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## **PART XII: Vapor Intrusion**

### **Chapter 37**

#### **VAPOR INTRUSION ATTENUATION FACTORS BASED ON LONG TERM MONITORING DATA**

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**Abstract:** Screening for vapor intrusion potential is likely to be required at a large number of sites in the future, due to federal or state requirements, real estate transactions, or voluntary cleanups. At most sites, the authors expect that only groundwater data will be available in sufficient quantity to conduct initial screening (as opposed to soil vapor or indoor air data). Therefore, groundwater data will tend to drive the need for additional vapor intrusion investigations at most sites. The current EPA subsurface vapor intrusion screening guidance (EPA 2002) assumes that soil vapor concentrations immediately above the water table are at equilibrium with groundwater concentrations (based on Henry's Law Constant) and that indoor air concentrations in overlying buildings are 1000 times lower (an attenuation factor of 1/1000), due to attenuation through the soil column and building shell. According to EPA (2002), attenuation factors based on empirical groundwater and indoor air measurements are less than 1/1000 approximately 95% of the time. Unfortunately, the resultant groundwater screening levels are often at or below federal drinking water standards (MCLs). In most cases however, the empirical data used to develop this attenuation factor were based on measurements of groundwater and indoor air at one point (24 hours) in time. Groundwater and indoor air monitoring at a five houses in Colorado over the past eight years has allowed comparison of attenuation factors based on single points in time and on long-term averages (annual and multi-year), based on 1,1-DCE, which has the advantage of having few confounding indoor sources. These data indicate that single point measurements can significantly over or under estimate long term average attenuation factors. Short-term attenuation factors were observed to vary by up to one order of magnitude over time within the individual homes in this study, and ranged from  $10^{-4}$  to  $10^{-6}$ . Inaccuracies in groundwater concentrations and seasonal variations in ventilation likely explain short term variations in attenuation factor. Vapor intrusion screening levels based on long term mean attenuation factors and groundwater concentrations would provide less conservative screening levels for vapor intrusion.

**Key words:** vapor intrusion; attenuation factor; long term monitoring; indoor air tests.

### **1. INTRODUCTION**

Vapor intrusion, or the movement of volatile chemicals from the subsurface into overlying buildings (EPA, 2002) has become a recent focus of the U.S. Environmental Protection Agency (EPA) and many state agencies (Eklund et al., 2006). As a result, investigation and mitigation of vapor intrusion may now be required at sites under RCRA, CERCLA, Brownfields, and voluntary cleanup programs (EPA, 2002). Further, the potential for vapor intrusion impacts, either due to on-site sources of contamination or off-site sources, may be pertinent to many Phase 1 environmental site

assessments (e.g., ASTM E-1527) conducted as part of real estate transactions (personal communication with Anthony Buonicore, President, Environmental Data Resources, Inc., September 2006).

## 1.1 Need for Vapor Intrusion Screening Process

Site specific evaluations of vapor intrusion (e.g., indoor air and sub-slab testing) can be intrusive, costly, and require months or even years to complete (EPA, 2002). Therefore, simple and inexpensive screening procedures are needed to separate sites where further evaluation is warranted from sites where no further action is necessary. The current EPA vapor intrusion guidance (EPA, 2002) provides such a screening step, in the form of generic or “Tier 2” screening tables for groundwater and soil vapor concentrations. The EPA groundwater screening levels are based on target indoor air concentrations for most common volatile chemicals and an “attenuation factor” of 1/1000.

The attenuation factor,  $\alpha$ , is equal to the indoor air concentration divided by the soil vapor concentration at the depth of concern (Johnson and Ettinger, 1991). EPA groundwater screening levels assume that soil vapor concentrations immediately above the groundwater table due to partitioning from the groundwater to the vapor phase, will be attenuated by a factor of 1000. Therefore, a soil vapor concentration equal to the indoor air target level multiplied by 1000 (or less) should be acceptable. The acceptable soil vapor concentration is converted to a groundwater concentration or screening level by dividing by the Henry’s Law Constant for the compound (EPA, 2002).<sup>2</sup> Although EPA is currently revising its vapor intrusion guidance, it does not expect to change the attenuation factor used to calculate groundwater screening levels (1/1000) in the revised guidance (Schuver, 2006). Unfortunately, the attenuation factor of 1/1000 results in groundwater screening levels that are often below or only slightly above MCLs. As a result, the mere presence of a contaminant plume containing dissolved concentrations above the MCL (often the definition of a plume) can be enough to trigger the need for further evaluation.

EPA (2002) attempts to reduce the conservatism of the screening levels by providing a “semi-site specific” or Tier 2a screening step, in which screening levels are adjusted based on depth to groundwater and soil type. The adjustments are based on the Johnson and Ettinger model (EPA, 2004) using conservative default parameters (EPA, 2002). However, groundwater screening levels can, at most, increase by a factor of 10 and then only for the least permeable soil types and depths to groundwater exceeding 10 m. EPA has proposed including a “constrained” version of the Johnson and Ettinger model and exterior soil vapor concentrations in the revised guidance, to replace the semi-site specific step (Schuver, 2006). However, as of the time of writing, the revised guidance has not been published. Further, the model would need to be conservative if based on exterior and limited data (Schuver, 2006), questions regarding the appropriate location and depth of soil vapor samples need to be resolved (e.g., Wertz, 2006), and soil vapor data are not available at many sites for screening purposes.

Therefore, a better approach to screening of sites using limited and non-intrusive data is still required, particularly to facilitate real estate transactions that would be burdened by expensive and prolonged investigations. Because groundwater data is more likely to be available than soil vapor data at sites requiring Phase 1 environmental site assessments, a screening approach using groundwater data is particularly desirable.

## 1.2 Empirical Basis of EPA Attenuation Factors

The EPA (2002) groundwater screening levels are based, in part, on an attenuation factor of 1/1000. This attenuation factor is, in turn, based on empirical data from a number of sites where indoor air and groundwater concentrations are available (EPA, 2002). These data were screened for data quality and potential background (i.e., indoor or ambient sources) influences, and then the 95<sup>th</sup>

<sup>2</sup> EPA (2002) sets the groundwater screening level to the federal safe drinking water MCL if the calculated risk-based value is less than the MCL. In the authors’ experience, states using the EPA guidance may or may not default to the MCL.

percentile of the empirical attenuation factors was selected for screening purposes. In other words, approximately 95% of the real world attenuation factors were less than 1/1000 (i.e., more attenuation occurred); therefore, only approximately 5% of sites with groundwater concentrations equal to the groundwater screening level are expected to exceed the target indoor air concentration.

Subsequent evaluations of additional empirical data by EPA have continued to show that the 1/1000 attenuation factor is conservative; i.e., nearly all real world attenuation factors are lower (Hers, Dawson, and Truesdale, 2006).

### **1.3 Long Term Attenuation Factors**

The empirical attenuation factors used by EPA to develop the 1/1000 attenuation factor for groundwater screening levels are based on indoor air concentrations and groundwater concentrations measured at one point in time; e.g., a 24 hour indoor air sample and an instantaneous groundwater sample (EPA, 2002). It is reasonable to expect that attenuation factors in any individual building will vary over time, due to various factors that affect indoor air and groundwater concentrations separately (e.g., Johnson and Ettinger, 1991; Johnson, 2005). For example, groundwater concentrations and other factors being equal, a short term change in the building air exchange rate would change the indoor air concentration of a chemical present due to vapor intrusion. Therefore, the observed attenuation factor would change, even though the groundwater concentration remained constant.

Because the empirical attenuation factors used by EPA (2002) are based on single data points in time (hereinafter referred to as “single point attenuation factors”), they represent not only the variation between individual buildings and sites, but also the variations over time at individual buildings.

Risk management decisions, such as the need for mitigation, are typically based on estimates of long term risk (e.g., EPA, 1992); therefore, it would also be reasonable to base vapor intrusion screening levels on long term average attenuation factors and groundwater concentrations. By definition, the variance of the long term average attenuation factors will be less than the variance of the underlying population of single point attenuation factors. Therefore, groundwater screening levels based on long term average attenuation factors would be lower and less conservative than the current EPA (2002) screening levels, while still having the same low level of false negatives based on long term risk.

The purpose of this study was to evaluate the variation in attenuation factor over time in homes with both long term indoor air and groundwater monitoring data.

## **2. METHODS**

Long term indoor air and groundwater monitoring has been conducted at a vapor intrusion site in Colorado for over eight years, where 1,1-dichloroethylene (DCE) is the principle compound of concern. Monitored homes include those that were mitigated by installing sub-slab depressurization systems (Folkes and Kurz, 2002), and homes surrounding the area where mitigation was required (verification monitoring homes). Indoor air monitoring has been conducted in verification monitoring homes on a quarterly, semi-annual, or annual basis depending on the location of the home with respect to the plume and the magnitude of concentrations found in adjacent, mitigated homes. Indoor air concentrations of DCE in the verification monitoring homes have remained below the action level (at the time) of 0.49  $\mu\text{g}/\text{m}^3$ , but were often detectable because of the proximity of the homes to the plume and mitigation area. Therefore, in some cases several years of quarterly monitoring data with detectable levels of DCE due to vapor intrusion are available for evaluation.

Groundwater monitoring has also been conducted in shallow wells on a quarterly basis for the past eight years. For the purposes of this study, we selected unmitigated homes where indoor air concentrations of DCE were generally detectable over a period of several years, and where a groundwater monitoring well was located nearby. Further, we narrowed the list to five homes where the geology and plume concentrations were relatively consistent and well understood, so that the selected well was likely to be reasonably representative of conditions in the vicinity of the home.

DCE is a particularly useful compound for studying vapor intrusion because it is seldom found in residential indoor air due to background sources (Kurtz and Folkes, 2002). Therefore, background contributions are unlikely to have contributed to the indoor air concentrations measured in these five homes.

## 2.1 Indoor Air Sampling and Analysis Methods

Indoor air samples were collected over a nominal 24 hour period in 6 liter Summa canisters equipped with flow regulators. The canisters were placed in the lowest potential living space of each home, away from doors, windows and vents. The canisters were cleaned, tested and certified to be clean to the analytical detection limit (see below) by the laboratory, and evacuated to a near complete vacuum (nominal 30" of mercury at sea level or 0.05 torr) prior to being shipped to the site. The canister pressure was checked by the sampling technician prior to use to ensure that air had not leaked into the canister during shipment. The pressure was checked again at the end of the sampling period and upon receipt by the laboratory to ensure sample integrity during shipment.

The indoor air samples were analyzed in accordance with EPA Toxic Organic Method TO-15 and CDPHE's Guidance for Analysis of Indoor Air Samples (CDPHE, 2000) using a mass spectrometer operated in the selective ion monitoring (SIM) Mode with a reporting limit of 0.04  $\mu\text{g}/\text{m}^3$  for 1,1-DCE. QA/QC samples included trip blanks and field duplicates at the rate of one per twenty samples.

## 2.2 Groundwater Sampling and Analysis Methods

Groundwater samples were collected from two inch diameter Schedule 40 PVC wells with threaded joints installed in eight inch diameter boreholes advanced by hollow-stem auger drill rigs. The bottom ten feet of the wells were screened with 0.02 inch sized machined slots and graded silica sand added in the annulus of the casing to a height of one to three feet about the top of the screened interval.

The wells were installed so that the static water level at the time of drilling was within the ten foot screened interval; therefore, the upper five to ten feet of the aquifer was typically screened.

Groundwater samples were collected by decanting with minimal agitation into lab-prepared sample vials leaving zero-headspace, after purging three casing volumes. Samples were immediately cooled to 4 degrees C, shipped to the laboratory and analyzed by EPA Method 8260B. QA/QC samples included field duplicates at the rate of one per ten samples and one trip blank per sampling event.

## 2.3 Calculation of Attenuation Factors

The indoor air and groundwater monitoring programs were designed with different objectives in mind; therefore, indoor air and groundwater samples were not necessarily collected at the same time. Nevertheless, there is no reason to believe that a groundwater sample collected in a well at the same time as an indoor air sample in a house will be representative of the groundwater below the house at that exact time, even when the well is near the house. Therefore, we estimated groundwater concentrations for the purposes of calculating attenuation factors by determining the average groundwater concentration of all samples collected in the well within 90 days before or after indoor air testing, except in two cases where data trends indicated that a particular test result would likely be more representative. If no groundwater sample fell within this time period, the indoor air test result was not used (i.e., an attenuation factor was not calculated). The attenuation factor (at a single point in time) was then calculated by the following equation:

$$\alpha = C_{IA}/(C_{GW} * H')$$

where  $C_{IA}$  is the concentration in indoor air,  $C_{GW}$  is the concentration in groundwater (compatible units), and  $H'$  is the dimensionless Henry's Law Constant for DCE of 1.07 (EPA, 2004).

### 3. RESULTS

Indoor air concentrations of DCE measured in each of the five homes (H1 through H5) over time ranged from less than  $0.04 \text{ ug/m}^3$  to  $2.9 \text{ ug/m}^3$ , and varied by a factor of approximately 5 to 10 in individual homes (Figure 1). Groundwater concentrations measured over time in nearby monitoring wells (average of all samples collected within 90 days of the indoor air sample date) ranged from  $0.34 \text{ ug/l}$  to  $480 \text{ ug/l}$ , and varied by a factor of approximately 2 at H1 to 20 at H5 (Figure 2). For convenience, wells are identified by the associated house number. Note that the same well is associated with houses H1 and H4, although sample dates and, therefore, average groundwater concentrations vary slightly for some samples.

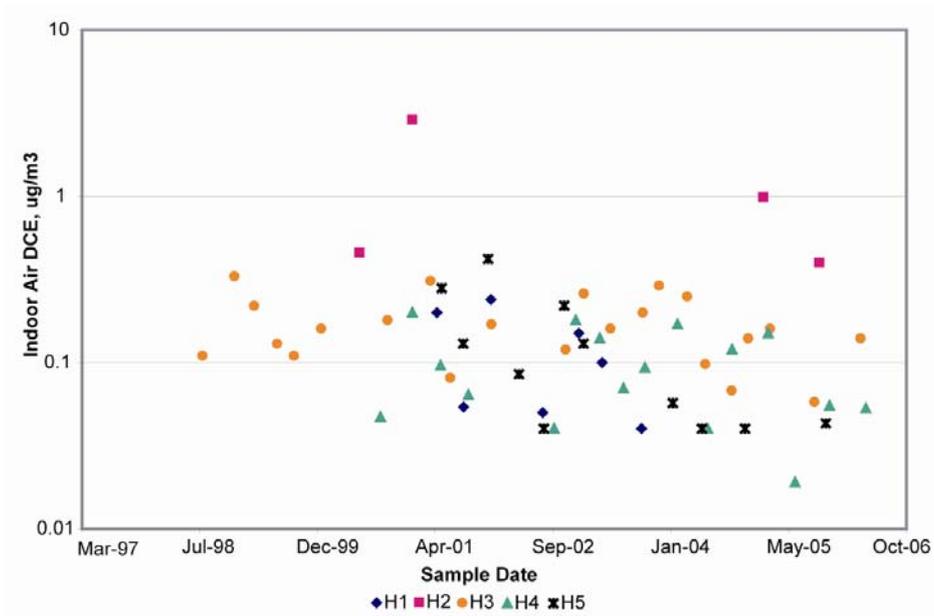


Figure 1. Indoor air concentrations of DCE

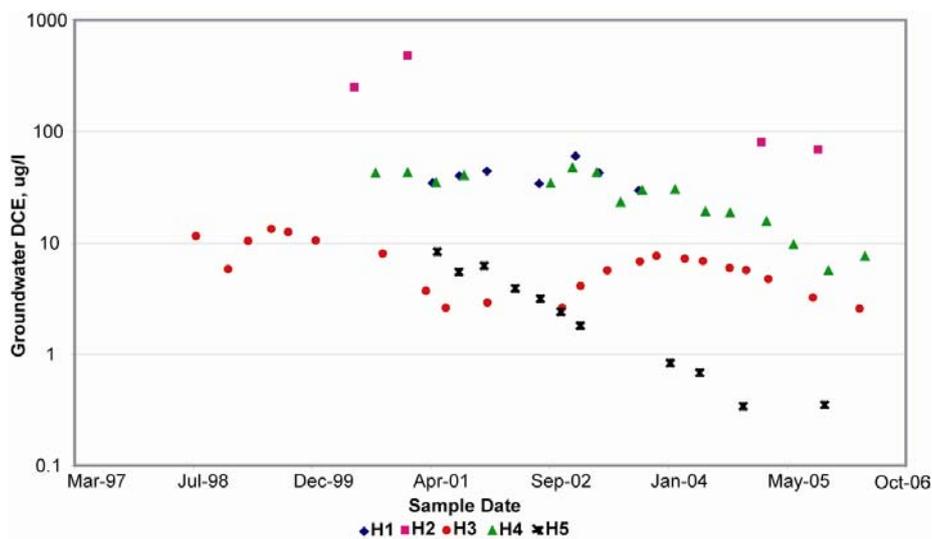


Figure 2. Groundwater concentrations of DCE

Calculated attenuation factors for all indoor air samples collected in all five homes range from approximately  $10^{-6}$  to  $10^{-4}$ , as shown on Figure 3. Attenuation factors are also ranked and plotted as a cumulative percentile distribution on Figure 4. The straight line distribution indicates that the single point attenuation factors are lognormally distributed. Also plotted are the average and geometric mean attenuation factors for each of the five homes.

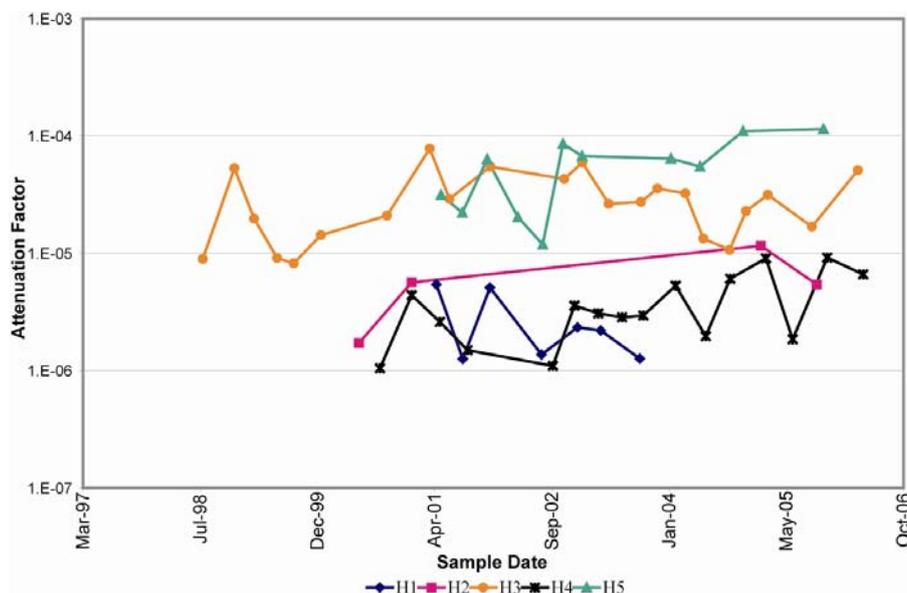


Figure 3. Single point in time attenuation factors

#### 4. DISCUSSION

The results of long term indoor air and groundwater monitoring at the five homes evaluated during this study show that empirical attenuation factors vary over time, typically by one order of magnitude (Figure 3). Therefore, empirical attenuation factors based on single, 24 hour indoor air tests, may over or underestimate the long term average or mean attenuation factor for a given building by up to half an order of magnitude.

Further, populations of single point attenuation factors, such as the database of attenuation factors used by EPA (2002) to develop its screening levels, will exhibit more scatter and broader distributions than the associated population of long term attenuation factors for the same buildings. Using these five homes as an example (albeit small) population of attenuation factors, the single point values vary from approximately  $10^{-6}$  to  $10^{-4}$  (Figure 4), with a 95 percentile of about  $8 \times 10^{-5}$ . However, the maximum geometric mean attenuation factor for any of the five homes is  $5 \times 10^{-5}$ , with a 95<sup>th</sup> percentile of approximately  $4 \times 10^{-5}$ . Therefore, a screening level based on the 95<sup>th</sup> percentile of the long term mean attenuation factor (applied to the long term average groundwater concentration) would be less conservative by a factor of 2. A much larger population of long term mean attenuation factors, however, would be required to establish such screening levels.

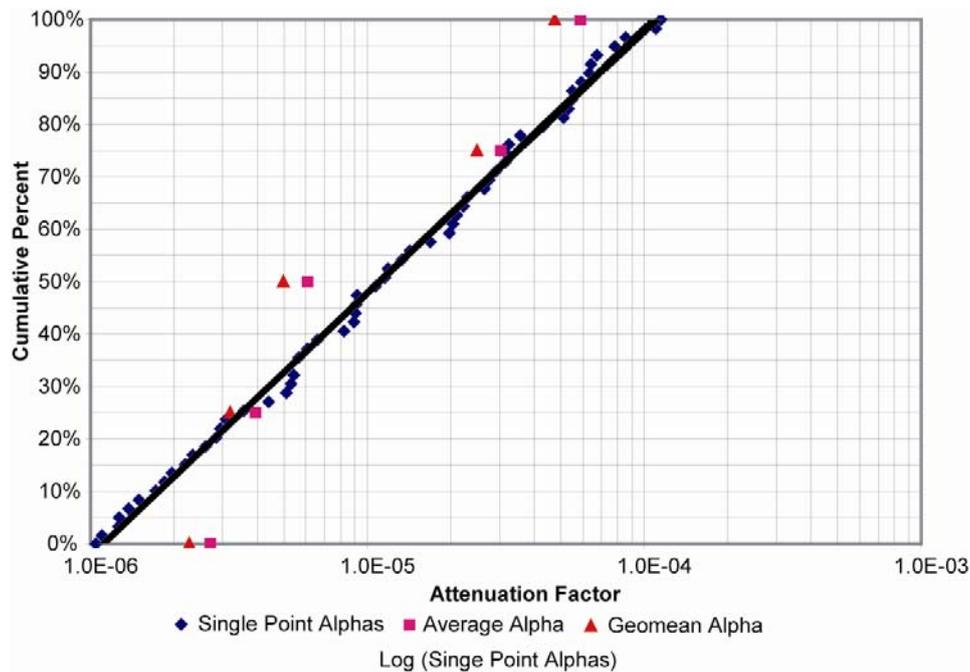


Figure 4. Single point attenuation factor distribution (5 homes)

Attenuation factors may vary over time due to variations in both subsurface and surface (or structural) conditions. For example, variations in depth to groundwater and groundwater temperatures could cause small changes in attenuation factor (EPA, 2004).

Inaccuracy in groundwater concentration estimates, however, could result in relatively large apparent variations in attenuation factor. For example, Figure 5 shows two scenarios where groundwater concentrations measured in a monitoring well upgradient of house (the same illustration would also apply for a downgradient well) vary over time. In the first scenario, the frequency of the fluctuations in concentration and the contaminant velocity result in concentrations below the house that, fortuitously, are similar at any point in time to those in the well. Therefore, the calculated attenuation factor would remain constant, assuming that the indoor air concentration varied in response to the groundwater concentration and no other factors affecting attenuation changed. In the second scenario, the concentration below the house fluctuates in the opposite direction to the concentration in the well; therefore, when the concentration is high in the well, it's low below the house, and vice versa. As a result, the calculated attenuation factor would vary simply because of the error in the groundwater concentration, all else being equal. In other words, although the indoor air concentration would rise due to the actual increase in groundwater concentration below the house, the groundwater concentration in the well would go down, resulting in a larger attenuation factor (less apparent attenuation). Conversely, when the indoor air concentration fell due to an actual decrease in groundwater concentration below the house, the corresponding higher concentration in the well would result in a smaller attenuation factor (more apparent attenuation).

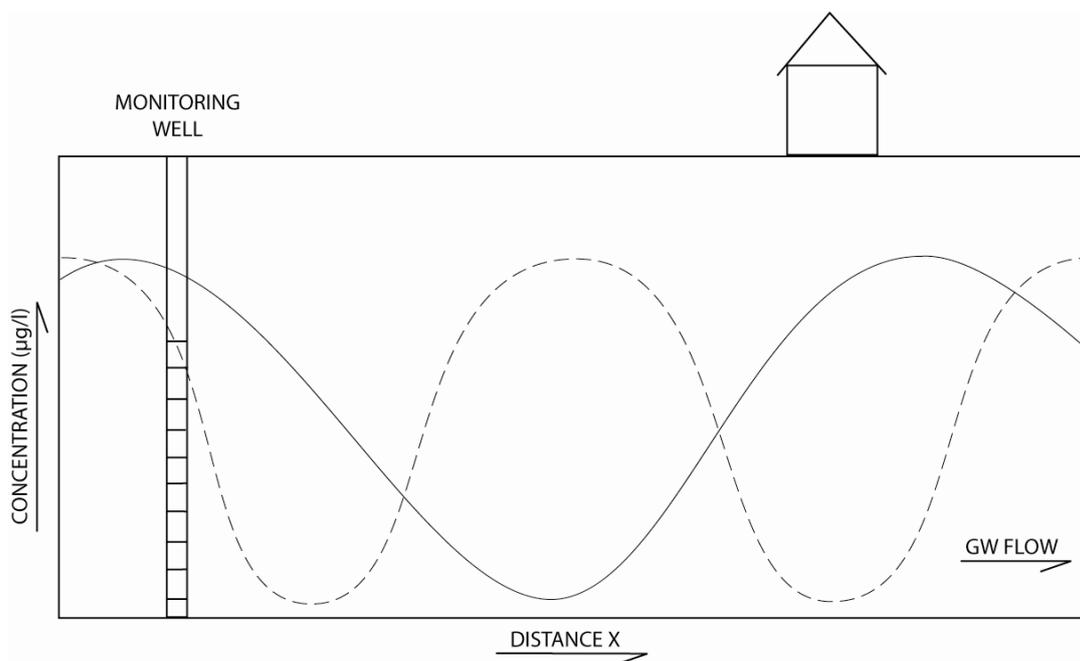


Figure 5. Concentration phase lag between well and house

Similarly, concentrations in wells might underestimate or overestimate concentrations below nearby houses due to long term rising and falling trends. For example, a well located upgradient of a house would indicate lower concentrations than below the house if plume concentrations were falling over time, and larger concentrations if the plume concentrations were rising over time. The magnitude of the error would depend on the rate of the rise in plume concentrations, the rate of plume migration, and the distance to the house.

On the other hand, short term fluctuations in groundwater concentrations might have little to no effect on vapor flux and, therefore, attenuation factor. As shown in Figure 6, short term increases or decreases in groundwater concentration below a house might cause the soil vapor concentration to increase or decrease above the water table as the chemical attempts to re-establish equilibrium concentrations above and below the interface. However, this change in vapor flux boundary conditions would not necessarily cause an immediate change in the soil vapor gradient, depending on how quickly vapors could move through the soil. In fact, for short term fluctuations in groundwater concentrations, the soil vapor gradient and flux rate would likely remain constant, based on the average boundary condition concentration (i.e., the average groundwater concentration over time). The definition of "short term", however, would be site specific and warrants more research. Therefore, single point attenuation factors based on groundwater concentrations that fluctuate over time might imply a variation in attenuation that does not actually occur (i.e., vapor flux is relatively constant, all other factors being equal).

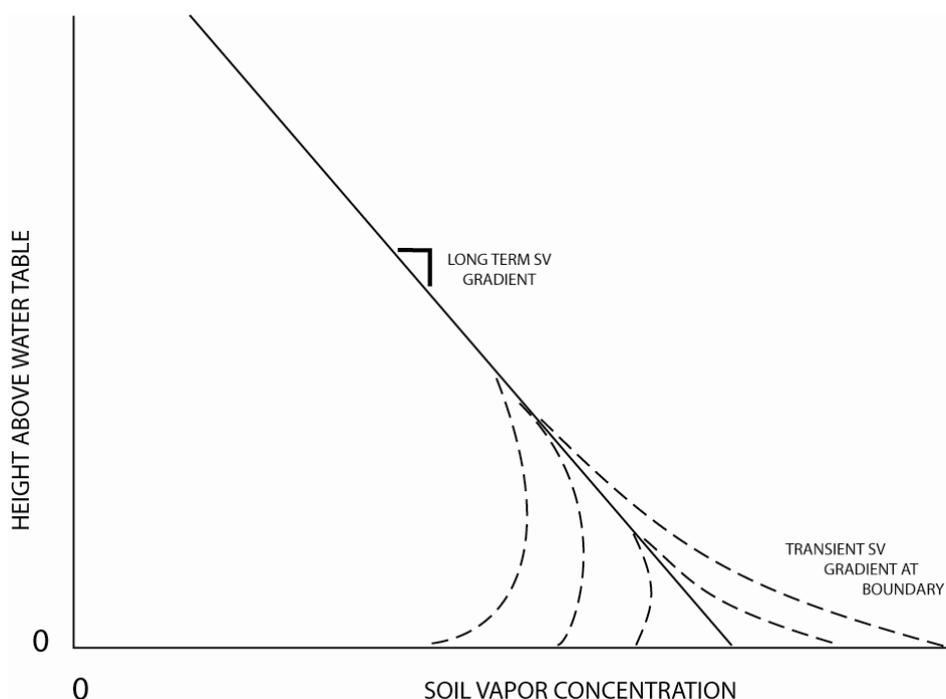


Figure 6. Affect of fluctuations in groundwater concentration on soil vapor gradient

A plot of calculated soil vapor concentrations immediately above the groundwater table, based on groundwater concentrations multiplied by the Henry's Law Constant for DCE and by 1000 to convert from ug/l to ug/m<sup>3</sup>, versus indoor air concentration, is shown on Figure 7 for each of the five houses. The indoor air concentrations show a general correlation with soil vapor (i.e., groundwater) concentrations, but the correlations are very weak. This indicates that a) the groundwater estimates are inaccurate, and/or b) that other factors have greater influence on variations in indoor air concentration. The first premise is likely true to some degree, and is also likely true for empirical attenuation factors at other sites included in the EPA database, unless unusual numbers of wells surrounded each of the houses for which attenuation factors are included. In fact, even if groundwater concentrations below the houses were accurately represented, the phenomenon suggested in Figure 6 may mean that using short term groundwater concentrations to calculate attenuation factors, rather than longer term average values, results in an apparent, rather than a true, attenuation factor.

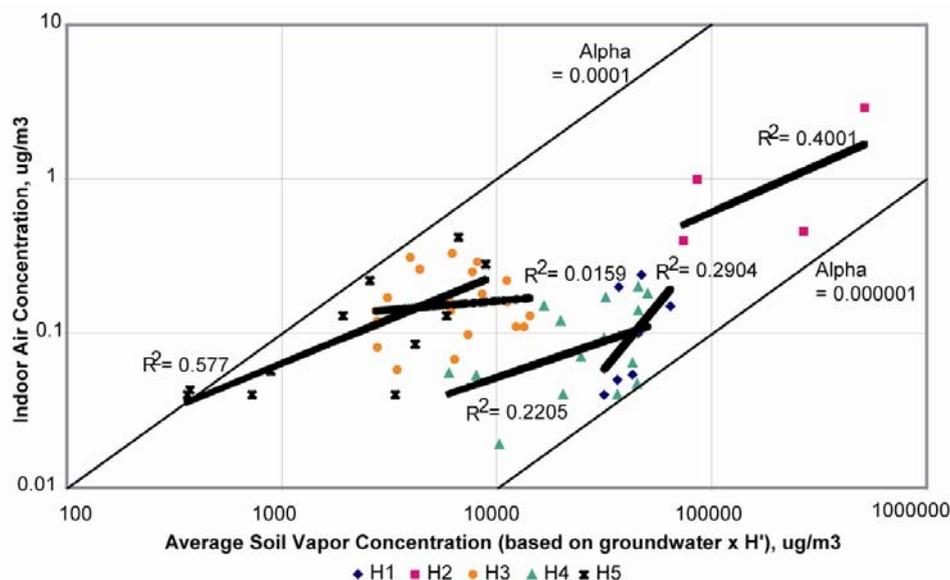


Figure 7. Correlation between indoor air and soil vapor (groundwater derived) concentrations

A plot of normalized attenuation factors (single point attenuation factors divided by the long term mean attenuation factor for each house) versus season shows that variations in attenuation factor correlate to season (Figure 8). Attenuation factors between December and March are above average nearly 90% of the time, meaning that less attenuation occurs during winter months. This behavior is likely due to less air exchange and greater depressurization due to heating in the winter, resulting in higher soil vapor fluxes into the homes and less dilution. Because diffusion is often the rate limiting factor at sites with silty and clayey vadose zone soils (Johnson, 2005), seasonal variations in air exchange rate might be the critical factor affecting variations in attenuation factor over time at these homes.

## 5. CONCLUSIONS & RECOMMENDATIONS

Groundwater screening levels are needed to screen out sites that do not warrant further evaluation for vapor intrusion, to avoid unnecessary investigations, particularly during real estate transactions. Unfortunately, the current EPA (2002) screening levels are near or below MCLs for many common compounds of concern, including TCE and PCE. Less conservative screening levels might be possible if screening levels were based on empirical estimates of long term attenuation factors, using long term mean estimates of groundwater concentration.

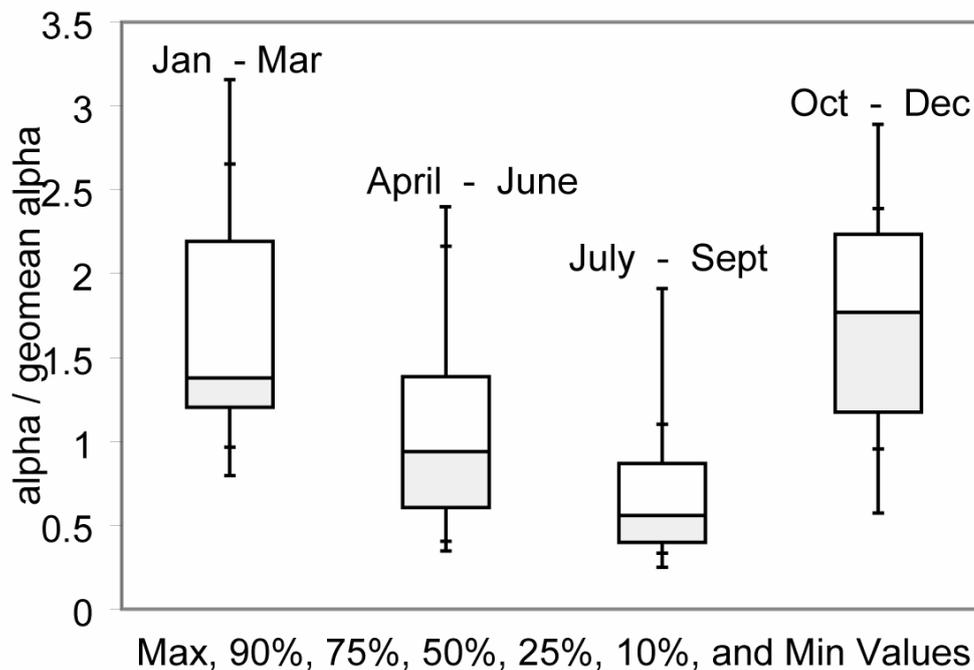


Figure 8. Seasonal variations in attenuation factor

More case history data with long term indoor air and groundwater monitoring data is required to develop an adequate database of long term attenuation factors for screening level development.

More research is required to evaluate the temporal effects of groundwater fluctuations on soil vapor flux. We might find that, in many cases, soil vapor flux is relatively insensitive to short term fluctuations, meaning that more emphasis should be placed on establishing long term mean concentrations of groundwater.

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