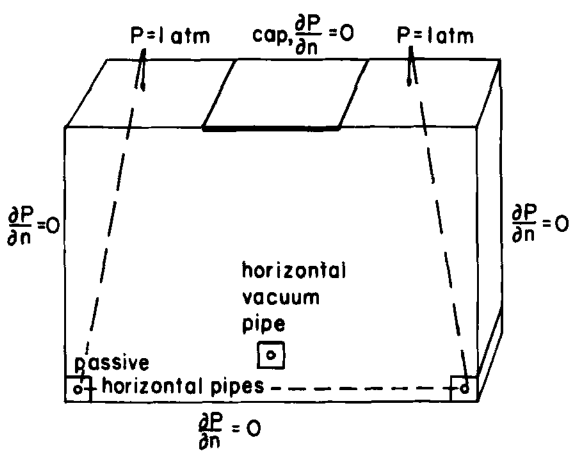

FIG. 1. Sketch of the setup for SVE with a horizontal slotted pipe.

TABLE 1
Standard Parameter Set for Simulations of Vapor Stripping with a Horizontal Slotted Pipe

Parameter	Value
Domain length	13 m
Domain depth	8 m
dx, dy	1 m
Packed radius of well	0.1 m
Wellhead pressure	0.75 atm
Temperature	14°C
Soil porosity	0.375
Specific moisture content	0.2
K_x, K_y	0.100 m^2/atm·s
Initial soil contaminant concentration	100 mg/kg
Soil density	1.7 g/cm^3
Effective Henry's constant	0.005

Figures 2 and 3 show streamlines and gas transit times for a horizontal slotted pipe which is screened just above the water table (Fig. 2) and one which is screened 4 m above the water table (Fig. 3). Gas transit time figures are given in units of 1000 s. Comparison of the streamlines indicates that the zones of near-stagnation in the lower corners of the domain are substantially smaller for the deeper well. Comparison of the transit times of the outermost streamlines indicates that in this critical region, where

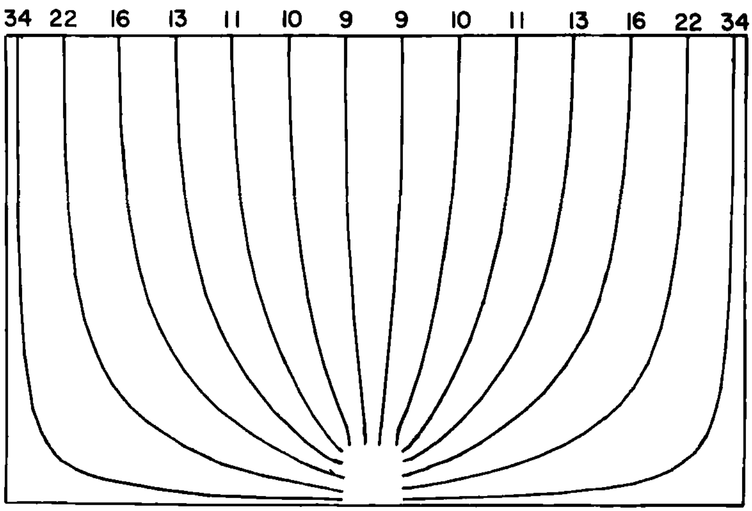

FIG. 2. Streamlines and gas transit times of the standard configuration, SVE with a horizontal slotted pipe just above the water table. See Table 1 for parameter values.

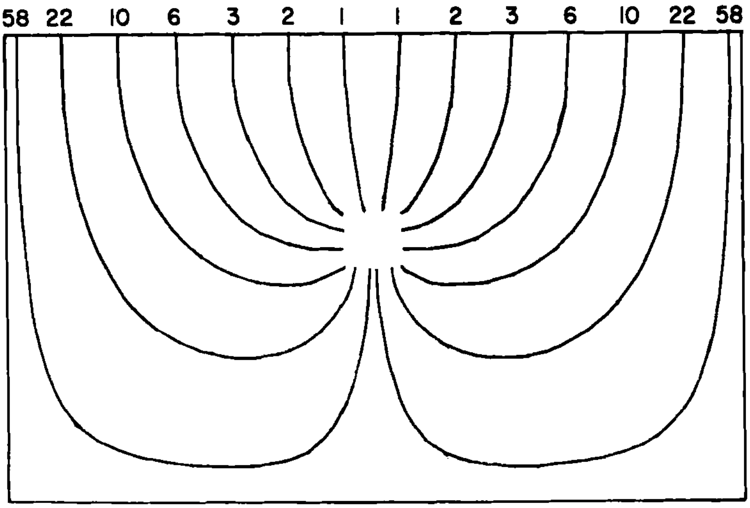

FIG. 3. Streamlines and transit times, SVE with a horizontal slotted pipe 4 m above the water table. See Table 1 for all unspecified parameter values for this and all following figures.

transit times tend to be quite long under the best of circumstances, the transit times for the deeper well are significantly shorter than those for the shallower well. Figure 4, in which $\log_{10}$ residual contaminant mass is plotted against time for heights of 0, 1, 2, 3, and 4 m above the water table, shows the effect of well depth quite clearly. Clean up to a given level of contaminant removal by the shallowest well takes about twice as long as it does for the two deepest wells.

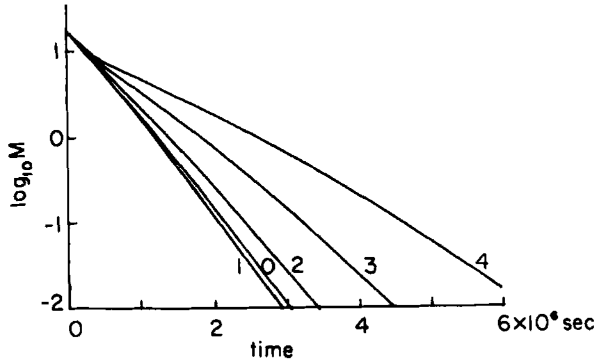

FIG. 4. Residual contaminant versus time; effect of height of horizontal slotted pipe above the water table. The ordinate is $\log_{10}$ total contaminant mass. Numbers beside the curves indicate distance of the pipe above the water table in meters.

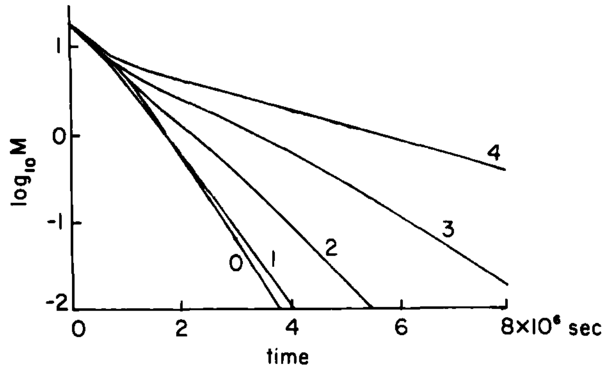

FIG. 5. Residual contaminant versus time; effect of a 50% decrease in the vertical component of the pneumatic permeability (K_y = 0.05 m²/atm·s). Numbers beside the curves indicate distance of the pipe above the water table in meters.

Comparison of Figs. 4, 5, and 6 shows how anisotropy in the pneumatic permeability modifies the effect of well depth on the rate of contaminant removal. The permeability in Fig. 4 is isotropic, the vertical permeability component K_y in Fig. 5 has been decreased by a factor of one-half, and the horizontal permeability component in Fig. 6 has been decreased by a factor of one-half. For shallow wells a decrease in the value of K_y even by only 50% has a devastating effect on well efficiency, although such a decrease in K_y has a rather minor impact on the efficiencies of the deep wells. Hydraulic permeabilities frequently are anisotropic with K_{vertical} less than $K_{\text{horizontal}}$; pneumatic permeabilities probably behave the same way, which

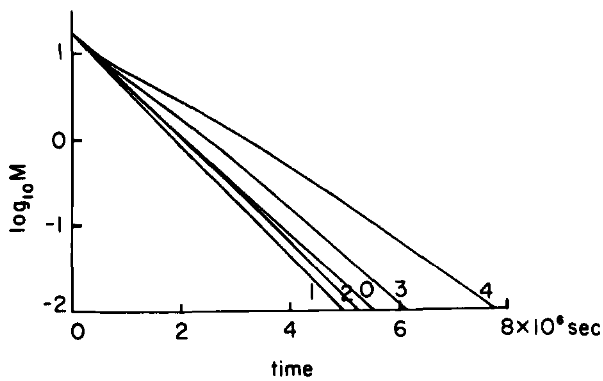

FIG. 6. Residual contaminant versus time; effect of a 50% decrease in the horizontal component of the pneumatic permeability K_x = 0.05 m²/atm·s). Numbers beside the curves indicate distance of the pipe above the water table in meters.

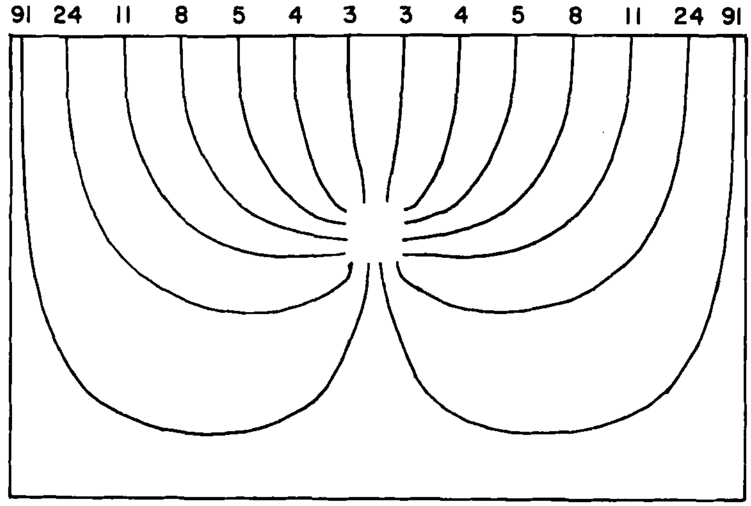

FIG. 7. Streamlines and soil gas transit times; effect of a 50% decrease in the vertical component of the permeability (K_y = 0.05 m^2/atm·s). Height of horizontal slotted pipe above the water table = 4 m.

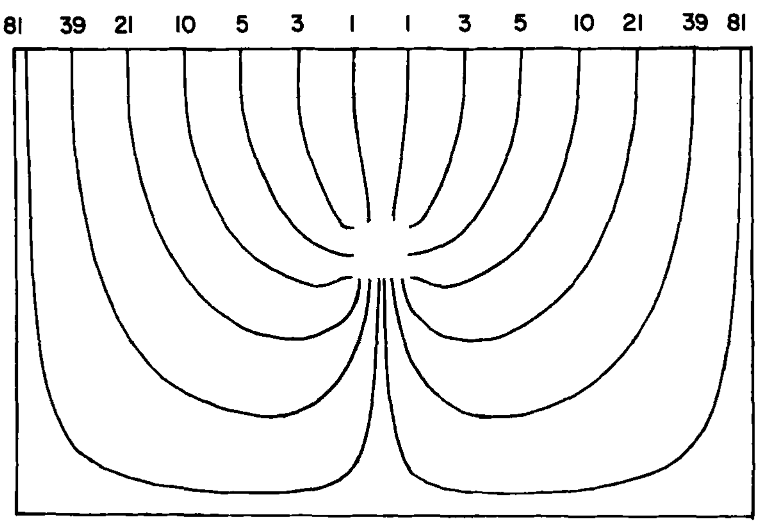

FIG. 8. Streamlines and soil gas transit times; effect of a 50% decrease in the horizontal component of the permeability (K_x = 0.05 m^2/atm·s). Height of horizontal slotted pipe above the water table = 4 m.

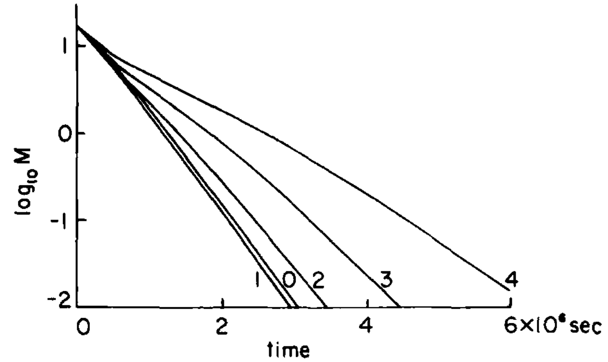

FIG. 9. Residual contaminant versus time; effect of an overlying impermeable cap of 1 m width. Numbers by the curves indicate the distance of the pipe above the water table in meters.

makes a very good argument for generally screening wells as close to the water table as conveniently possible. The effect of a decrease of 50% in K_x, shown in Fig. 6, is much less marked for both shallow and deep wells. Figures 3, 7, and 8 show the streamlines and transit times for the gas flow for the shallowest well (4 m above the water table) for these systems. The outermost streamlines for the run shown in Fig. 7, for which K_y has been reduced by 50%, fail to penetrate into the lower corners of the domain of influence and show quite long transit times compared with both Figs. 3 (isotropic permeability) and 8 (K_x reduced by 50%), which explains the very slow rate of clean up achieved in this run.

Figures 9, 10, and 11 show the effects of well depth on clean-up rate

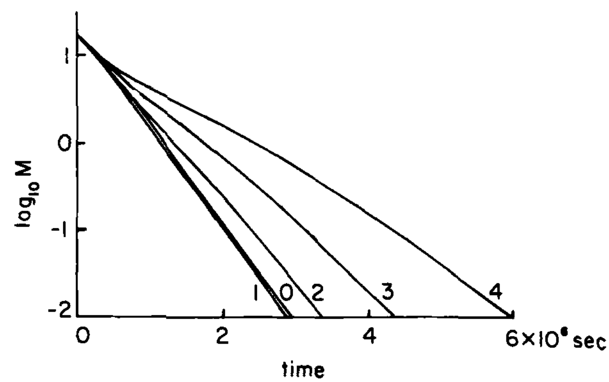

FIG. 10. Residual contaminant versus time; effect of an overlying impermeable cap of 5 m width.

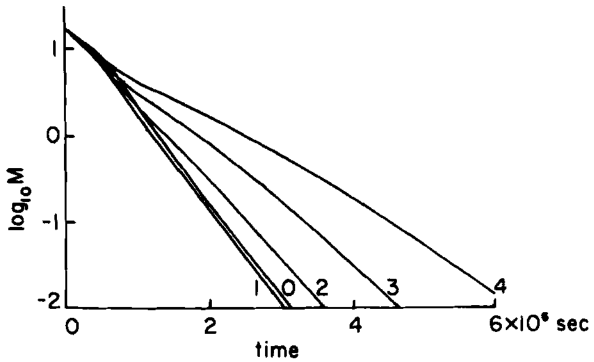

FIG. 11. Residual contaminant versus time; effect of an overlying impermeable cap of 9 m width.

when an overlying impermeable cap is present. In all cases, wells are screened at the water table and 1, 2, 3, and 4 m above it. In Fig. 9 the cap width is 1 m; in Fig. 10, 5 m; in Fig. 11, 9 m. The permeability is isotropic. The results indicate that, while the runs made with the 5-m cap show most rapid clean up, the differences are relatively minor. One would probably not regard them as sufficient to warrant the expense and inconvenience of installing the cap.

Figures 12–15 show clean-up rates and representative streamlines for systems equipped with passive horizontal slotted pipes in the lower corners of the domain. The presence of the passive wells very markedly improves

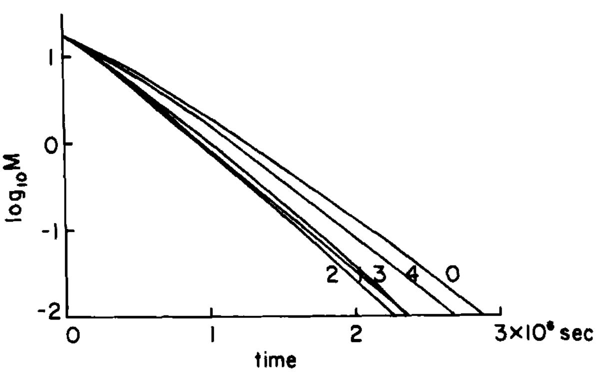

FIG. 12. Residual contaminant versus time; the lower borders of the domain of influence contain passive horizontal vent pipes. The numbers by the curves indicate the height of the vacuum well above the water table in meters. No cap is present.

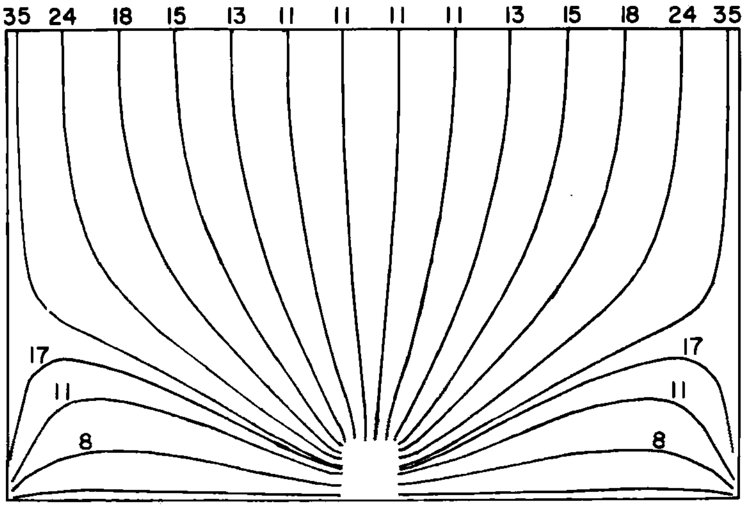

FIG. 13. Streamlines and gas transit times in the presence of passive horizontal vent pipes at the lower borders of the domain of influence. The horizontal vacuum pipe is at the water table.

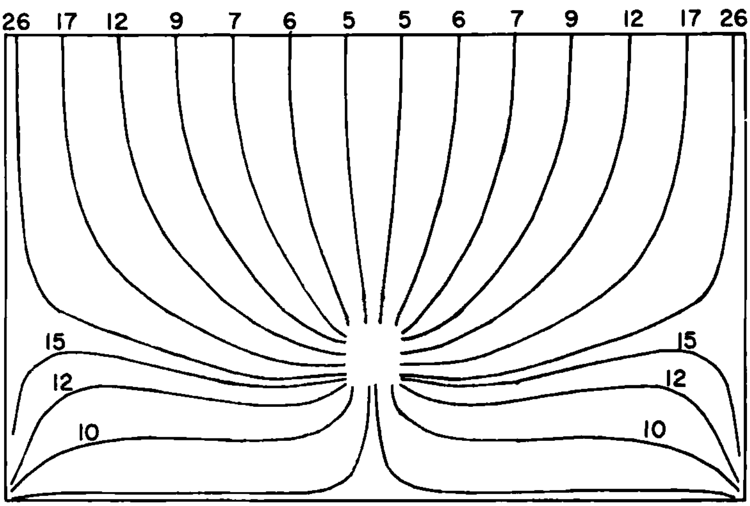

FIG. 14. Streamlines and gas transit times in the presence of passive horizontal vent pipes at the lower borders of the domain of influence. The horizontal vacuum pipe is 2 m above the water table.

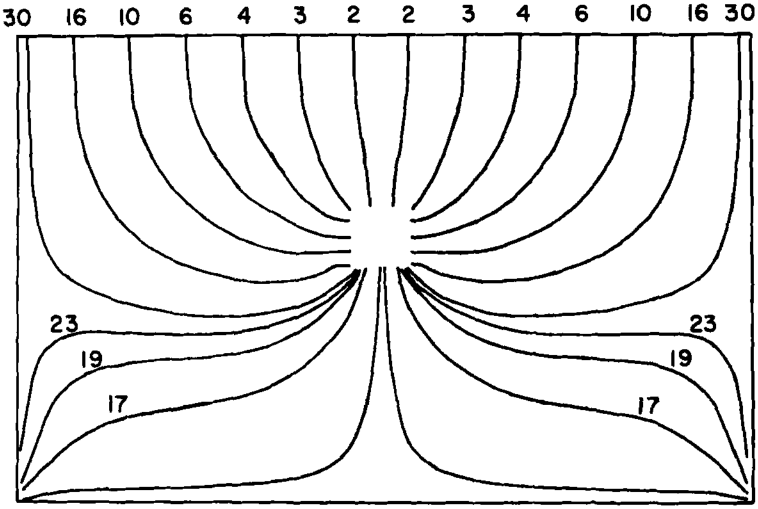

FIG. 15. Streamlines and gas transit times in the presence of passive horizontal vent pipes at the lower borders of the domain. The horizontal vacuum pipe is 4 m above the water table.

the performance of a shallow vacuum well, as seen in Fig. 12. The reason is apparent when one inspects the streamlines and transit times in Figs. 13–15. In all of these figures the zones of stagnation appear to be quite small, and even the largest of the gas transit times is comparatively short.

The effects of combined passive horizontal slotted pipes and overlying impermeable caps are shown in Figs. 12 and 16–19. The presence of a 5-m cap produces relatively little increase in clean-up rate, as seen by

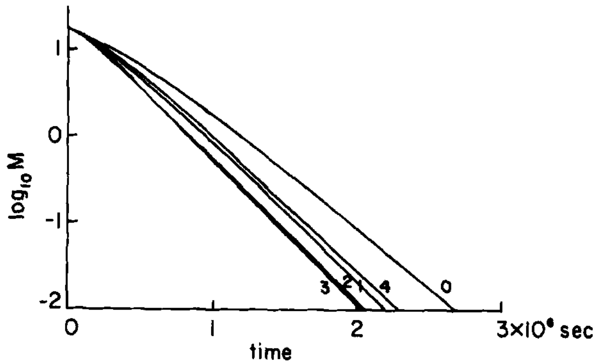

FIG. 16. Residual contaminant versus time; passive horizontal vent pipes and an overlying impermeable cap of 5 m width are present. Numbers by the curves indicate height of the vacuum pipe above the water table in meters.

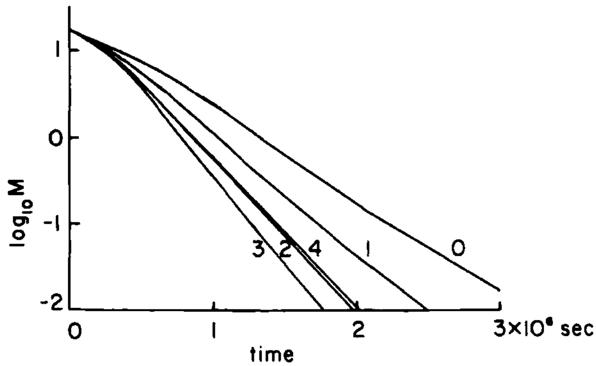

FIG. 17. Residual contaminant versus time; passive horizontal vent pipes and an overlying impermeable cap of 9 m width are present. Numbers by the curves indicate height of the vacuum pipe above the water table in meters.

comparing Figs. 12 (no cap) and 16 (5-m cap). This slight increase in clean-up rate continues until the cap width approaches 9 m (Fig. 17), at which point further increases in cap width cap to 11 m (Fig. 18) and 13 m (complete coverage of the domain, Fig. 19) result in a drastic decrease in the removal rate of the deepest wells, while the shallower wells are less severely affected. Examination of the streamlines and transit times for these runs (not shown here) provided the explanation. As the cap size increases above 9 m, there is a progressively increasing zone of stagnation in the center of the domain of influence and immediately under the cap. This zone is smaller if the well is shallow than it is if the well is deep. On the other hand, the

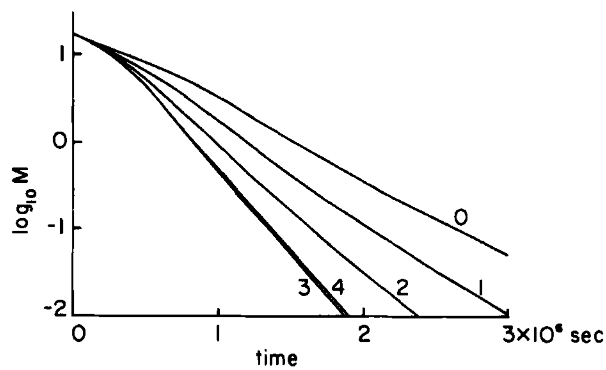

FIG. 18. Residual contaminant versus time; passive horizontal vent pipes and an impermeable cap of 11 m width are present. Numbers indicate height of the vacuum pipe above the water table in meters.

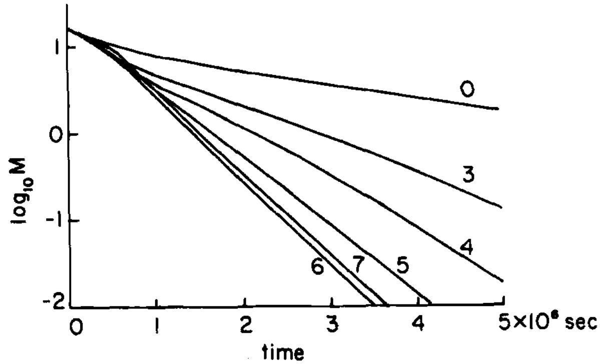

FIG. 19. Residual contaminant versus time; passive horizontal vent pipes and an impermeable cap covering the top of the entire domain of influence (13 m width) are present. Numbers indicate height of the vacuum pipe above the water table in meters.

gas transit times for the outer streamlines decrease with increasing cap width. The interplay between well depth and cap width is therefore rather complex. A well drilled to 3 m above the water table and having a cap 9 m wide yielded a clean-up rate 75% *larger* than that of the standard configuration (well drilled to the water table and no cap).

The calculations done here are all based upon a local equilibrium model. Such models have been found adequate for use at some sites (*8* and *9*, for example). Other sites exhibit kinetics-limited soil vapor extraction in which diffusion and/or desorption kinetics reduce the rate of removal of VOC below what one would expect if local equilibrium were valid. Fall et al. (*13*), Hutzler, McKenzie, and Gierke (*14*), and Sterrett (*15*) have reported observing kinetic limitation experimentally in lab or field studies. DiGiulio et al. (*16*) have described a quite straightforward procedure for determining if kinetic limitations are significant and for estimating the magnitude of the time constant associated with them. Their procedure involves the placing of a vacuum well which is isolated from the bulk of the zone of contamination by placing several passive wells screened along their entire length on a circle, the center of which is occupied by the vacuum well. The vacuum well can then be operated until its effluent solid gas VOC concentrations are nearly zero, at which point it is shut down for a period, after which soil gas samples are taken for analysis to determine the extent to which diffusion and desorption have caused the VOC concentrations to increase.

A similar approach can be used with horizontal slotted pipes. One places the vacuum pipe in the center of the domain to be tested, and flanks it on either side by trenches filled with crushed rock. These act as isolation boundaries, preventing the vacuum well from drawing gas from outside the region bounded by the two trenches. One then operates the vacuum well until the effluent soil gas VOC concentrations have decreased to nearly zero, shuts down for a period, and then takes soil gas samples for analysis exactly as in the other procedure.

In conclusion, we note that streamlines and gas transit times can be calculated very rapidly and provide a quite useful qualitative guide to the design of soil vapor extraction systems. The more lengthy calculations of the removal of VOC by SVE can thus be reserved for a more limited number of systems which have been optimized by the faster calculations. This and other calculations (*11*) demonstrate the importance of including information about stratification, anisotropy, and other aspects of soil structure in the model when such information is available. The calculations also indicate the utility of horizontal slotted pipe for SVE, especially when the water table is relatively shallow.

Acknowledgment

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