Vapor Intrusion as a Function of Lateral Distance from a Groundwater Plume Boundary[1]

David J. Folkes, Jeffrey P. Kurtz, and Charoen Sanpawanitchakit
EnviroGroup Limited, 7009 S. Potomac Street, Suite 300, Centennial, CO 80112

ABSTRACT

Screening for vapor intrusion potential will likely be required at a large number of sites in the future pursuant to federal and state regulations, real estate transactions, and voluntary cleanups. The EPA subsurface vapor intrusion guidance document and several state guidance documents only require vapor intrusion assessment if an existing or future building is located near a subsurface source of volatile chemicals, such as contaminated groundwater. The definition of "contaminated groundwater" in these guidance documents varies from analytical detection limits to compound-specific screening levels, while the definition of "near" varies from 30 to 100 feet, when specified (the shorter distance applying to biodegradable petroleum compounds). Very little empirical data are available in the literature, however, to substantiate these lateral distance screening criteria. Indoor air monitoring over the past eight years at 225 unmitigated residential homes in Denver, Colorado has allowed comparison of indoor air 1,1-dichloroethylene (DCE) concentrations to lateral distance beyond the edge of the groundwater plume based on the DCE MCL of 7 ug/L. Indoor air concentrations decrease rapidly with distance beyond the edge of the plume, consistent with predictions of Lowell and Eklund (2004) based on lateral diffusion of vapors in the vadose zone. Low but detectable indoor air concentrations of DCE beyond the 100 foot distance (below the indoor air action level for this site) are consistent with low concentrations of DCE in groundwater that extend beyond the edge of the plume. Therefore, the applicability of the 100 foot lateral distance criterion will depend, to some degree, on the definition of the "edge of contamination", the indoor air concentrations considered significant, and the groundwater concentration gradient beyond the edge of the defined plume. If the "edge of contamination" is defined by the analytical detection limit or a conservative vapor intrusion screening level, and groundwater concentrations continue to decrease beyond the edge of the plume, vapor diffusion theory and empirical data at this site both indicate that a 100 foot lateral distance screening criterion should be reasonable and conservative at most sites; i.e., in the former case, indoor air concentrations beyond 100 feet will likely be less than detection, and in the latter case, indoor air concentrations will likely be less than the target level used to define the groundwater screening level.

INTRODUCTION

Vapor intrusion, or the movement of volatile chemicals from the subsurface into overlying buildings, has become the recent focus of the U.S. Environmental Protection Agency (EPA) and many state agencies.[1,2] Several case histories over the past eight years have shown that relatively low concentrations of certain volatile organic compounds in groundwater can cause indoor air concentrations to exceed target risk-based concentrations in residential settings.[3] As a result, vapor intrusion investigations

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may be required at many sites in the future under RCRA, CERCLA, Brownfields, and voluntary cleanup programs[1]. Further, the potential for vapor intrusion impacts, either due to on-site or off-site sources of contamination, may be an issue for parties involved in many real estate transactions.

Site-specific evaluations of vapor intrusion can be intrusive (e.g., indoor air and sub-slab testing), costly, and require months or even years to complete[1]. Therefore, simple and inexpensive screening procedures are needed to distinguish sites where further evaluation is warranted from sites where no further action should be necessary. 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 initial vapor intrusion screening process at most sites. The simplest screening step is to exclude sites where volatile chemicals are not present in the subsurface (i.e., in soil, groundwater, or non-aqueous phase liquids) near occupied buildings. Such a screening step requires, however, definitions of "not present" and "near", i.e., a *lateral distance screening criterion.*

EPA Lateral Distance Screening Criterion

EPA suggests that the vapor intrusion pathway can be considered incomplete and no further consideration of the pathway is needed when buildings are more than 100 feet beyond the known or interpolated extent of contamination in groundwater or soil gas.[1] EPA bases this 100 foot distance on vapor intrusion fundamentals, typical uncertainty associated with the delineation of subsurface contamination, and empirical data from Colorado sites (one of which is the subject of this paper). According to EPA:

> *"The recommended lateral distance is supported by empirical data from Colorado sites where the vapor intrusion pathway has been evaluated. At these sites, no significant indoor air concentrations have been found in residences at a distance greater than one house lot (approximately 100 feet) from the interpolated edge of groundwater plumes." (at page 17)*[1]

Based on this explanation, EPA is defining "not present" as being beyond the extent of contamination or the groundwater plume, and "near" as being less than 100 feet. The groundwater plumes at the Colorado sites referenced by EPA were based on the federal drinking water Maximum Contaminant Level (MCL) for 1,1-dichloroethene (DCE) of 7 ug/L[4]; therefore, one might assume that the EPA lateral distance screening criterion means "100 feet beyond the edge of groundwater plumes defined by the MCL".

It is also unclear what EPA means by "no significant indoor air concentrations" in residences; however, the Colorado 10^{-5} risk-based action level (at the time) of 0.49 ug/m^3 for DCE was not exceeded in residences located more than 100 feet beyond the edge of the plume defined by the MCL, as discussed herein. It should be noted that Colorado raised the DCE residential indoor air action level from 0.49 to 5 ug/m^3 in 2004.

EPA suggests that the 100 foot criterion may not be applicable to all sites or contaminants and recommends the use of professional judgment when applying the criterion.[1] For example, EPA suggests that impacts may extend further than 100 feet if significant preferential pathways exist (although the criterion for a "significant" preferential pathway is not well defined in the literature or guidance) or if the potential for density-driven vapor cloud migration exists. EPA also states that the 100 foot distance will be re-evaluated and possibly adjusted by EPA as additional empirical data are compiled. At present, however, there is little published empirical data relating observed indoor air concentrations of groundwater contaminants to lateral distance from a plume boundary.

State Lateral Distance Screening Criteria

Several states have also recently developed vapor intrusion guidance that include the concept of excluding from further evaluation sites where volatile chemicals are not present in the subsurface near occupied buildings. For example, the New York State Department of Health (NYSDOH) published guidance in 2006 stating that vapor intrusion investigations are appropriate when an existing (or likely) subsurface source of volatile chemicals is near buildings (existing or future).[5] However, NYSDOH does not *"support the use of pre-determined concentrations of volatile chemicals (i.e., screening criteria) in either groundwater or soil to trigger a soil vapor intrusion investigation."* Therefore, we assume that NYSDOH considers vapor intrusion investigations to be appropriate when volatile chemicals are detected (or are likely to be detected) in the subsurface near buildings. The NYSDOH guidance also does not define what it means by "near".

On the other hand, the Colorado Department of Public Health and Environment (CDPHE) is more specific, suggesting that indoor air assessments are probably not necessary if buildings are more than 100 feet beyond the extent of groundwater concentrations exceeding Colorado vapor intrusion screening levels (very similar to EPA generic screening levels[1]), provided that VOCs are not present in NAPL or soil at "levels of concern"[6]. Colorado also bases its lateral distance criterion on experience at vapor intrusion sites in Colorado, stating:

> *"Experience indicates that a two-house buffer zone (or approximately 100 feet) beyond the edge of a well-defined ground water plume is adequate to encompass homes potentially subject to soil vapor intrusion." (p. 25).*[6]

The New Jersey Department of Environmental Protection (NJDEP) recommends conducting vapor intrusion investigations where groundwater concentrations exceed its groundwater screening levels (GWSLs) within 100 feet of existing or potential future buildings (30 feet for petroleum constituents)[7]. The GWSLs are based on predicted indoor air concentrations using the Johnson and Ettinger model with New Jersey specific parameter values and target indoor air levels based on a 10^{-6} excess cancer risk or a hazard index of 1 for non-carcinogens[7].

The California Department of Toxic Substance Control (DTSC) guidance suggests that vapor intrusion is not of concern when the edge of the building is more than 100 feet beyond the edge of groundwater or soil vapor plumes defined by "appropriate analytical detection limits"[8]

As of 2006, several other states apply lateral distance criterions of 100 feet, including New Hampshire, Pennsylvania, Alaska, Ohio, and Indiana (100 feet for chlorinated compounds and 50 feet for BTEX compounds), while Connecticut and Massachusetts employ a 30 foot lateral distance criterion[2].

Empirical Data Supporting Lateral Distance Criteria

Clearly, EPA and several states have recognized the need for lateral distance criteria for screening purposes. The recommended distance, however, varies between guidance documents in both magnitude and specificity, from 30 feet to 100 feet and from vague (unspecified) to very specific distances (100 feet from the edge of the plume to the edge of the building), while the applicable concentration varies from unspecified levels (assumed to be equal to analytical detection limits) to MCLs and screening levels based on empirical and modeled attenuation factors.

The basis for any of these distance and concentration criteria is generally not well defined. The most specific basis for a distance of 100 feet appears to be experience at sites in Colorado[1,6], although mathematical modeling of diffusion of soil vapor in the vadose zone also indicates that soil vapor concentrations will decrease by one to three orders of magnitude (depending on the thickness of the vadose zone) over a lateral distance of 100 feet from a groundwater "source" zone.[9]

This paper presents data for one of the Colorado sites relied on by EPA and CDPHE as a basis for the 100 foot lateral distance criterion for groundwater plumes. We also evaluate the applicability of the 100 foot criterion to the Colorado site and chlorinated VOC sites in general. Conditions at the Colorado site may not be directly applicable to sites with significantly different hydrogeologic conditions, building types, or climates, although the Colorado site encompasses a wide range of soil types, depths to groundwater, and house construction styles, and includes testing in all four seasons. This paper does not address distance criteria that may be applied to petroleum compounds (which typically biodegrade more rapidly than chlorinated compounds), soil vapor plumes, soil contamination, or NAPL. Further, this paper does not address vertical distance screening criteria.

SITE CONDITIONS

Groundwater containing dissolved concentrations of DCE, trichloroethylene (TCE), tetrachloroethylene (PCE), and 1,1,1-trichloroethane (TCA) has migrated under a number of residential homes at a site in Denver, Colorado. Indoor air concentrations of DCE exceeded the Colorado action level for DCE at the time of 0.49 ug/m^3 in approximately 380 homes, requiring the installation of sub-slab depressurization systems (as permitted by the home owners).[4] The extent of homes exceeding the indoor air action level for DCE was very similar to the extent of DCE in groundwater exceeding the MCL of 7 ug/L. Indoor air testing has been conducted in 225 homes surrounding the mitigated area for the past six to eight years, 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 homes prior to mitigation. As a result, several years of monitoring data are available for approximately 225 unmitigated homes located beyond the edge of the groundwater plume.

Shallow groundwater at the site flows through silts, sands, and fine gravel deposits within alluvial channels incised in Denver Formation bedrock, consisting of inter-bedded claystone, siltstone, and some fine-grained sandstone. In some areas, shallow groundwater also flows through more permeable, weathered zones in the bedrock. The margins of the groundwater plume have been quite stable since monitoring began nine years ago, except for long term reductions in concentrations due to groundwater containment and remediation systems. Fine-grained sands, silts, and clays (alluvial and loess deposits) typically overlie the water table in most of the plume areas, with the depth to groundwater ranging from about 10 to 45 feet below ground surface. In some areas, the water table is within the weathered bedrock, which in turn is overlain by fine-grained alluvium and loess deposits.

Groundwater monitoring has been conducted in shallow wells (screened across the water table) on a quarterly basis for the past eight years. For the purposes of this study, we selected unmitigated homes adjacent to the plume where indoor air concentrations of DCE, and other chlorinated solvents have been measured over a period of several years and where the interpolated plume boundary is reasonably well defined based on groundwater monitoring wells and a good understanding of hydrogeologic conditions. Within most of the plume, DCE is more abundant than TCA, TCE, and PCE. In general, the concentrations of TCA, TCE, and PCE are less than their respective MCL concentrations at the DCE plume boundary.

DCE is a particularly useful compound for studying vapor intrusion because it is seldom found in residential indoor air due to background sources[10]. On the other hand, background indoor sources of TCA, TCE, and PCE are relatively prevalent and can confound the interpretation of the vapor intrusion pathway.[10]

METHODS

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, in order 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 in the Selected Ion Monitoring (SIM) mode and CDPHE's Guidance for Analysis of Indoor Air Samples[11] using a mass spectrometer operated in the selective ion monitoring (SIM) mode with typical reporting limits of 0.04 μg/m^3 for 1,1-DCE, 0.26 to 0.027 μg/m^3 for TCE, 0.68 μg/m^3 for PCE, and 0.6 μg/m^3 for TCA. QA/QC samples included trip blanks and field duplicates at the rate of one per twenty samples.

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 above the top of the screened interval. All but three of the 32 plume boundary wells used for this study are screened across the water table; therefore, the upper five to ten feet of the aquifer was typically screened. The other three wells have screened intervals just below (<10 feet) the water table and COC concentrations have been consistently below detection in these wells since installation approximately 7 years ago.

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.

Plume Boundary Definition

The groundwater plume boundary was based on the DCE MCL of 7 ug/L (Figure 1) and was derived by interpolation of concentrations measured at 32 wells near the plume boundary. Interpolation of the plume boundary was also based on professional judgment, considering groundwater flow directions and lithology (e.g., the locations of paleochannel boundaries). Monitoring over the past several years has shown that the boundary of the plume has been very stable, except for reductions in concentrations near the source area (southern portion of the plume) due to implementation of groundwater containment and remediation systems.

Groundwater concentration gradients (at right angles to the flow of groundwater) are steep in the weathered bedrock and narrow paleochannel areas near the source, allowing relatively precise definition of the plume boundary in these areas. On the other hand, lateral concentration gradients are relatively flat in the more distal alluvial sediments in the northern portion of the plume, making delineation of the plume less precise in these areas. An additional factor that contributes to the relative accuracy of the plume boundary is the density of monitoring wells, which are generally more closely spaced near the source and more widely spaced in the distal portion of the plume. The homes selected for this study are in areas near wells where the authors believe the plume boundary has been accurately defined to within +/- 50 feet.

Distance from the plume boundary to each house was determined by estimating the centroid of each property and then measuring the shortest distance to the plume boundary. In all, data for 225 single-family homes, on or beyond the plume boundary, were considered in the evaluation. Commercial buildings, apartments and condominiums were excluded from the evaluation.

Figure 1. DCE Plume Boundary, Monitoring Wells, and Tested Homes

Indoor Air Concentrations

In order to provide a conservative (protective) estimate of vapor intrusion impacts as a function of distance from the plume boundary, the maximum measured indoor air DCE concentration measured at each home (and the corresponding TCE, TCA and PCE concentrations from the same sample) was compared to the lateral distance of the home from the edge of the DCE plume. It should be noted that for homes where a number of samples were collected over time, concentrations generally varied by a factor of two or three about the long term mean concentration.[12]

RESULTS

We first considered VOC concentrations measured in homes located in three areas with respect to the groundwater plume: 1) homes overlying the groundwater plume, 2) homes outside of but within 100 feet of the groundwater plume, and 3) homes located more than 100 feet beyond the groundwater plume. In each case, we looked at the maximum indoor air concentration of DCE measured in the home, and the TCA, TCE, and PCE concentrations measured on the same date.

In homes overlying the groundwater plume, maximum indoor air concentrations of DCE ranged up to 131 $\mu g/m^3$ and generally exceeded 0.49 ug/m^3 prior to mitigation. Vapor intrusion derived concentrations of TCE, TCA, and PCE ranged up to 22 $\mu g/m^3$, 110 $\mu g/m^3$, and 30 $\mu g/m^3$, respectively.

In homes located outside, but within 100 feet of the groundwater plume, the maximum DCE concentration was 0.66 ug/m^3, and the mean DCE concentration was 0.15 ug/m^3, as indicated on Table 1. DCE concentrations measured in homes within the 100 foot zone were typically one to two orders of magnitude lower than measured in homes over the plume (prior to mitigation). Note that several homes straddling the plume boundary required mitigation.

Table 1. Indoor air VOC concentrations in 79 homes located beyond the plume boundary (within 100 feet of the plume).

Statistic	1,1-DCE	1,1,1-TCA	PCE	TCE
% Detects	94%	66%	86%	51%
Maximum	0.66	60	34	21
Mean	0.15	4.9	2.7	0.62
Median	0.11	1.4	1.6	<0.26

* All values are in $\mu g/m^3$ and non-detects are assigned values equal to ½ the detection limit.

Concentrations of TCA, TCE, and PCE show less of a decline from the plume to the 100 foot zone, but this likely reflects in part the contributions of background sources as discussed below.

Summary statistics for VOC concentrations in homes located more than 100 feet beyond the plume boundary are summarized on Table 2. The maximum DCE concentration was 0.39 ug/m^3, with a mean maximum concentration of 0.065 ug/m^3. DCE was never detected in 41% of the homes located more than 100 feet beyond the edge of the groundwater plume. The mean and maximum DCE concentrations are approximately half those measured in the 100 foot zone (Table 1). Note that while the maximum TCE concentration went down, the maximum TCA and PCE concentrations were actually higher beyond the 100 foot zone.

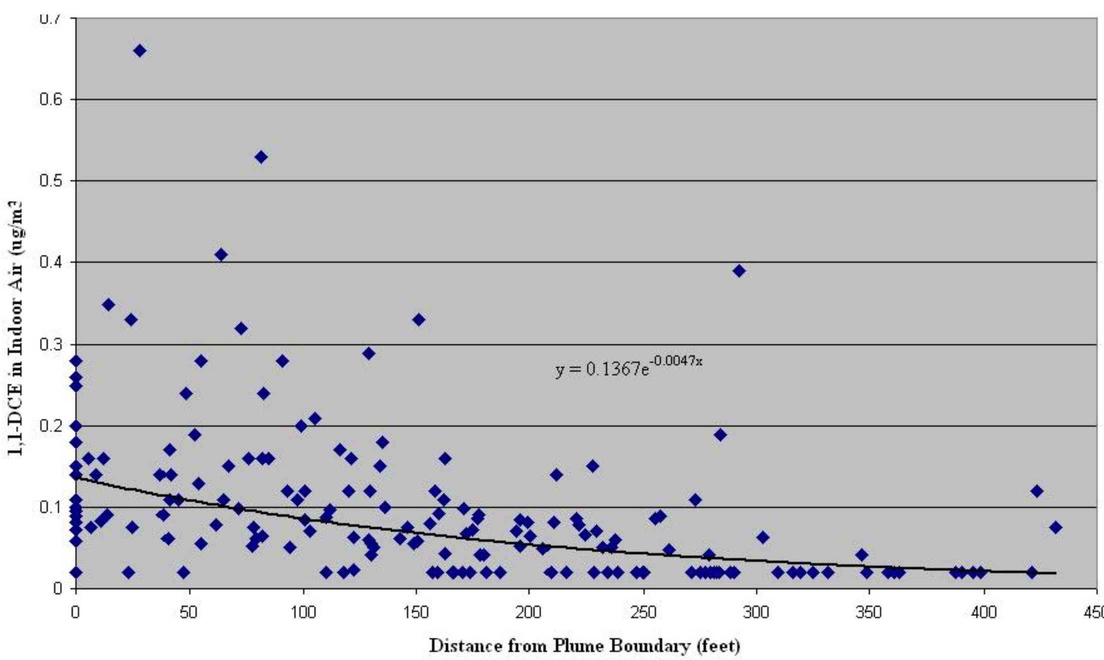
Table 2. Indoor air VOC concentrations in 146 homes located more than 100 feet beyond the plume boundary.

Statistic	1,1-DCE	1,1,1-TCA	PCE	TCE
% Detected	59%	74%	89%	25%
Maximum	0.39	83	48	4.2
Mean	0.065	4.9	3.1	<0.26
Median	0.049	1.2	1.5	<0.26

* All values are in µg/m^3 and non-detects are assigned values equal to ½ the detection limit.

We also plotted the maximum indoor air DCE concentrations measured at houses beyond the plume boundary (i.e., data summarized in Tables 1 and 2) versus distance, as shown on Figure 2. The DCE concentrations decrease exponentially with distance from the plume boundary and are generally below detection within 300 feet of the plume boundary. It should be noted that one elevated value (approximately 0.4 ug/m^3 at a distance of nearly 300 feet) was measured in a home where low concentrations of DCE (below 7 ug/L) follow a shallow bedrock valley and extend well beyond the plume boundary.

Figure 2. Indoor air DCE concentrations vs. distance from plume boundary.



The indoor air TCE, PCE and TCA concentrations (Figures 3, 4 and 5 respectively) show little to no trend as a function of distance from the plume boundary. To a large extent, this is because groundwater concentrations at the plume boundary are relatively low; therefore, background sources dominate vapor intrusion impacts and trends with distance.

Figure 3. Indoor air TCE concentrations vs. distance from plume boundary.

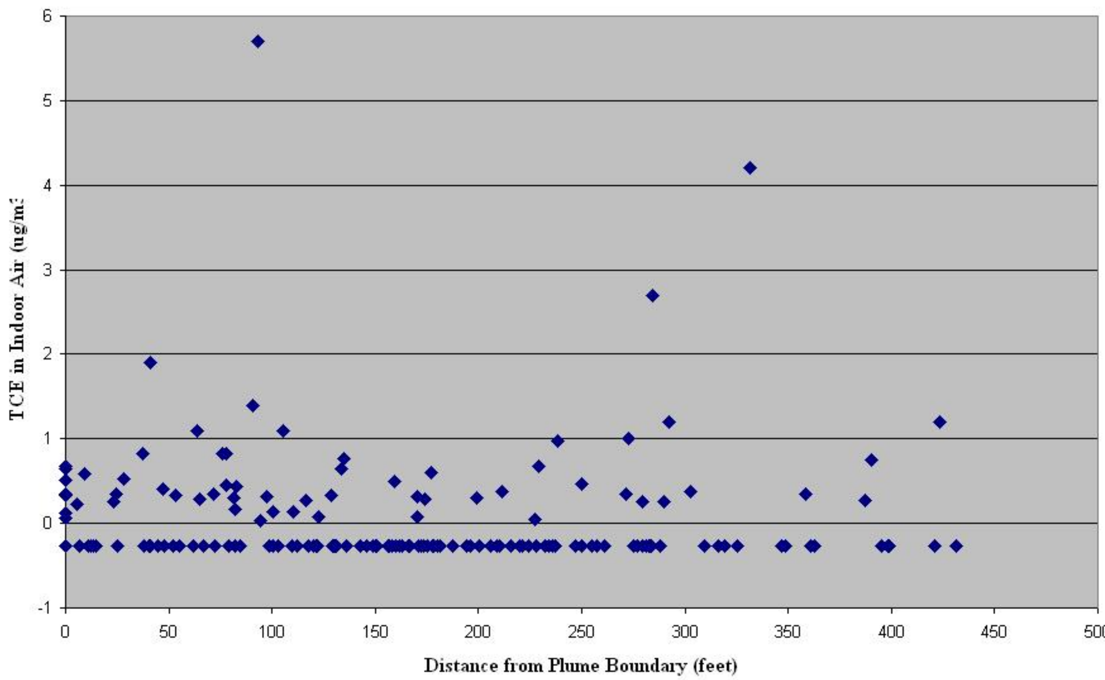


Figure 4. Indoor air TCA concentrations vs. distance from plume boundary.

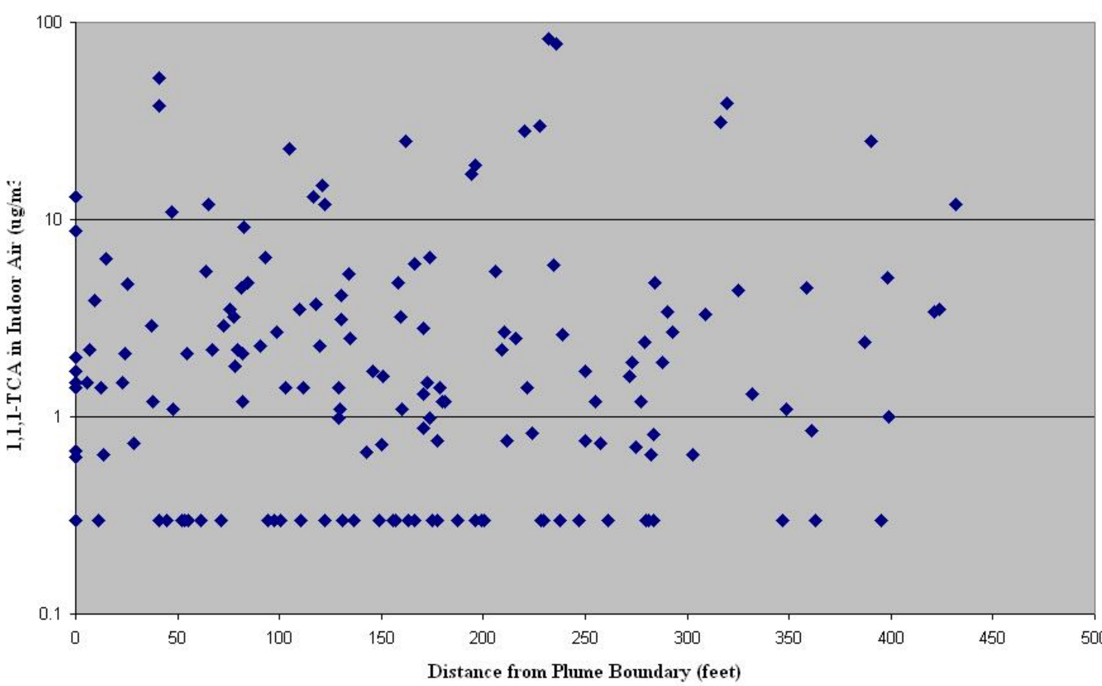
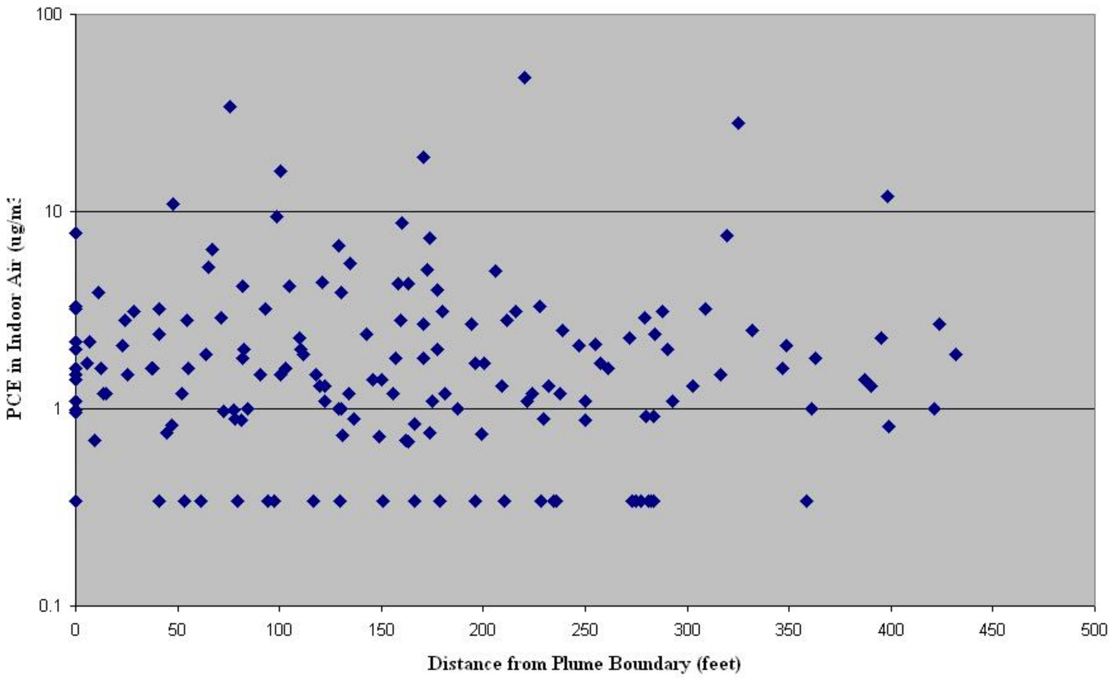


Figure 5. Indoor air PCE concentrations vs. distance from plume boundary.



Comparison to Theoretical Predictions

We also compared the VOC concentration trends with distance beyond the groundwater plume with theoretical predictions, based on theoretical lateral and vertical diffusion of gases in the vadose zone above a groundwater source. Lowell and Eklund[9] derived a theoretical expression for VOC vapor flux due to diffusion as a function of lateral distance from a plume edge, as described in equations 1 to 5 below:

$$\chi(\eta,\zeta) = 2\sum_{n=1}^{\infty}\frac{1}{\lambda_n^2}e^{-\lambda_n\eta}\sin\lambda_n \qquad (1)$$

$$\chi = C/C_o \qquad (2)$$

$$\eta = x/H \qquad (3)$$

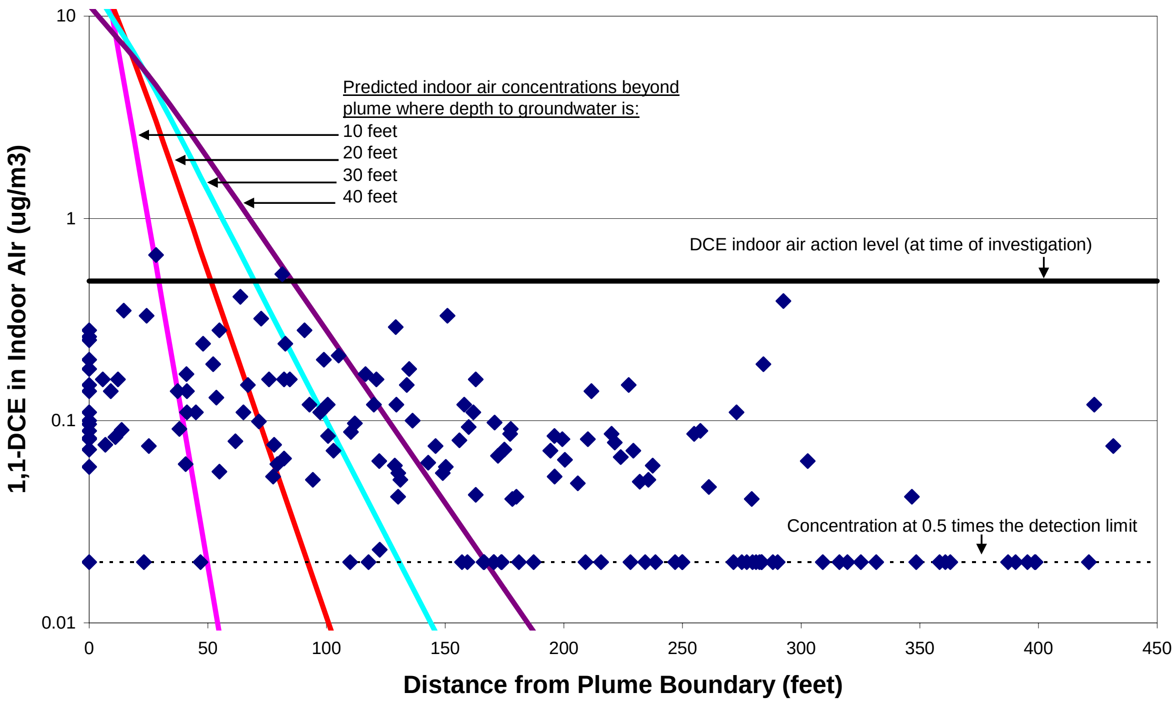
$$\zeta = y/H \qquad (4)$$

$$\lambda_n = (2n-1)\pi/2 \qquad (5)$$

where: C is concentration of vapor at a given x and y,
C_o is the concentration of vapor at the source,
H is the vadose zone thickness,
x is the lateral distance from the edge of the source,
y is the vertical distance from the above the saturated zone,
n is the summation term.

Predicted DCE concentrations, based on the equations of Lowell and Eklund, are compared to the measured indoor air DCE concentrations on Figure 6. In deriving the predicted concentrations, the groundwater concentration was assumed to be 7 ug/L inside the plume and 0 ug/L outside. Soil vapor concentrations were then calculated for a depth of 6 feet below ground surface (because most of the homes have basements), and for assumed depths to groundwater of 10, 20, 30, and 40 feet, encompassing the general range of vadose zone thicknesses at the site. Finally, the calculated soil vapor concentrations were divided by 100, consistent with EPA's deep soil vapor attenuation factor[1] and observed sub-slab attenuation factors at the Endicott site in New York[13], to simulate indoor air concentrations. It should be noted that it is not the intent of this exercise to model indoor air concentrations, but to simply compare the predicted rate of decrease in soil vapor concentrations due to diffusion with the actual rate of decrease in indoor concentration with distance from the plume. By dividing the modeled soil vapor concentrations by a constant factor of 100, it is easier to compare the two trends on the graph.

Figure 6. Comparison of Predicted and Measured Indoor Air Concentrations

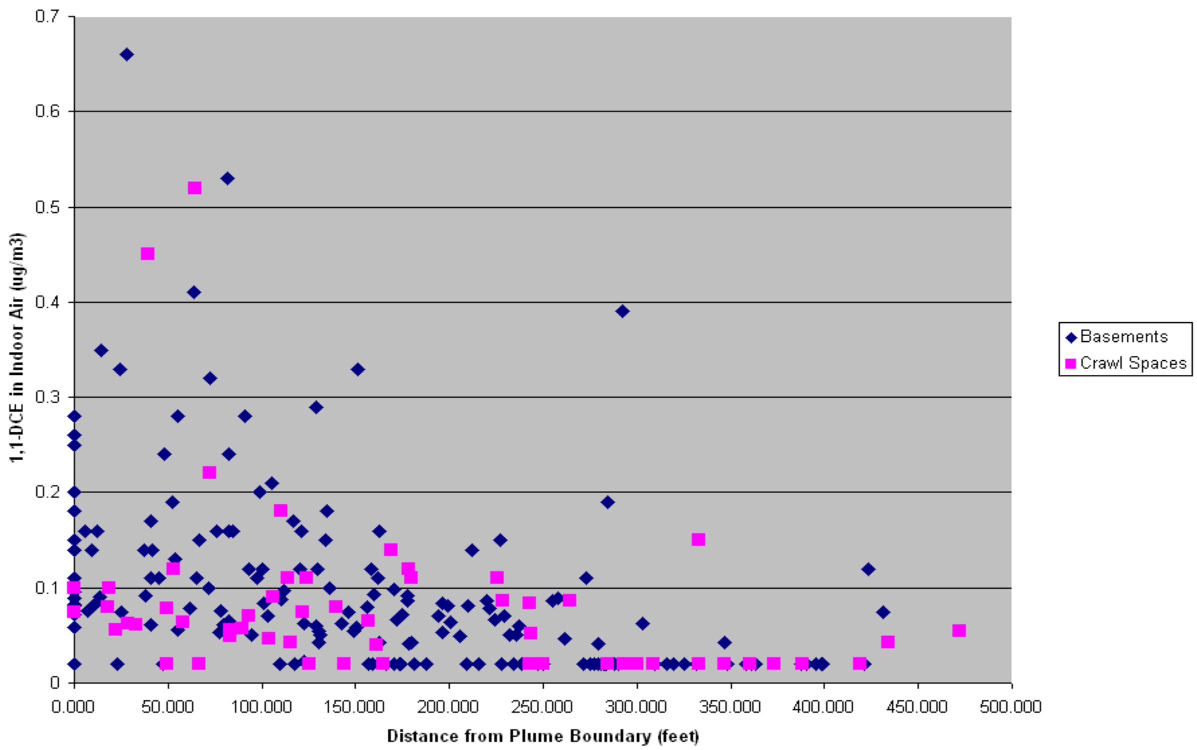


The Lowell and Eklund equations predict more rapid, exponential decreases in DCE concentrations with distance for shallower sources. For deeper sources, the exponential decrease is more gradual, but the predicted VOC concentrations still drop to concentrations that are below detection at a distance of approximately 150 feet from the source. The measured indoor air concentrations shown on Figure 6 generally decrease at a similar rate to the predicted concentrations within 100 to 150 feet of the plume boundary (recalling that concentrations within the plume generally ranged from 0.49 to 131 ug/m^3 prior to mitigation); however, low concentrations of DCE (below the indoor air action level) extend a greater distance beyond the plume than predicted by diffusion alone.

Construction Style

The majority of the homes at the site are built with either full basements or full crawl spaces. A few of the homes have partial basements and crawl spaces or small crawl spaces with slab-on-grade construction. A comparison of the indoor air DCE concentrations, in homes with full crawl spaces (55) or with full basements (170), versus distance from the plume boundary indicated no discernable differences in indoor air concentrations as a function of distance for the two home construction types. This observation generally supports the existing empirical data[14], which indicate similar attenuation for homes with crawl spaces and with basements.

Figure 7. DCE in Indoor Air for Homes with Basements or Crawl Spaces vs. Distance



DISCUSSION

The results of indoor air tests in 225 homes over the past several years at the Colorado site indicate that vapor intrusion is not occurring at levels of concern in homes located more than 100 feet beyond the edge of the groundwater plume. In this case, the contaminant of concern was DCE, the edge of the plume was defined by the MCL of 7 ug/L, and the indoor air action level was 0.49 ug/m^3 (subsequently raised to 5 ug/m^3). At the same time, it is apparent that the extent of vapor intrusion beyond the edge of a groundwater plume depends on a number of factors, as discussed below.

Indoor Air Action Level

The indoor air concentration of concern is a key parameter affecting the extent of vapor intrusion impacts beyond a plume. For example, if the indoor air action level at the Colorado site was based on a 10^{-6} risk level (0.049 ug/m^3), vapor intrusion impacts would be observed more than 100 feet beyond the plume boundary. Similarly, vapor intrusion impacts would be observed well beyond the 100 foot distance if vapor intrusion impacts were defined by the detection limit of 0.04 ug/m^3. However, the authors strongly discourage the use concentrations at or near the analytical detection (or reporting) limit to define the extent of vapor intrusion, because analytical imprecision and, for many compounds, background levels, will lead to an excessive number of false positives.

Groundwater Concentration Defining Plume Boundary

The groundwater concentration that defines the boundary of the plume is another key parameter. The 7 ug/L concentration used to define the plume boundary at the Colorado site happens to be coincident with the general extent of vapor intrusion impacts based on the 0.49 ug/m^3 indoor air action level for DCE. If the plume was defined by some higher number (say the MCL happened to be 10 ug/L), vapor intrusion impacts might extend more than 100 feet beyond the edge of the new plume boundary. Therefore, the relationship between oral toxicity criteria for drinking water and inhalation toxicity criteria for indoor air may affect the appropriateness of the 100 foot lateral distance criterion.

If the detection limit in groundwater is used to define the plume boundary, the detection limit of the compound in indoor air may limit the extent of detectable impacts. For example, if we assume a detection limit in groundwater of 1 ug/L and a relatively high Henry's Law Constant of 1 (similar to the value for DCE), the theoretical vapor concentration immediately above the groundwater table at equilibrium would be 1,000 ug/m^3. Assuming a conservative ratio (or attenuation factor) between indoor air and deep soil vapor concentrations of 0.001 (as used by EPA for its groundwater screening levels[1]), the indoor air concentration at the edge of the plume would be 1 ug/m^3. The indoor air concentration would only have to decrease a small amount (less than one order of magnitude, to be less than the detection limit for most compounds measured by EPA Method TO-15 (full scan mode). Therefore, the 100 foot distance criterion should be conservative in most if not all cases when the plume boundary is defined by the detection limit in groundwater.

Groundwater Concentration Gradient

If the compound of concern is not present in groundwater beyond the edge of the plume, as assumed by the equations of Lowell and Eklund, then lateral diffusion of vapors in the vadose zone is the only transport mechanism beyond the edge of the plume. In these cases, we would expect vapor and, therefore, indoor air concentrations, to decrease rapidly beyond the edge of the plume. Based on the curves shown in Figure 6, vapor concentrations would decrease by more than one order of magnitude at a distance of 100 feet for a 40 foot depth to groundwater; by approximately two orders of magnitude for a 30 foot depth to groundwater; and by approximately three orders of magnitude for a 20 foot depth to groundwater.

In most situations, however, VOCs will be present in groundwater beyond the edge of plume, albeit at diminishing concentrations, even if the edge is defined by the detection limit. In these cases, both partitioning from the groundwater phase and lateral diffusion of vapors from areas of higher concentration will contribute to soil vapor concentrations beyond the plume. This is the case at the Colorado site, where we observe indoor air concentrations declining more slowly with distance than predicted by the Lowell and Eklund equations. Therefore, flat concentration gradients in groundwater (perpendicular to the plume boundary) may control the lateral extent of vapor intrusion beyond the plume, subject to the influence of the other factors discussed above.

Variations over Time

Indoor air concentrations due to vapor intrusion typically vary over time due to variations in building ventilation and depressurization, even if groundwater concentrations remain constant. For example, indoor air concentrations in each home at the Colorado site typically varied by a factor of 2 to 3 about the long term mean concentration.[12] Therefore, the lateral extent of impacts could also vary over time, if based on indoor air measurements at one point in time. At the Colorado site, groundwater concentrations generally decreased by an order of magnitude over the 100 foot distance beyond the plume; as a result, temporal variations were not sufficient to cause the lateral extent of vapor intrusion to vary significantly over time. Temporal variations in the extent of vapor intrusion might be observed, however, at sites where the lateral groundwater concentration gradient is flatter.

CONCLUSIONS

The results of this study indicate that the 100 foot lateral distance criterion recommended by EPA and several state agencies is likely conservative in most situations, particularly when the edge of the groundwater plume is based on the detection limit of the compound, or when groundwater concentrations decrease rapidly with distance beyond the edge of the plume. The 100 foot lateral distance criterion should also be conservative when the edge of the plume is defined by a conservative groundwater screening level for the vapor intrusion pathway (e.g., based on the upper bound of empirical attenuation factors), provided that the groundwater screening level and the indoor air action level are based on the same risk level and the screening levels are otherwise applicable to site conditions. It should be noted that EPA[1] defaults to the MCL when risk-based screening levels would be lower than the MCL; in these cases, the 100 foot criterion may not be valid if the indoor air action level is still based on the lower risk level.

Professional judgment should be applied when the plume boundary is defined by a concentration that exceeds applicable groundwater screening levels, or when the groundwater concentration gradient if very flat (i.e., concentrations do not decrease very quickly) beyond the plume boundary.

Finally, the validity of the 100 ft lateral distance criterion also depends on the accuracy of plume boundary definition, which may be uncertain when only a few wells are available, or groundwater concentrations may vary over time.

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KEYWORDS

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