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Examination of the U.S. EPA's vapor intrusion database based on models

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Abstract

In the United States Environmental Protection Agency (U.S. EPA)'s vapor intrusion (VI) database, there appears to be a trend showing an inverse relationship between the indoor air concentration attenuation factor and the subsurface source vapor concentration. This is inconsistent with the physical understanding in current vapor intrusion models. This paper explores possible reasons for this apparent discrepancy. Soil vapor transport processes occur independently of the actual building entry process, and are consistent with the trends in the database results. A recent EPA technical report provided a list of factors affecting vapor intrusion, and the influence of some of these are explored in the context of the database results.

Introduction

Since the release of U.S. EPA's Office of Solid Waste and Emergency Response (OSWER) draft guidance (1) concerning the vapor intrusion pathway, the U.S. EPA has been collecting site monitoring data to improve its knowledge and understanding of vapor intrusion, and sharing these data and experiences with investigators across the country (3-4). As of 2012, 2,929 paired measurements from 42 vapor intrusion sites across the country have been included in U.S. EPA's Vapor Intrusion database (2). Of these measurements, "1,021 (35 percent) are paired groundwater and indoor air measurements, 235 (8 percent) are paired exterior soil gas and indoor air measurements, 1,582 (54 percent) are paired subslab soil gas and indoor air measurements, and 91 (3 percent) are paired crawlspace and indoor air measurements" (4). The building types represented include "residential (85 percent), institutional or commercial (10 percent), and multi-use (residential and non-residential) buildings (5 percent)" (4). Currently, the foci of the database are both chlorinated volatile organic chemicals (VOCs) and volatile petroleum hydrocarbons (PHCs), the latter of which, however, comprise only 3 percent of the data set (4). Moreover, other contaminants with vapor intrusion potential, such as mercury or semi-volatile organic chemicals (SVOCs) are not included (4).

Consultants and state regulators have made contribution to the database, and some data were also provided by the EPA's regional offices. Both sampling design information and vapor analytical methods were evaluated to make sure that the sites were correctly characterized and the reported values reliable (3).

The database consists of a spreadsheet of measured data from vapor intrusion sites. These data have been used to evaluate the importance of various factors governing vapor intrusion. The ratios of indoor air concentration to subsurface source vapor concentration or subslab

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vapor concentration, termed vapor intrusion attenuation factors, are given particular attention in the database (3-4). As temporal variability exists for every VI site, a possible solution is to use statistical approaches to analyzing data. For such a huge pool of data in EPA's VI database, the influences of random fluctuations would average out.

In the analyses that accompany this database, most of the focus has been on the indoor air concentration attenuation factors. As is commonly accepted, the attenuation of contaminant concentration in a vapor intrusion pathway occurs during two processes; the first is the transport of the contaminant through the soil and, and the second, its entry into the enclosed space of the buildings of concern. These steps are different, and relatively independent of each other in most cases (see below). The understanding of these two processes is critical to understanding the data.

Figure 1 shows the measured indoor air concentration (c_{in}) attenuation factor (c_{in}/c_s) as a function of groundwater source vapor concentration (c_s), calculated from Henry's law, based upon measured contaminant concentration in groundwater. All groundwater source vapor concentrations in the EPA database and this paper were calculated in this way, but what are shown here are only values taken from the EPA database itself. Figure 1 immediately raises questions regarding the ability of any modeling approach that primarily has a transport focus to capture the trends that are shown. All transport scenarios that do not include biodegradation-type reaction processes should show no trend in attenuation factor with concentration. Leaving out the petroleum data from Figure 1(a) (which are the data that could potentially be subject to biodegradation processes), does not fundamentally alter this picture, as shown in Figure 1 (b). In this study, the chlorinated solvents such as PCE and TCE are considered as non-biodegradable, since compared to PHCs, they biodegrade much more slowly, often incompletely, and primarily under anaerobic conditions in the subsurface (4). Published studies show that the mean half-lives of PCE and TCE are years (5-6).

Thus there is immediately a question regarding the reliability of any transport-based predictive models of vapor intrusion, as these cannot predict the trends shown in Figure 1. The issue becomes clearer, however, when considering the same data set, but instead plotting the attenuation factor from calculated contaminant source vapor concentration (c_s) to measured contaminant subslab concentration (c_{ss}), as shown in Figure 2. Here there is still significant data scatter, but more importantly, the trend with concentration is much weaker, if present at all.

The implications of this observation are considered below, in the context of the usual soil vapor transport and building entry models used to describe VI.

The equations governing transport in VI scenarios

Soil vapor transport

For a groundwater source of contaminant vapor, the soil vapor transport process begins with contaminant being released from that source into the vapor and ends with it arriving at a building foundation.

The general governing equation for soil vapor transport is (7):

$$\phi_{g,w,s} \frac{\partial c_{ig}}{\partial t} = -\nabla \cdot (q_g c_{ig}) - \nabla \cdot \left(\frac{c_{ig}}{H_i} q_w \right) + \nabla \cdot (D_i \nabla c_{ig}) - R_i \quad (1)$$

$$\text{Where } \phi_{g,w,s} = \phi_g + \frac{\phi_w}{H_i} + \frac{k_{oc,i} f_{oc} \rho_b}{H_i} \quad (2)$$

In equation (1) $\phi_{g,w,s} \frac{\partial c_{ig}}{\partial t}$ represents the time dependence of contaminant mass contained in the soil gas, soil moisture and soil organic carbon as represented in equation (2);

$-\nabla \cdot (q_g c_{ig}) - \nabla \cdot \left(\frac{c_{ig}}{H_i} q_w \right)$ is the convection term reflecting contaminant movement with soil gas and, if relevant, groundwater flow; $\nabla \cdot (D_i \nabla c_{ig})$ describes the diffusion of contaminant in the soil gas phase (contaminant diffusion through the water phase is neglected due to much lower diffusivity in a condensed phase as compared to a vapor phase); q_g is the soil gas flow per unit area [$L^3_{\text{gas}}/L^2_{\text{soil}}/T$]; q_w is the groundwater flow per unit area [$L^3_{\text{water}}/L^2_{\text{soil}}/T$]; ϕ_g is the air filled porosity [$L^3_{\text{gas}}/L^3_{\text{soil}}$]; ϕ_w is the moisture filled porosity [$L^3_{\text{water}}/L^3_{\text{soil}}$]; H_i is the contaminant Henry's Law constant [$(M_i/L^3_{\text{gas}})/(M_i/L^3_{\text{water}})$], linearly relating vapor phase contaminant concentration to water phase concentration; $k_{oc,i}$ is the sorption coefficient of contaminant i to organic carbon in the soil [$(M_i/M_{oc})/(M_i/L^3_{\text{water}})$]; f_{oc} is the mass fraction of organic carbon in the soil [M_{oc}/M_{soil}], ρ_b is the soil bulk density [$M_{\text{soil}}/L^3_{\text{soil}}$], c_{ig} is the concentration of contaminant i in the gas phase [M_i/L^3_{gas}], D_i is overall effective diffusion coefficient for transport of contaminant i in porous media [L^2/T], R_i is the contaminant i loss rate by biodegradation [$M_i/L^3_{\text{soil}}/T$] and $\phi_{g,w,s}$ is the effective transport porosity [$L^3_{\text{air}}/L^3_{\text{soil}}$], defined in equation (2).

Except possibly for the last term in equation (1), this equation is linear in c_{ig} , meaning that it can be rewritten entirely in terms of a non-dimensional contaminant vapor concentration. The normally selected reference concentration is that of the contaminant vapor at its source, c_s . The result would be, for example:

$$\phi_{g,w,s} \frac{\partial c^*}{\partial \theta} = -\nabla^* \cdot C^* - \nabla^* \cdot \left(\frac{c^*}{H_i} \frac{q_w}{q_g} \right) + \nabla^* \cdot (D^* \nabla C^*) - r_i \quad (3)$$

Where ∇^* represents the non-dimensional ∇ operator, non-dimensionalized with respect to

some characteristic length scale L , $C^* = \frac{c_{ig}}{c_s}$, $\theta = \frac{t q_g}{L}$, $D^* = \frac{D_i L^3}{q_g}$ and $r_i = \frac{R_i}{c_s}$. Solution for the entire vapor concentration profile in the domain of interest is completely independent of the choice of c_s (i.e., the source vapor concentration), which can even be true for $R_i \neq 0$, if the biodegradation rate is first order in c_{ig} . Of course, equation (3), or the equivalent equation (1), is used in some form in virtually every vapor intrusion model. The value of q_g , which may influence some aspects of the solution of soil gas contaminant profile, normally comes from solution of Darcy's Law for soil gas. This equation does not include any terms that depend on c_{ig} , because the contaminant vapor concentration is always much too low to influence overall soil gas concentration or transport. The above results are consistent with the lack of trend in c_{ss}/c_s with concentration in Figure 2, in the sense that the concentration of the source should not affect the normalized subslab concentration at steady state.

Entry into the building

The attenuation of contaminant soil vapor concentration also occurs during the process of entry into a building. Generally entry is a result of both diffusion and convection of contaminant through entry cracks or holes, and convection is induced by the indoor air pressurization or depressurization, as appropriate.

The common way to handle this issue is to represent the enclosed space of concern as continuous stirred tank(s) (CST), which are purged by normal building air exchange processes but which receive contaminant through foundation breaches. The two main factors that determine the indoor air attenuation factor are then the total contaminant mass entry rate and separately total building air entry rate, which purges the space of concern (8). It is the ratio of contaminant entry rate to air entry rate that determines indoor air concentration:

$$c_{in} = \frac{J_s + V_b A_e c_{atm}}{V_b A_e + Q_s} \approx \frac{J_s}{V_b A_e} \quad (4)$$

Where $V_b A_e + Q_s$ is the total air entry rate [L^3/T], $J_s + V_b A_e c_{atm}$ is the total contaminant mass entry rate including any possible atmosphere sources [M/T], c_{in} is the indoor air concentration of the contaminant [M/L^3], J_s is the contaminant mass entry rate from the subsurface alone [M/T], V_b is the volume of the enclosed space [L^3], c_{atm} is the contaminant concentration in atmosphere [M/L^3], A_e is the air exchange rate of the enclosed space [$1/T$] and Q_s is the volumetric flow rate of soil gas into the enclosed space [L^3/T]

The contaminant mass entry rate can be obtained for entry through a crack, as is assumed in many common VI models (7-13)

$$J_s = \begin{cases} \frac{c_{ss} Q_s}{1 - \exp\left(-\frac{Q_s d_{ck}}{A_{ck} D_{ck}}\right)}, & Q_s \neq 0 \\ \frac{c_{ss} A_{ck} D_{ck}}{d_{ck} V_b A_e}, & Q_s = 0 \end{cases} \quad (5)$$

Where A_{ck} is the area of the crack [L^2], c_{ss} is the contaminant subslab crack concentration [M/L^3], $c_{in} \ll c_{ss}$ is assumed, D_{ck} is the contaminant effective diffusivity in the crack [L^2/T] and d_{ck} is the thickness of the crack [L].

Substituting equation (5) into (4)

$$\frac{c_{in}}{c_{ss}} \approx \begin{cases} \frac{\frac{Q_s}{V_b A_e}}{1 - \exp\left(-\frac{Q_s d_{ck}}{A_{ck} D_{ck}}\right)}, & Q_s \neq 0 \\ \frac{A_{ck} D_{ck}}{d_{ck} V_b A_e}, & Q_s = 0 \end{cases} \quad (6)$$

Again, equation (6) shows the indoor air concentration, as normalized by subslab soil vapor concentration, should be independent of the reference (source) concentration, since it has already been established that all normalized soil gas concentration profiles (including subslab) are independent of absolute source concentration; that is, the attenuation factor for indoor air relative to source concentration should thus also be independent of source concentration. This is contrary to Figure 1. Hence it appears that it is in taking the step from soil gas transport models to the building entry models that the basic structure of current VI models is inconsistent with a concentration dependent trend, such as that shown in Figure 1.

Scenarios involving a permeable wall contaminant entry will be similar to the case for the crack entry scenario in the sense that they will similarly scale linearly with source (and subslab) concentration. Hence, it is not the assumption of crack entry that represents the origin of the problem; any plausible model of entry into the structure should be linear in subslab concentration. Figure 2 has shown that the origin of the strange inverse correlation of indoor air concentration with source concentration does not arise from a peculiarity in soil transport, and the analysis of all plausible entry models likewise cannot offer an explanation of that trend. It remains to look at the factors that actually determine indoor air concentrations, given a certain entry rate of contaminant.

Discussion

Indoor air contaminant concentration calculations

Figure 3 presents the measured subslab-to-indoor air concentration attenuation factor as a function of measured subslab soil vapor concentration, from the EPA's VI database results. The trend with concentration is again quite obvious, and once more shows that the measured subslab-to-indoor air concentration attenuation factor is inversely related to measured subslab soil vapor concentration, as expected, given the results of Figure 1 and the conclusion regarding soil transport processes not being source concentration dependent.

The trend in Figure 3 can be explained by considering rough limits on absolute indoor air concentrations, such that the measured levels of c_{in} are actually relatively constant in the range of 0.1 to 10 $\mu\text{g}/\text{m}^3$. It is the act of "normalizing" the data set of indoor concentrations by measured subslab vapor concentration that leads to an apparent trend with subslab concentration. The measured data on the ordinate of Figure 3 appear mostly to fall in the

range of $\frac{0.1 \left[\mu\text{g}/\text{m}^3 \right]}{c_{ss}}$ to $\frac{10 \left[\mu\text{g}/\text{m}^3 \right]}{c_{ss}}$. This range is substantiated by what is presented in Figure 4 (a), which shows the actual measured indoor air concentration as a function of measured subslab vapor concentration. This figure shows that there is, in fact, no significant trend of indoor air concentration with subslab concentration, perhaps contrary to expectations. In Figure 4 (b), the measured indoor air concentration again ranges over 1-2 orders of magnitude, but here is shown as a function of calculated groundwater source vapor concentration. Because the groundwater source and subslab soil vapor concentration were not measured together for all VI sites included in the EPA VI database, a full comparison of all site data cannot be offered. What Figure 4 (b) shows is that there is only a very weak trend of indoor air concentration with groundwater source concentration. Compared to the wide variation of calculated groundwater source vapor and measured subslab vapor concentrations (7 orders of magnitude), most of the data representing measured indoor air concentration fall in a much narrower range as claimed above. This shows that there must exist processes which keep the measured indoor air concentration from changing linearly with calculated groundwater source vapor or measured subslab soil vapor concentration.

What can help explain data such as those in Figure 4 are two things. First, typical detection/reporting limits for compounds such as those of interest in Figure 4 are tenths of parts-per-billion-by-volume (PPBv), which corresponds to values of order 0.1 to 1 $\mu\text{g}/\text{m}^3$, depending upon the compound of interest. Thus it is not surprising to find this as a lower limit to the measured indoor air concentration data; anything lower could not be classified as evidence of vapor intrusion.

The apparent upper limit of 1 to 10 $\mu\text{g}/\text{m}^3$ presently has no obvious explanation. It implies some measure of control of maximum contaminant concentration by other factors. The levels are typically so low that building occupant response to odor threshold is unlikely to be responsible. Instead, there might be factors such as the existence of indoor adsorption equilibria that might come into play. Another possible, but less likely, explanation could be that ambient natural or anthropogenic background concentrations determine the upper limit (14).

The two orders of magnitude scatter in measured indoor concentration data could itself be due the uncertainty or variability of indoor environment, which determines the indoor depressurization and indoor air exchange rates. The uncertainty in these factors makes it unrealistic to hope to calculate more accurately an attenuation factor for the indoor air concentration relative to subslab (or source) contaminant concentration. In 2005, Johnson et

al. (15) suggested an empirical air exchange/soil gas entry rate ratio ($\frac{Q_s}{V_b A_e}$) to replace both the widely used Nazaroff equation (16), which has been used to calculate soil gas entry rate through a perimeter crack (Q_s), and the indoor air exchange rate (A_e). These were previously introduced as independent parameters in the Johnson-Ettinger (J-E) model (8). In other words, this alternative factor requires establishing a reasonable range of indoor air/subslab contaminant concentration ratio based on data from previous vapor intrusion investigations. This is similar to the idea of dilution factor in models like DF Sweden (17) and DF Norway (18-19), where an empirical parameter for the ratio of indoor air to source concentration is used. But reference to equation (6) shows that use of this new factor cannot explain data such as those in Figure 1 or 3, since the result still should be independent of calculated groundwater source vapor concentration, when expressed as a non-dimensional concentration.

The conclusion is that the EPA VI database, while quite valuable for understanding some aspects of the vapor intrusion process, cannot be looked to for validation of predictions of indoor air contaminant concentrations by VI models. There remain factors which are not yet fully understood, governing the observed indoor air concentrations.

Next, attenuation is turned to a different, but related question. If use is made of VI models that are believed to properly represent all key factors, how well do these do in predicting the values reported in the EPA database?

The environmental factors and soil vapor transport

The conclusion from most modeling analyses of vapor intrusion is that soil vapor transport processes are relatively independent of the building entry process and therefore the former should normally not be much affected much by human activities or indoor environment (7, 20-21). Soil transport processes can be simulated by using well established methods that are known to depend on certain key factors as may be inferred from equation (1). Site investigation data on in-soil attenuation should be explicable by using measurements of agreed upon specific environmental factors. If transport models are to be judged against field data, this should first be done using data free from biodegradation effects, and free from the inherent unpredictability of indoor processes.

Based on Abreu and Johnson's 3-D numerical model (7, 10, 22), US EPA's OSWER in 2012 published a technical report entitled, "Conceptual model scenarios for the vapor intrusion pathway" (23), in which a summary of factors affecting vapor intrusion were presented in the context of conceptual scenarios (see Table 1). Those factors can be classified into three major groups, which are contaminant source, soil conditions and building conditions. Except for indoor air depressurization and exchange rate, most of them can affect soil vapor transport or at least play a role in establishing the upper boundary conditions (i.e. open ground or building foundation) for this transport.

As shown in Table 1, there are enough factors that may have potential influence on soil vapor transport that it is generally difficult to obtain all necessary input values during routine site investigation. So the question remains which factors are the most important in particular cases, and this is where modeling work can be of considerable benefit.

The overestimation of measured subslab concentrations in the EPA database

Figure 5 shows data that speak to the importance of including certain factors into models of vapor intrusion. Yao et al. (20) have shown that for a uniform soil and contaminant vapor

source, the full 3-D model predictions of perimeter subslab (crack) concentration beneath a structure can be approximated by

$$\frac{c_{ss}}{c_s} = \left(\frac{d_f}{d_s} \right)^{0.7} \quad (7)$$

where d_f is the foundation (subslab) depth and d_s is the depth of a contaminant groundwater source. This result compared reasonably well with numerous steady-state uniform soil calculations using 3-D fluid dynamics models (7, 20).

It is obvious from Figure 5 that the above correlation (and thus the simulations that support it) fails badly at capturing the real data trends in the EPA's VI database. The points shown are all for PCE and TCE, and thus again free from the influence of biodegradation. These are now subslab concentrations, free of the influences of unknown factors discussed above in connection with indoor contaminant concentrations.

The modeling "failure" illustrated by these results cannot be attributed to a general failure of soil transport models. Consider the dotted line in Figure 5. This is a line of

$$\frac{c_f}{c_s} = \frac{d_f}{d_s} \quad (8)$$

Here c_f refers to a contaminant concentration at depth d_f in the absence of a building slab. Equation (8) is nothing more than the linear concentration gradient between a vapor source c_s at a depth d_s and a ground surface at zero concentration. This must be the situation that exists at steady state, for any uniform soil, and it does not depend on diffusivity or other model details. It is the most basic consequence of diffusion in porous media. This line must define the lowest possible concentration at any depth d_f because any blockage, such as by a foundation slab at the surface, must raise concentrations in the soil below it. Once again, the EPA VI database data fall mainly below this line, which seems to call into question even the most basic aspects of our physical understanding of the soil transport problem in VI modeling. Additionally, recent studies, comparing VI screening tools and site data, also suggested that the VI models tend to overestimate the soil air concentration (24-25). This necessarily raises the question as to whether the source concentration, c_s , has been correctly characterized. It must seemingly be lower than typically assumed.

The importance of source characterization

Normally, an assumption of Henry's law is used to relate measured groundwater source plume concentration to the calculated vapor concentration at this boundary. There are some uncertainties associated with application of this law. In series of studies by Goss and his colleagues, it was shown that partitioning of organic compounds in different phases can be affected significantly by temperature and relative humidity (26-35), while Spencer et al. found that the accumulation of organic chemicals at the soil surface following water evaporation may enhance the volatilization of chemicals with low Henry's law constant (36). Recent research shows that in a three phase (soil, gas and groundwater) system, the observed partial vapor pressure of toluene can be one order of magnitude lower than the predictions by Henry's law (37).

Though such uncertainties in Henry's law constant might exist, it is difficult to imagine many orders of magnitude error attributable to this source. Thus, the evidence points in the direction of the assumed groundwater source leading to a lower contaminant vapor concentration than calculated from Henry's law.

As already noted, Yao et al. (20) used modeling to show for a scenario with uniform contaminant source and uniform soil diffusivity, that subslab contaminant concentration can be estimated as a simple function of the ratio of foundation depth to source depth using equation (7). This conclusion is not influenced by building operational conditions, and it agrees with the general conclusion that the magnitude of indoor pressurization is always too small to affect soil vapor concentration profile. (Advection can play a role in determining contaminant entry through the building foundation but this is a different part of the process). Following an earlier analysis by Lowell and Eklund (38), the Yao et al. analysis has been extended to examining the potential influence of an offset in a lateral (or horizontal) direction between groundwater source and receptor building (39). The results of this analysis are also shown in Figure 5 (b).

Often, quite limited groundwater monitoring well data have been used to define a contaminant source plume. What has not often been taken into account is the possibility of a lack of vertical uniformity in the plume. If the surface of a contaminated groundwater plume actually consists of relatively clean water, as compared with more contaminated deeper water, then there is an important question of what to use as “source concentration”. Even if a plume is relatively uniform in cross-section in some locations, it need not be so everywhere. Thus one way of looking at the potential problems associated with plume characterization is shown in Figure 5 (b), based on calculations of soil gas contaminant concentration profiles, including subslab, resulting from a source offset from a building (39). Here, it is assumed that groundwater exists beneath the site, but that the edge of the plume that serves as a real contaminant vapor source is located at a horizontal distance d_h from the edge of the structure of concern. Figure 5 (b) illustrates how some displacement of the effective plume edge (shown as r , the ratio of horizontal displacement to source depth) can bring the predictions of subslab concentration much more into line with measured values in the EPA VI database. The required values of r are not large.

Another set of comparison results is based on the work of Shen et al. (40). Figure 5 (b) shows the influence on soil contaminant vapor transport modeling of using an explicit representation of the capillary zone above the water table. This is a zone of very low diffusivity, and it effectively places a zone of “clean water” above the groundwater source. Once again, very reasonable representation of an effect of displacing the “groundwater source” just a bit from where it is typically assumed is seen to have a major effect on prediction of subslab concentration. In one report, it was suggested that only the first 10 cm below groundwater table be used for risk assessment (41).

It is thus seen as imperative to have a more accurate picture of the groundwater source than has typically been provided by field studies.

Once an estimate of effective source vapor concentration is established, comparison of that value with concentration beneath a large capped area (either non-ventilated subslab or underneath a large paved area) should offer some agreement, since the capping of the ground surface should lead to a concentration that approaches that of the source, as illustrated in Figure 6. Figure 6 shows the result of a 3-D simulation of a steady state VI scenario with uniform soil underlying a structure. It is a simulation for a large structure (or large capping area) which results in the subslab (sub-cap) concentrations approaching effective source concentration. Obviously, if there is significant advective purging of the subslab/sub-cap area, this picture would not apply. But in the absence of such purge, the picture is typical. Failure to achieve this level of agreement between the estimate of c_s and a subslab or sub-cap concentration suggests that the situation with respect to understanding the source is imperfect, or that transient effects of significance are present.

Thus, there are some important directions suggested by the results of these analyses, which should help advance both VI modeling efforts and field investigations:

1. Indoor air concentrations can be constrained by both detection limits and some other uncertain factors defining typical maximum concentrations. Hence, subsurface-to-indoor air concentration attenuation factors will remain difficult to predict until more is known about the role of such factors.
2. Apparent groundwater-to-subsurface concentrations attenuation is a process that can be influenced by uncertainty in “source” characterization.
3. Related to the above, investigation and evaluation of a vapor intrusion site requires careful contaminant characterization of groundwater source plumes. Much apparent attenuation may actually occur in the groundwater itself.

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FIGURE 1.

Calculated groundwater source vapor-to- measured indoor air concentration attenuation factor for (a) all contaminants (b) Tetrachloroethylene (PCE) and Trichloroethylene (TCE) data taken from the U.S. EPA's VI database (2)

FIGURE 2.

Calculated groundwater source vapor-to-measured subslab soil vapor concentration attenuation factor for (a) all contaminants (b) PCE and TCE in data taken from the U.S. EPA's VI database (2)

FIGURE 3. Measured subslab-to-indoor air concentration attenuation factor for (a) all contaminants (b) PCE and TCE in EPA's VI database (2)

FIGURE 4.

Measured indoor air concentration data from the U.S. EPA's VI database (2). (a) measured indoor air concentration as a function of subslab concentration; (b) measured indoor air concentration as a function of calculated groundwater source vapor concentration

FIGURE 5.

The influence of source characteristics on subslab contaminant concentration predictions. Subslab concentrations were normalized by vapor concentrations at an assumed groundwater source beneath the building (see Figure 6 for an example of concentration profiles). Actual

data points from the U.S. EPA's VI database for PCE and TCE. $r = \frac{d_h}{d_s}$ indicates horizontal source-building separation to source depth, and the lines are for otherwise uniform soil. The shaded bands represent calculations for various soil types, in which the influence of capillary zone resistance is taken into account, consistent with realistic soil moisture distribution (source depths of 4 and 8m assumed for illustration) (21)

FIGURE 6. Simulated normalized vapor concentration profile for a typical house with basement scenario.

TABLE 1

Summary of factors affecting vapor intrusion (23)

Contaminant source	Soil	Building
Source concentration; Source depth ^T ; Source-building separation; Multiple sources;	Soil permeability; Effective diffusivity; Layered soil of different effective diffusivity or permeability (horizontal and vertical) ^T ; Biodegradation rate (for petroleum hydrocarbon); Sorption ^T ;	Building foundations (basement, crawl space and slab-on-grade); Multiple buildings; Indoor pressurization ^T ; Indoor air exchange rate; Impermeable surface cover; Indoor pressure distribution (wind load) ^T ;

The superscript ^T means the factor takes on special significance in transient cases. Sorption and indoor pressure distribution (wind load) mainly matters in transient cases while factors such as source depth and indoor pressurization matter in both steady and transient cases.