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Soil Vapor Extraction System Design: A Case Study Comparing Vacuum and Pore Gas Velocity Cutoff Criteria

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Abstract

Soil vapor extraction (SVE) systems are typically designed based on the results of a vadose zone pumping test (transient or steady state) using a pressure criteria to establish the zone of influence (ZOI). A common problem associated with pressure based SVE design is overestimating the ZOI of the extraction well. The vacuum criteria commonly used to establish the boundary of the ZOI results in large areas with very low pore velocities and thus long cleanup times. As a result, design strategies based upon critical pore gas velocity (CPGV) have increased in popularity. The CPGV is used in an effort to loosely incorporate the effects of

mass transfer limitations into the design of SVE systems. Critical pore gas velocity designs use a minimum pore gas velocity rather than minimum vacuum to identify the extent of the treatment zone of an SVE system. The CPGV is typically much larger than the pore gas velocity at the perimeter of vacuum based (ZOI) designs resulting in shorter cleanup times.

In this paper, we report the results of testing performed at the Savannah River Site (SRS) to determine the influence of a vapor extraction well based upon both a pressure and pore gas velocity design criteria. Results from this testing show that a SVE system designed based upon a CPGV is more robust and will have shorter cleanup times due to increased flow throughout the treatment zone. Pressure based SVE design may be appropriate in applications where soil gas containment is the primary objective; however, in cases where the capture and removal of contaminated soil gas is the primary objective, CPGV is a better design criteria.

Introduction

In recent years, soil vapor extraction (SVE) has become one of the most widely deployed remediation technologies for the treatment of volatile organic compounds (VOC) in the vadose zone. When properly applied, it is one of the most cost effective, energy efficient, remediation technologies available to the environmental engineer or scientist for the treatment of sediments with VOC contamination. Soil vapor extraction systems are relatively simple units with low operating costs. They strip contaminants from the unsaturated sediments by the advective removal of soil gas. A vacuum blower (commonly a rotary lobe blower) is generally used to apply vacuum to a network of SVE wells thereby resulting in the removal of soil gas from the vadose zone. As the contaminated soil gas is removed from the vadose zone it is ultimately replaced by clean air from above the ground surface. Remaining residual contamination then partitions and diffuses into the clean soil gas.

The most common approach for SVE well field design is to use vacuum as a criteria for well spacing. In this approach a critical or cut-off vacuum is established based on the natural variation in subsurface gas pressure that results from atmospheric waves that are transmitted through connected pores in the unsaturated zone (barometric pressure differential). Calculations are then performed using pilot test data and the appropriate analytical model to determine the distance from the well where the critical vacuum is achieved. The volume contained within this radius is referred to as the Zone of Influence (ZOI).

A common problem associated with pressure based SVE design is overestimating the ZOI of the extraction well. This can produce dead zones where there is little or no meaningful air flow. Dead zones are areas between extraction wells where soil gas is stagnant and can occur when the well spacing is inadequate. Furthermore, SVE designs based solely on vadose zone pressure distributions neglect the important fact that a measured pressure differential may not correspond to meaningful vapor flow towards the extraction well. Therefore, SVE design based upon ZOI alone will ensure vapor containment but not necessarily vapor capture (EPA 2001, Johnson and Ettinger, 1994).

An alternative method to design an SVE well field is to determine the Zone of Capture (ZOC). The ZOC is based on pore-gas velocity calculations using permeability test data and includes the volume that has a pore-gas velocity greater than a previously established value. The critical pore-gas velocity is selected based on mass transfer kinetics and the desired clean-up time. The critical pore-gas velocity can be defined as the minimum pore-gas velocity necessary to produce timely remediation (EPA 2001). Using this method, the ZOC is defined as the volume contained within the maximum radial distance from the well where the critical pore-gas velocity is maintained.

A ZOC based on pore-gas velocity helps to ensure that extraction well spacing will be sufficient to cause meaningful airflow towards the well. The ZOC for an individual extraction well based upon pore-gas velocity will typically be smaller than the ZOI based on pressure distribution depending on the cutoff values chosen for each method. Hence, it is important to establish clear objectives prior to the design of the SVE system. If vapor containment is the objective, a ZOI based approach may be sufficient; however, if vapor collection is the objective, a ZOC approach may be more appropriate.

The purpose of this paper is to present the results from testing at the U.S. Department of Energy's Savannah River Site (SRS) near Aiken, South Carolina to determine the influence of a vapor extraction well based upon both a pressure and pore gas velocity design criteria. Data from the testing was analyzed to determine the ZOI based on pressure criteria and ZOC based on pore gas velocity for a small scale SVE system.

Discussion

The SVE system chosen for this analysis consisted of a single pumping well and three observation wells. These test wells are located at the A-Area Burning/Rubble Pit (ABRP) in the northwest portion of the SRS. The contaminated zone of interest is in a medium to fine grained sand overlain by a clayey layer. The clayey layer restricts air flow across the top boundary of the contaminated zone and can be simulated as a semi-confining layer. Figure 1 shows the conceptual model for the site. Several transient vadose zone pumping tests were conducted to establish the physical properties of the shallow, unconsolidated sediments.

Data from pumping tests were analyzed using a modified Hantush method for semi-confined aquifers (Hantush, 1964). Massman (1989) documented the assumptions and limitations associated with modeling vapor flow with conventional groundwater flow equations. The most significant assumption is that vapor flow can be modeled using the equation for incompressible fluid flow when pressure variations within the model domain are on the order of one half atmosphere (~ 500 cm H_2O). The Hantush model provided a good fit to the field data validating the use of a semi-confined aquifer analog for the contaminated vadose zone at the ABRP, Figure 2. The results of these transient pumping tests and several others have been reported by Dixon and Nichols (2005).

Dixon and Nichols (2005) gave a detailed description of the SRS site geology and the methods used to analyze the field data to determine the physical properties of the vadose zone sediments. The median physical properties based on testing conducted on well ASH-06 as reported by Dixon and Nichols (2005) were used in the ZOI/ZOC analyses presented in this paper. These properties are summarized in Table 1.

Zone of Influence

For a ZOI analysis, a minimum vacuum criteria must be established below which it is assumed the extraction well exerts limited influence. Several different minimum values have been proposed ranging from 0.25 to 2.54 cm of water to 10% of the applied vacuum. In order to establish an appropriate cutoff vacuum for the ABRP test site, both atmospheric pressure and subsurface gas pressure were monitored during a pretest period, Figure 3. Fluctuations in barometric pressure at the ground surface are transmitted through the unsaturated subsurface in the form of pressure waves that are typically damped and delayed to degrees dependent on the effective permeability of the unsaturated media (Weeks, 1978). This dampened and delayed response is evident in the pretest data at the ABRP test site, Figure 3. When the subsurface pressure data were corrected for the delay, the magnitude of the difference between the subsurface and barometric pressure was found to average about 2.54 cm of water. In order to ensure a containment vacuum greater than the typical variation between barometric and subsurface gas pressure, a cutoff vacuum of 2.54 cm of water was selected to define the boundary of the ZOI.

The ZOI for the extraction well was estimated using the Hantush leaky aquifer method (Hantush, 1964) as outlined by Walton (1991). Steady state drawdown was calculated for several different pumping scenarios. The median physical properties from the transient testing as reported by Dixon and Nichols (2005) were used to describe the vadose zone (Table 1). Walton (1991) gives the equation for drawdown in a leaky confined aquifer as:

$$s = \frac{Q}{4\pi T} W(u, \beta) \tag{1}$$

where Q is the extraction flow rate, T is the transmissivity. W(u, β) is the Hantush leaky well function defined by:

$$W(u, \beta) = \int_u^\infty \frac{1}{y} e^{\left\{-y - \frac{\beta^2}{4y}\right\}} dy \tag{2}$$

where:

$$u = \frac{r^2 S}{4Tt} \tag{3}$$

and

$$\beta = \frac{r}{\sqrt{\left(\frac{Tb'}{k'}\right)}} \tag{4}$$

where r is the radial distance from the extraction well, S is the storativity, t is time, b' is the confining layer thickness, and k' is the permeability of the confining layer.

A user defined excel function was created to calculate the pressure drawdown in the vadose zone at varying radial distances from the extraction well using Equations 1 through 4. The output from the function was verified against tabulated values for W(u, β) in Walton (1991). Figure 4 shows the results of the pressure response calculations for several extraction flow rates as a function of radial distance. An extraction flow rate of 1.42 m^3/min (50 scfm) produced a ZOI of about 56.4 m (185 ft) using a cutoff criteria of 2.54 cm. Similarly, for an extraction flow rate of 0.71 m^3/min (25 scfm) produced a ZOI of about 18.3 m (60 ft). An extraction flow rate of 0.28 m^3/min (10 scfm) did not produce vadose pressures above the cutoff criteria of 2.54 cm.

Zone of Capture

The computer program AIR2D, which is a public domain Fortran code, was used to determine the pore-gas velocity distribution in the vadose zone (Joss and Baehr, 1997). AIR2D is a two-dimensional, steady-state, axisymmetric air flow model that simulates air movement either to or from extraction or injection wells in the vadose zone. The program has the capability to model systems open to the atmosphere or bounded by a leaky confining layer.

For this analysis, the leaky confining layer option was chosen and the analytical solution used is documented by Baehr and Joss (1995). Figure 5 shows the pore-gas velocity as a function of radial distance for various flow rates. EPA (2001) selected a critical pore-gas velocity of 0.01 cm/sec for a contaminated site located in the sandy sediments of the Atlantic Coast Plain. The ABRP is also underlain by coastal plain sediments and therefore a critical pore-gas velocity of 0.01 cm/sec was adopted for this study. Using a critical pore gas velocity of 0.01 cm/sec, the ZOC for an extraction flow rate of 1.42 m^3/min (50 scfm) was predicted to be about 15.2 m (50 ft) and for an extraction flow rate of 0.71 m^3/min (25 scfm) the predicted ZOC was about 7.6 m (25 ft). An extraction flow rate of 0.28 m^3/min (10 scfm) was also simulated to examine the ZOC of low flow soil vapor extraction. The ZOC was found to be on the order of about 3 m (10 ft) for this flow rate (Figure 5)

Table 2 shows a comparison of the ZOI based on the steady state pressure distribution and the ZOC based on critical pore gas velocity. The radius of the ZOC based on the attainment of a critical pore-gas velocity is less than 1/3 the radius of the ZOI determined using the pressure response method for an extraction flow rate of 1.42 m^3/min.

Figure 6 shows the pressure profile for the model domain as simulated using the AIR2D model. This figure clearly shows the effect of the leaky confining layer on the pressure distribution around the extraction well. Darcy's law was used to calculate the pressure distribution for the confining layer. This distribution was then superimposed onto the pressure distribution generated by AIR2D to show the effect of the confining layer.

Figures 6 and 7 show the contrast in predicted ZOI based on pressure versus ZOC based on pore-gas velocity for an extraction flow rate of 1.42 m^3/min (50 scfm). Using the typical cutoff value of 2.54 cm H_2O vadose zone vacuum yields a ZOI of about 58 m (190 ft) which is consistent with the ZOI predicted using the Hantush method described earlier. Figure 7 shows that the ZOC is much smaller (15.2 m) based on pore-gas velocity using the cutoff velocity of 0.01 cm/sec. Similarly, for a flow rate of 0.71 m^3/min, the predicted ZOC (7.6 m) was much less than the ZOI (18.3 m) based on the pressure criteria.

While the treated zone for each extraction well is smaller when ZOC is used for the well field design, the treatment time will be significantly reduced for ZOC based design due to the increased pore-gas velocities within the treatment zone. Additionally, more pore volumes of soil vapor will flush the treatment zone in ZOC designs for the same treatment period..

Multi-Well Analysis

EPA (2001) developed a three dimensional flow model for steady state simulations of soil vapor extraction wells. The model “MAIRFLOW” can be used for steady state simulations of multi-well extraction systems in homogeneous porous media. EPA (2001) used MAIRFLOW to evaluate the design of a fully operational SVE system with regard to ZOC based on a critical pore gas velocity of 0.01cm/sec. The original system used seven wells operating at a cumulative flow rate of 28.3 m^3/min (1000 scfm). They reported that after simulating several alternative well field designs, a well field of sixteen properly located SVE wells pumping at a cumulative rate of only 11.3 m^3/min (400 scfm) could achieve a ZOC similar to the seven well system operating at 28.3 m^3/min.

MAIRFLOW was used to conduct multi-well simulations for the ABRP waste unit to determine if a series of SVE wells could be used in the place of a single well pumping at 1.14 m^3/min (40 scfm) to reduce the size of the soil vapor extraction and treatment system necessary to achieve remediation. Multi-well simulations were conducted using three and four wells (Figure 1) to study whether or not multiple wells could be used to reduce the pumping requirements of the SVE system similar to that reported by EPA (2001).

The Darcy velocity field generated by MAIRFLOW for each of the scenarios was converted to pore velocity by dividing the Darcy velocity by the effective porosity determined during analysis of pumping test data. Tecplot™ visualization software for numerical simulation, was used to plot and analyze the pore velocity field using three dimensional interpolation and reverse particle tracking.

Particle tracking was performed by releasing seeds an 30 degree arcs at a distance of 100 cm from each extraction well at the top, middle, and bottom of the permeable zone. Figure 8 shows a plan view of the flow field through the middle of the model domain for three different scenarios. Markers on the flow lines represent 0.5 day travel times. The low permeability of the overlying semi-confining layer coupled with a high anisotropy ratio ($k_r/k_v = 5$) in the pumped zone produced a flow field that is predominantly horizontal within both the ZOI and the ZOC. . Figure 9 shows the pore gas velocity profile through the middle of the model domain and through the center of the screen zone for the wells. The slight upward curvature of the flow lines in Figure 9 is due to leakage through the semi-confining layer. Steeper flow lines are originating out of the plane being viewed and actually have the same slope as those parallel to the plane coming from each side.

The ZOC (CPGV > 0.01 cm/sec) for the three scenarios had approximately the same areal extent (radius = 12.1 m); however, the three well scenario had a large zone between the wells with pore velocities less than the criteria as would be expected, Figure 8. The addition of the fourth well in the middle greatly reduced the amount of area with pore velocities less than the criteria. Periodic variation in flow rates can be used to address these small zones within the ZOC where the pore gas velocity is less than CPGV.

Comparison of the particle tracking results show that all three scenarios produce similar average travel times for soil vapor originating on the periphery of the ZOC. In the example described above with an extraction rate of 1.14 m^3/min, the travel time from the perimeter of the ZOC is 0.7 days while the travel time from the perimeter of the ZOI is 10.4 days, Figure 10. The large increase in travel time is due to the lower pore gas velocities at greater distances from the pumping center and the longer travel distance from the perimeter of the ZOI. The pore gas velocity profiles in Figure 10 more clearly illustrate the difference between the scenarios within the ZOC. While the distance from the perimeter of the ZOC to a given extraction well is shorter in the three and four well scenarios, the average pore gas velocity along the flow path is smaller resulting in approximately the same travel times for each of the scenarios.

Conclusions

The criteria used for the design of soil vapor extraction systems varies significantly from site to site. The most common criteria, zone of influence (ZOI) and zone of capture (ZOC) produce different well spacings. Either criteria may be appropriate depending on the objective of the soil vapor extraction system.

ZOI criteria is most often set based on the minimum vacuum that can be measured using readily available field equipment and is commonly 2.54 cm H_2O vacuum. Natural diurnal fluctuations in atmospheric pressure produce subsurface pressure fluctuations of 1.27 to 2.54 cm H_2O. Therefore, to ensure containment, a ZOI criteria of 2.54 cm of H_2O vacuum is recommended.

Most ZOC designs use a critical pore-gas velocity to locate soil vapor extraction wells within a contaminated area. There are no generally accepted methods for determining the appropriate critical pore-gas velocity. The EPA (2001) conducted a comprehensive analysis of methods for determining critical pore-gas velocity based different theories related to mass transfer within the vadose zone and ultimately used 0.01 cm/sec for a field site located in sandy Atlantic Coastal Plain sediments.

Pore-gas velocity decreases rapidly with distance from an extraction well and therefore the selection of critical pore-gas velocity has a significant impact on SVE systems designed by ZOC analysis. The use of the ZOC concept in the design of soil vapor extraction systems to remove contaminants produces a more robust system to achieve cleanup based on the current criteria commonly used for ZOI and ZOC analysis.

ZOC was used to design an SVE system for use in coastal plain sediments on the SRS. Results from the analysis showed that the radius of the ZOC for a single well operating at a flow rate of 1.14 m^3/min would be 15 m. Similarly, four wells spaced such that that the radius of the ZOC of the four wells combined equaled that of the single well required pumping at a cumulative flow rate of 1.14 m^3/min. This result is not consistent with the previously mentioned EPA (2001) study where the cumulative flow rate from the SVE system could be reduced by incorporating additional extraction wells.

Finally, an SVE system for the ABRP waste unit designed using ZOC analysis will cleanup the site approximately 15 times faster than a ZOI design. Conversely, the ZOC design will require a network of four to six wells pumping at a combined flow rate of 6.0 to 7.0 m^3/min as compared to one well pumping at a flow rate of 1.42 m^3/min.

References

Baehr A. L. and C. J. Joss. (1995). An updated model of induced airflow in the unsaturated zone. Water Resources Research, 31(2) 417 - 421.

EPA. (2001). Development of recommendations and methods to support assessment of soil venting performance and closure. EPA/600/R-01/070. National Risk Management Research Laboratory, Office of Research and Development, U. S. EPA, Cincinnati, OH.

Dixon, K. L. and R. L. Nichols. (2005). Permeability estimation from transient vadose zone pumping tests in shallow coastal plain sediments. Environmental Geosciences, 12(4), 279-289.

Hantush, M. S. (1964) Hydraulics of Wells. In: Advances in Hydroscience Vol. 1, Ed. V. T. Chow. Academic Press, N. Y., N. Y.

Johnson, P. C. and R. A. Ettinger. (1994). Considerations for the design of in situ vapor extraction systems: radius of influence vs. zone of remediation. Groundwater Monitoring and Remediation, Spring 1994, 123-128.

Massman, J. W. 1989. Applying groundwater flow models in vapor extraction system design. Journal of Environmental Engineering, American Society of Civil Engineers. Vol. 115, No. 1, pp. 129-149.

Walton, W. C. (1991). Principles of Groundwater Engineering. Lewis Publishers Inc., Chelsea, MI.

Weeks, E. P. 1978. Field determination of vertical permeability to air in the unsaturated zone. U. S. Geological Survey Professional Paper 1051. U. S. Geological Survey, Lubbock, TX.

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Biographical sketches

Kenneth Dixon is a Principal Engineer at the Savannah River National Laboratory (SRNL) where he has conducted research related to soil and groundwater characterization and remediation for 15 years. He received B.S. and M.S. degrees in Agricultural Engineering from the University of Georgia and a M.E. degree in Civil Engineering from the University of South Carolina. His primary research interests are in pilot scale testing of innovative remedial technologies and numerical modeling of contaminant fate and transport in the vadose zone.

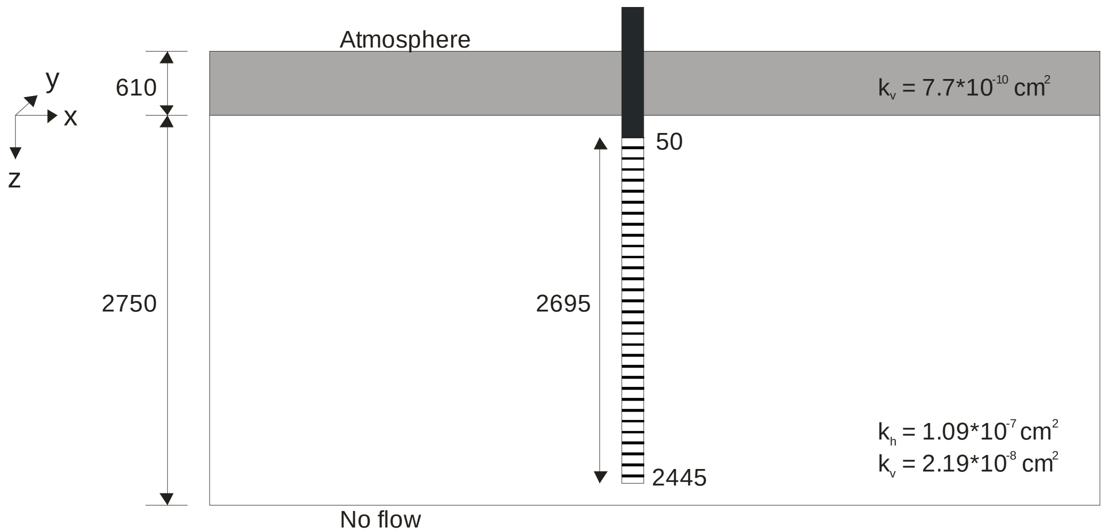
Ralph Nichols is a Fellow Engineer at the Savannah River National Laboratory (SRNL) where he has conducted research related to soil and groundwater characterization and remediation for 18 years. He received a B.S. degree in Geological Engineering from the University of Missouri-Rolla and an MS degree in Civil Engineering from the University of Oklahoma. His primary research interests are in the collection and synthesis of data from multiple scales into conceptual models that are used to develop sustainable environmental management strategies.

	T m^2/min	S	k_r (darcies)	k_z (darcies)
Minimum	0.0063	0.000023	5.2	1.0
Maximum	0.0138	0.001066	11.2	2.3
Median	0.0115	0.000289	9.4	1.9
Average	0.0112	0.000352	9.2	1.8

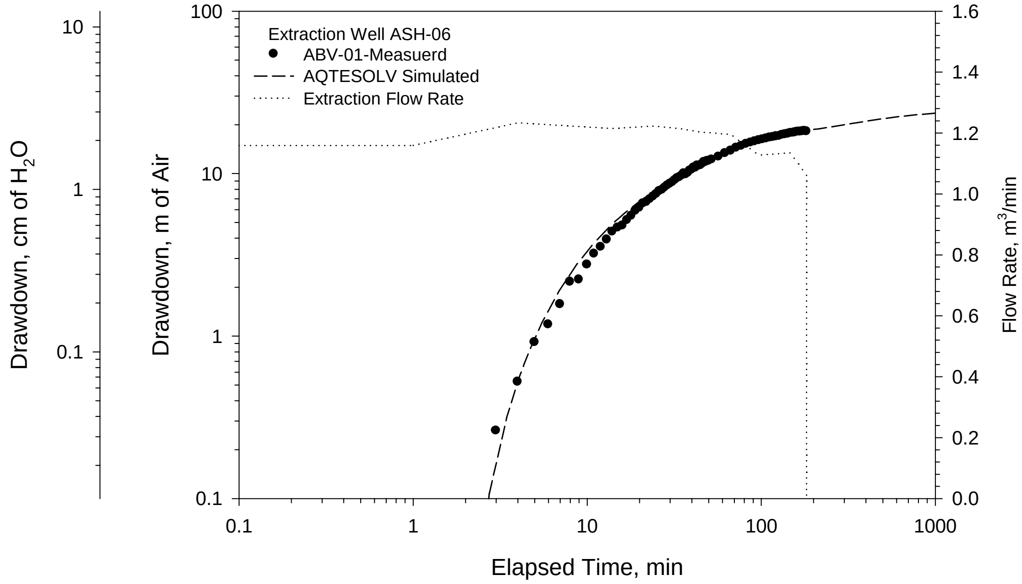
Dixon – Table 1

	Zone of Influence (Vacuum > 2.54 cm H_2O)		Zone of Capture (Critical Pore Gas Velocity ≥ 0.01 cm/sec)	
Extraction Flow Rate m^3/min	Radius (m)	Pore Gas Velocity @ Edge (cm/sec)	Radius (m)	Vacuum @ Edge (cm H_2O)
1.42	56.4	0.0023	15.2	5.9
0.71	18.3	0.0041	7.6	3.9
0.28	0.0		3.0	2.0

Dixon – Table 2



Dixon – Figure 1



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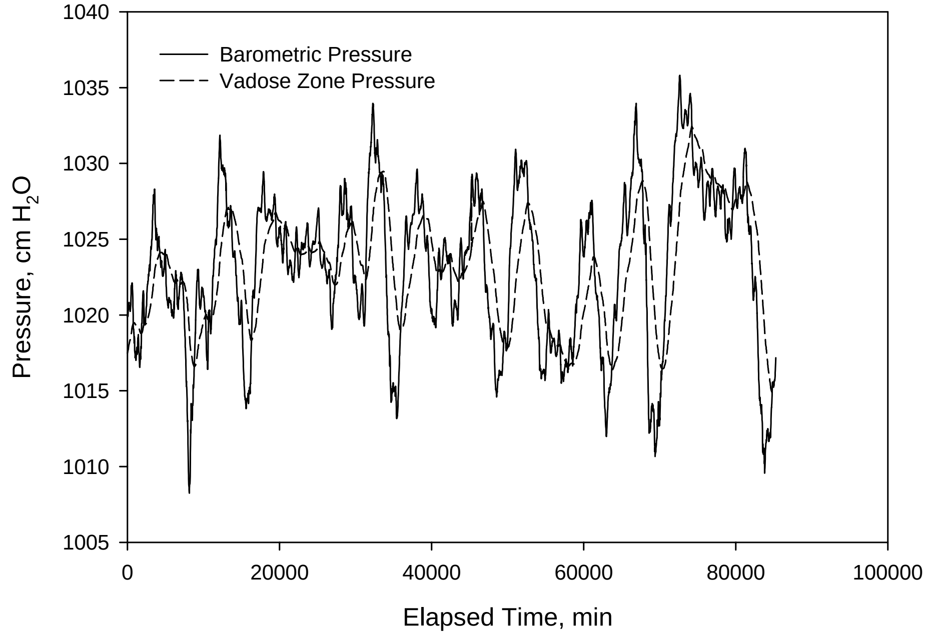

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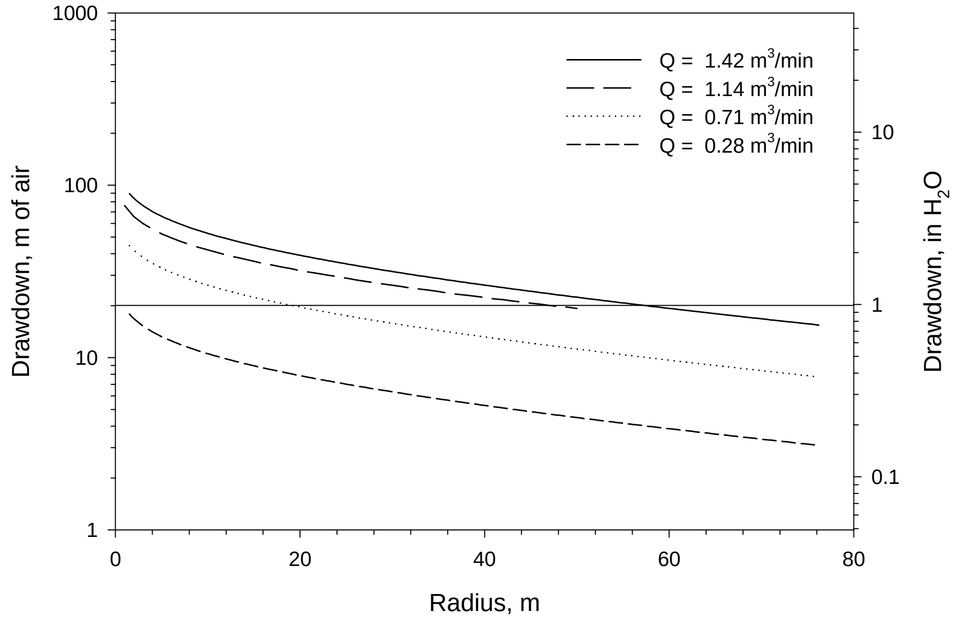

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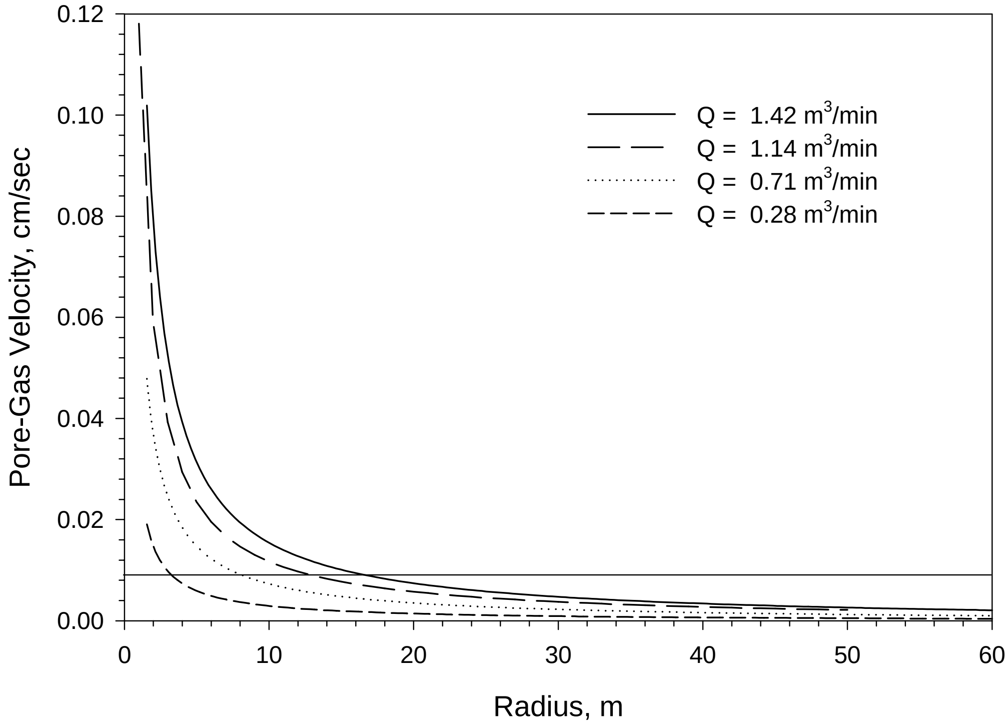

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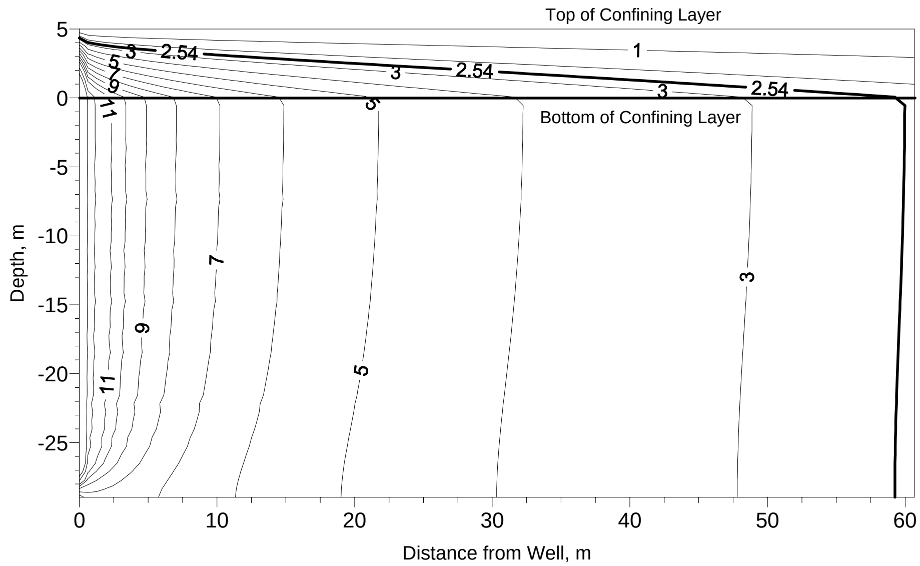

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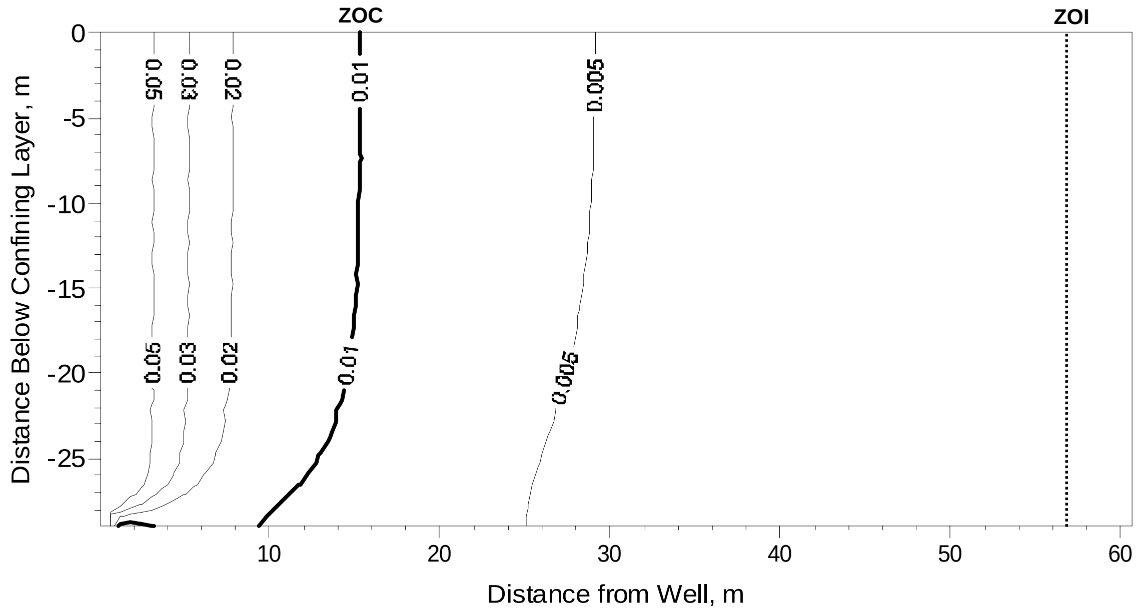
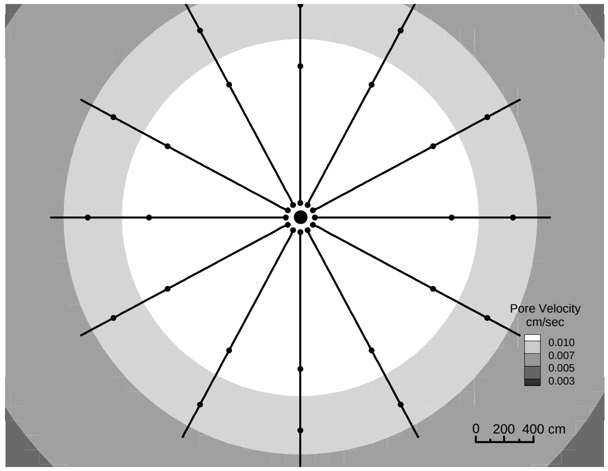


Dixon – Figure 7



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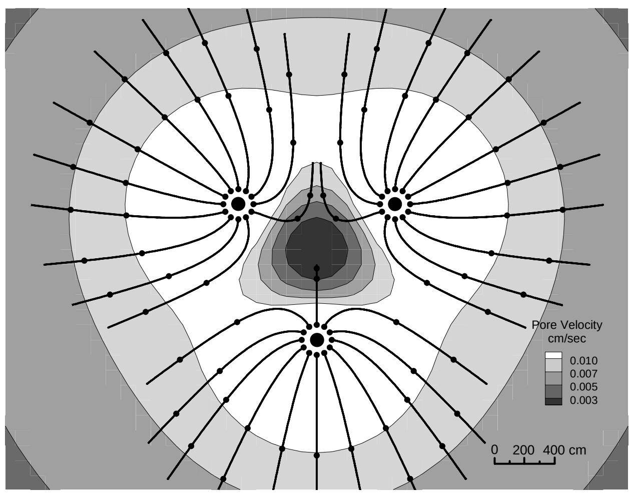

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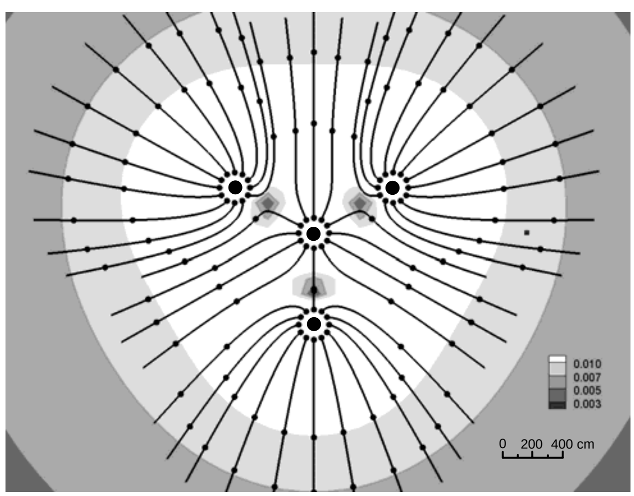
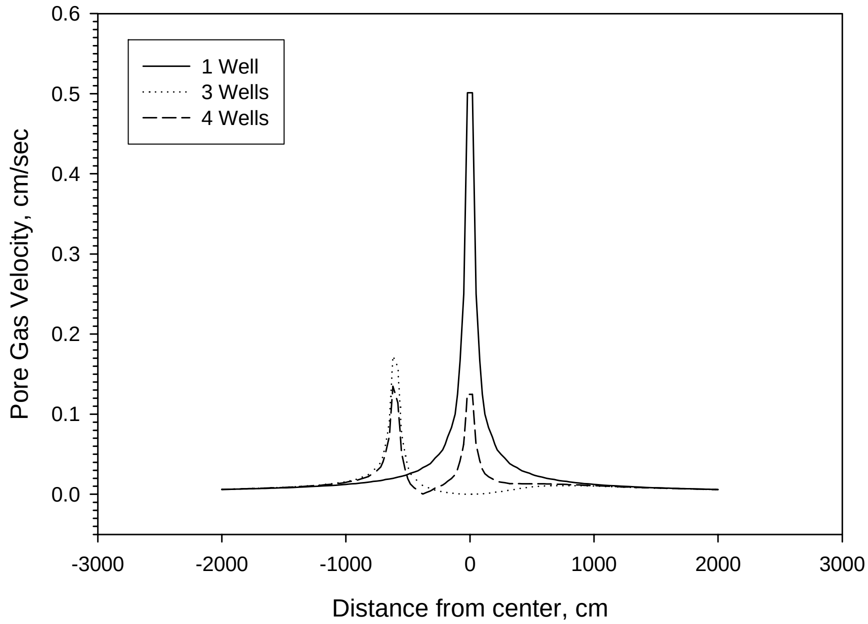


(c)

Dixon – Figure 8



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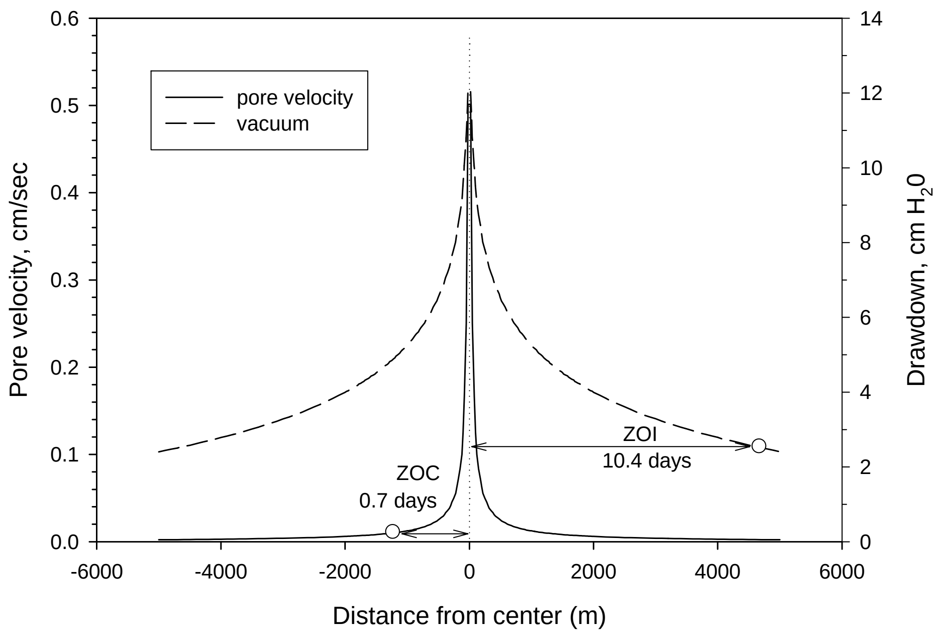
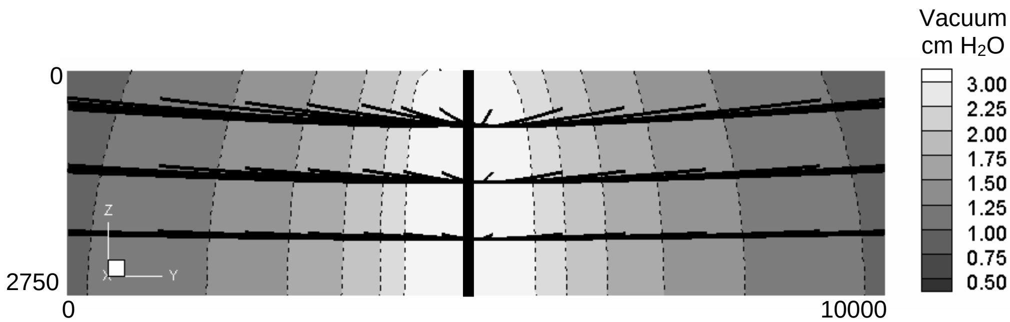


(b)

Dixon – Figure 9



Dixon – Figure 10

Table Captions

Table 1. Summary of Vadose Zone Physical Properties.

Table 2. Comparison of Vacuum Based ZOI and Pore Gas Velocity Based ZOC.

Figure Captions

Figure 1. Conceptual model and well locations for different pumping scenarios. Units = cm unless noted otherwise.

Figure 2. Transient response of vadose zone pressure to soil vapor extraction zone at the A-Area Burning Rubble Pit.

Figure 3. Response of vadose zone pressure due to fluctuations in atmospheric pressure at the A-Area Burning Rubble Pit.

Figure 4. Predicted vacuum drawdown as a function of radial distance for flow rates of 1.42, 0.71, and 0.28 m^3/min.

Figure 5. Pore-gas velocity as a function of radial distance for extraction flow rates of 1.42, 0.71, and 0.28 m^3/min.

Figure 6. Predicted steady state vacuum (cm of water) profile for extraction flow rates of 1.42 m^3/min (50 scfm).

Figure 7. Predicted pore-gas velocity (cm/sec) profile for an extraction flow rate of 1.42 m^3/min (50 scfm).

Figure 8 Pore-gas velocity (cm/sec) at the middle (z = 1350 cm) of the model domain for a single well pumping at a flow rate of 1.14 m^3/min. Markers on flow lines represent 0.5 day intervals starting 100 cm from the well: . (a) one well scenario. (b) three well scenario, (c) four well scenario.

Figure 9. Velocity profile through the center (x = 5000) and the middle (z = 1350) of the contaminated zone: (a) for one, three, and four well cases and (b) comparison of ZOC and ZOI for a single well.

Figure 10. Vertical cross-section of model domain with four wells pumping at a total flow rate of 1.14 m^3/min (vertical exaggeration ~1).