

An Empirical Analysis of the Groundwater-to-Indoor-Air Exposure Pathway: The Role of Background Concentrations in Indoor Air

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To further our understanding of the groundwater-to-indoor-air exposure pathway, a database of 270 paired groundwater and indoor air measurements of volatile organic compounds (VOCs) from 31 sites has been compiled and analyzed. Using regression analyses, these data have been analyzed to (1) detect evidence of indoor air impacts from dissolved petroleum hydrocarbons or chlorinated solvents in underlying groundwater, (2) estimate the true attenuation factor for volatilization from groundwater to indoor air, and (3) assess the utility of popular groundwater-to-indoor-air transport models for evaluating this exposure pathway. Key findings include the following: (1) >95% of the indoor air concentrations fall within or below the range of national background indoor air values; (2) there is no correlation between petroleum constituent concentrations measured in groundwater and the concentrations of these VOCs in indoor air of overlying structures; and (3) for chlorinated solvent cases, a correlation between groundwater and overlying indoor air is observed; however, the average true attenuation factor, after correcting for background, is approximately 6.9×10^{-5} , well below the default 1×10^{-3} value used by USEPA Vapor Intrusion Guidance to determine groundwater screening levels.

Keywords: vapor intrusion, background indoor air sources

Introduction

Although the scientific and regulatory communities have been aware of the subsurface-to-indoor-air vapor intrusion pathway for over two decades, most of the early focus regarding this pathway was limited to the migration of radon and landfill gas into indoor air (Folkes and Arell, 2003; Altshuler and Burmaster, 1997; Richardson, 1997). In the early nineties, this pathway drew renewed interest from the regulatory community due to the implementation of risk-based corrective action (RBCA) concepts (ASTM, 1994) at corrective action sites, and due to the publication of the Johnson-Ettinger Model (Johnson and Ettinger, 1991). The Johnson-Ettinger model extended some of the assumptions employed originally in radon vapor intrusion models to represent diffusive and pressure-driven (i.e., advective) transport of volatile organic compounds (VOCs) from a subsurface vapor source to indoor air. In the mid-nineties, several state regulatory agencies and the United States Environmental Protection Agency (USEPA, 2000) applied the Johnson-Ettinger model (Johnson, 2002), together with conservative assumptions, to develop risk-based groundwater screening levels that would be protective of human exposure to indoor air impacted by vapor intrusion. Early attempts to validate the Johnson-Ettinger model, or groundwater screening levels derived from this model, using

field data have yielded mixed results (Fitzpatrick and Fitzgerald, 1996). More recent attempts to validate the model attribute all indoor air contamination to subsurface groundwater and fail to account for background indoor air sources or any biodecay occurring in the vadose zone (Hers et al., 2003).

In the late 1990s, the groundwater-to-indoor-air vapor intrusion pathway received national attention when two Colorado sites with chlorinated solvent groundwater plumes were found to have elevated levels of chlorinated VOCs in the indoor air of overlying surface structures (Renner, 2002). Largely in response to the findings at the two Colorado sites, the Corrective Action Branch of the Office of Solid Waste and Emergency Response (OSWER) at the USEPA developed and released a draft supplemental guidance in 2001 (USEPA, 2001) to facilitate the determination of vapor intrusion at RCRA corrective action facilities. In November 2002, the USEPA issued the Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (“USEPA Vapor Intrusion Guidance”; USEPA, 2002), to extend the evaluation of the groundwater-to-indoor-air vapor intrusion pathway to Superfund and other corrective action sites (Folkes and Arell, 2003).

In the 1990s, the groundwater-to-indoor air vapor intrusion pathway was typically either not evaluated or was modeled using a simple analytical model such as Johnson and Ettinger (1991). As a result, direct measurements of indoor air quality were rarely required. However, the USEPA Vapor Intrusion Guidance (USEPA, 2002) recommends against the use of models in the absence of confirmation sampling at most sites. As

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a result, compliance with this guidance will result in measurement of indoor air quality at a large number of corrective action sites.

The USEPA Vapor Intrusion Guidance (USEPA, 2002), in its current form, provides groundwater concentration screening limits for the groundwater-to-indoor-air exposure pathway. These screening limits are based on groundwater-to-indoor-air attenuation factors derived using a database of paired groundwater and indoor air measurements from corrective action sites. The USEPA Vapor Intrusion Guidance (USEPA, 2002) recommends the application of site-specific vapor sampling if these screening limits are exceeded. However, for a number of common VOCs, such as trichloroethene and benzene, the vapor intrusion screening limits proposed by USEPA are equal to drinking water maximum contaminant levels (i.e., 5 $\mu\text{g/L}$)—a “screening level” that, in fact, screens out very few of the nearly 400,000 groundwater corrective action sites in the nation. Rather, these conservative screening limits suggest that the presence of low-ppb levels of VOCs in groundwater could pose an unsafe indoor air exposure, triggering the need for a site-specific evaluation at nearly all groundwater remediation sites. However, site-specific evaluations of alleged vapor intrusion, particularly those involving the measurement of indoor air VOC levels, can prove highly problematic due to the presence of common indoor sources of VOC vapors (e.g., smoking, cleaning agents, paint, adhesives, aerosols, building materials, automobiles, etc.). To date, very little effort has been expended to quantify contributions to indoor air VOC levels from background sources.

Proper interpretation of indoor air concentration data from groundwater impact sites requires consideration of potential background indoor air conditions in the absence of volatilization of contaminants from groundwater. For a building overlying groundwater containing VOCs, the measured concentration of a VOC in indoor air will be the sum of (1) the background indoor air concentration (i.e., volatile chemicals not originating from groundwater) and (2) the contribution from the groundwater. To improve our understanding of this potential exposure pathway and evaluate the efficacy of the USEPA Vapor Intrusion Guidance (USEPA, 2002) screening criteria, this article presents an analysis of a database of 270 paired measurements of mean VOC concentrations in groundwater and overlying indoor air space compiled from a total of 31 sites located in the United States. Using regression analyses, these data have been analyzed to (1) characterize the relative contribution of background indoor air sources versus groundwater volatilization to the measured indoor air concentrations for this site population, (2) detect evidence of indoor air impacts from dissolved petroleum hydrocarbons or chlorinated solvents in underlying groundwater, (3) estimate the true attenuation factor for volatilization from groundwater to indoor air when such impacts are observed to occur, and (4) assess the utility of current screening criteria and popular groundwater-to-indoor-air transport models for evaluating this exposure pathway.

Comparison of National Background Indoor Air Concentrations to Risk-Based Target Indoor Air Concentrations

In order to evaluate the potential of background VOC sources in indoor air to interfere with the identification of groundwater-to-indoor-air impacts, average background indoor air values (or ranges) determined from measurements at locations where no affected groundwater was present, have been summarized in Table 1. This table summarizes the results of a number of studies of VOC concentrations in indoor air that have been described in the literature. The indoor air studies summarized in the USEPA Vapor Intrusion Guidance (USEPA, 2002) have not been directly reviewed for this work and are not described in the guidance document. Shah and Singh (1988) summarize indoor air measurements compiled from various sources into a single database. Their database includes measurements from both commercial and residential buildings and consists of between 96 and 2278 data points for each of the chemicals listed in Table 1. Although data from 16 states are included, 90% of the data are from California or New Jersey and 98% of the data are from 1981 to 1984. Stolwijk (1990) summarizes data primarily from a study of 500 houses in Germany conducted in the mid-1980s. Foster et al. (2002) and Kurtz and Folkes (2002) summarize the results of measurements in apartment buildings and single-family houses near the Colorado DOT-MTL site and the Redfield Rifle site, respectively, near Denver, Colorado, from 1996 to 2001. These studies summarize the results of 427 measurements and 282 measurements, respectively, for each chemical. Although these studies provide the most recent indoor air measurements available, the authors of the studies caution that the results may underestimate typical VOC concentrations because the residents around these sites have been provided with extensive public information concerning VOCs in indoor air and in some cases residents were advised to remove potential sources of VOCs prior to sample collection. The studies reviewed indicate that volatile chemical concentrations vary greatly between individual buildings. A lognormal distribution is typically observed with individual chemical concentrations ranging from nondetect to $10\times$ or more above the average concentration. Although limited, the data presented does not show any clear trends in indoor air quality over time. The use of some VOCs, such as TCE, in consumer products has decreased over time, leading to speculation that indoor air concentrations of these VOCs has also likely decreased. However, the use of other VOCs such as benzene and PCE is still widespread, suggesting that indoor air concentrations of these VOCs are less likely to have decreased significantly over time.

In Table 2, the national background indoor air concentration ranges of three risk-driving VOCs are compared to their respective risk-based target indoor air concentrations established for the air inhalation exposure pathway by various regulatory agencies. As shown in Table 2, the background ranges generally tend to greatly exceed the risk-based target concentration range set by the USEPA Vapor Intrusion Guidance

Table 1. Summary of average background indoor air concentration ranges from various nationwide studies

Chemical of concern	CAS #	USEPA (2002)										Range of values ($\mu\text{g}/\text{m}^3$)
		Brown et al. (1994) ppbv	Sheldon (1992) ppbv	EPA IAQ (1991) ppbv	Shah and Singh (1988) ppbv	Stolwijk (1990) ppbv	Foster et al. (2002) ppbv	Kurtz and Folkes (2002) ppbv	Range of values ppbv			
Benzene	71-43-2	2.51	0.69	4.39	5.16	3.16	1.28	—	0.69–5.16	2.14–16.8		
Ethylbenzene	100-41-4	1.15	—	3.23	2.89	2.32	—	—	1.15–3.23	5.08–14.3		
Hexane, n-	110-54-3	3.41	—	—	—	2.85	—	—	2.85–3.41	10.0–12.2		
Styrene	100-42-5	—	0.24	1.41	—	—	—	—	0.24–1.41	1.04–6.13		
Tetrachloroethene	127-18-4	1.03	0.04	4.12	3.06	—	0.24	0.17	0.04–4.12	0.29–27.8		
Toluene	108-88-3	9.83	—	16.21	7.39	2.20	—	—	7.39–22.0	26.9–80.0		
Trichloroethene	79-01-6	—	—	1.68	1.35	—	0.03	0.03	0.03–1.68	0.15–9.01		
Trimethylbenzene, 1,2,4	95-63-6	—	—	—	0.57	2.00	—	—	0.57–2.00	2.87–10.0		
Trimethylbenzene, 1,3,5	108-67-8	—	—	—	0.91	1.00	—	—	0.91–1.00	4.57–5.00		
Xylene, m-p	1330-20-7	5.54	—	—	—	4.57	—	—	4.57–5.54	20.0–24.2		

Note: — = no value reported.

Table 2. Comparison of background air concentrations to risk-based exposure limits

Chemical	Background indoor air conc. range ($\mu\text{g}/\text{m}^3$)	Risk-based target indoor air concentration ($\mu\text{g}/\text{m}^3$)	
		USEPA (2002)	USEPA (2003)
Benzene	2.24–16.76	0.31–31	0.23
Trichloroethene	0.16–69.70	0.022–2.2	0.016
Tetrachloroethene	0.28–37.51	0.81–81	0.31

(USEPA, 2002) for screening purposes, making it difficult to distinguish an impacted structure from a nonimpacted one. Moreover, the USEPA Region 3 Risk-Based Concentrations (RBCs) for air inhalation are significantly less than the minimum average indoor air background concentrations reported for benzene and TCE.

The USEPA Vapor Intrusion Guidance (USEPA, 2002) recommends the direct measurement of indoor air concentration in overlying buildings as a primary tool for identifying groundwater-to-indoor-air impacts at corrective action sites where the groundwater concentration exceeds preliminary screening levels. However, because the regulatory levels proposed for indoor air are either below or in the same range as background concentrations, the direct measurement of VOC concentration will likely exceed the regulatory level, even in the absence of a groundwater-to-indoor-air impact. Hence, direct indoor air measurements cannot be used as reliable indicators for groundwater-to-indoor-air impacts.

Database of VOC Concentrations in Groundwater and Indoor Air at Corrective Action Sites

To evaluate the groundwater-to-indoor-air exposure pathway at corrective action sites, a database has been compiled consisting of 270 paired groundwater and indoor air measurements for VOCs collected from 31 corrective action sites. Sources of data include Fitzpatrick and Fitzgerald (1996) for the Massachusetts Department of Environmental Protection (MADEP), the USEPA Vapor Intrusion Guidance database (USEPA, 2002), and published vapor intrusion studies. When multiple measurements were available for the same chemical at the same location (e.g., because of multiple sampling events), then the mean concentration was used. Data sources for which the average values could not be obtained (e.g., only the maximum of multiple measurements was provided) were not used. Furthermore, individual buildings were evaluated separately; therefore, a “case” of paired data was defined as a single residence overlying affected groundwater. All of the sites are located within the United States, with 1 site in California, 3 sites in Colorado, and 27 sites in Massachusetts.

The paired groundwater and indoor air measurements were conducted by various parties at corrective action sites where

groundwater-to-indoor-air impacts were already suspected to have occurred or where site characteristics were considered to pose a potential for groundwater-to-indoor-air impacts (e.g., volatile chemicals in shallow groundwater overlain by highly permeable soils). Unsaturated soils at 29 of the 31 sites in this data set are characterized by gravel or sand, while only 2 of the sites are characterized by silt or sandy silt soils. At 26 of the 31 sites, the depth to groundwater was less than 10 feet below ground surface. Fifteen of the 31 sites have petroleum hydrocarbon contamination, and the remaining 16 sites have chlorinated solvent contamination in groundwater. Measurements for petroleum hydrocarbon constituents include benzene, ethylbenzene, toluene, xylenes, and methyl-t-butyl ether (MTBE). The chlorinated solvents include 6 unsaturated chlorinated aliphatics (i.e., tetrachloroethene, trichloroethene, cis-1,2-dichloroethene, trans-1,2-dichloroethene, 1,1-dichloroethene, and vinyl chloride) and 4 saturated chlorinated aliphatics (e.g., 1,1-dichloroethane, 1,2-dichloroethane, 1,1,1-trichloroethane, and 1,1,2-trichloroethane).

Within the database no correlation was observed between the measured attenuation factor and either depth to groundwater or soil type for petroleum hydrocarbons or chlorinated solvents (results not shown). However, due to the predominance of sites with shallow groundwater and sand or gravel soil, this data set may not be sufficient to identify such relationships. Based on the prevalence of sandy soils and shallow groundwater, the sites in the database most likely represent site conditions posing the highest risk for groundwater-to-indoor-air impacts. Due to the limited geographical distribution of sites in the database, the data set may not fully reflect the influence of different climactic conditions on vapor intrusion processes.

Correlation Between Measured Indoor Air and Groundwater Concentrations

The use of groundwater screening concentrations to identify corrective action sites at risk for indoor air impacts assumes a relationship between the concentration of volatile chemical measured in groundwater and the resulting concentration in indoor air. In other words, if vapor intrusion were occurring, corrective action sites with higher chemical concentrations in groundwater would also be expected to have higher chemical concentrations in indoor air. Figure 1 shows the correlation between groundwater concentrations and indoor air concentrations measured for petroleum hydrocarbons and chlorinated solvents. For the sites included in the database, the data show no correlation between groundwater and indoor air concentrations for petroleum hydrocarbons ($p = 0.50$). However, the data for chlorinated solvents do evidence a moderate correlation between concentrations measured in groundwater and indoor air ($p < 0.001$). In addition, for >95% of the petroleum hydrocarbon and chlorinated solvent indoor air measurements, the measured concentration falls within or below the range of average background indoor air concentrations for BTEX compounds and chlorinated solvent compounds. Thus, for the population of corrective action sites included in

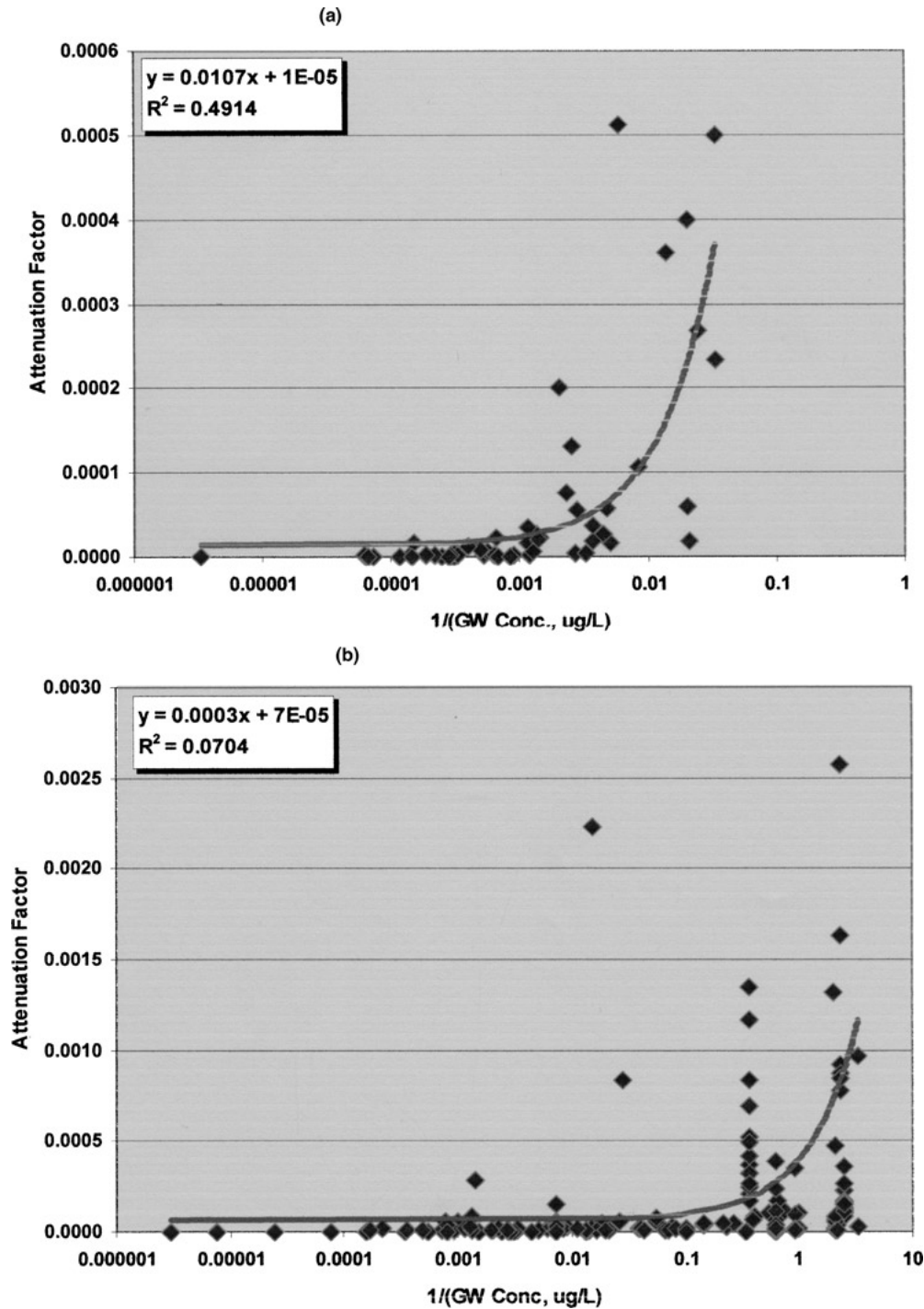


Figure 1. Measured attenuation factor versus inverse groundwater concentration. Graphs show data for individual (a) petroleum hydrocarbons and (b) chlorinated solvents at 31 corrective action sites. The lines are the best-fit linear regression for the equation $AF_{measured} = C_{bk} \times (1/C_{gw}) + AF_{true}$, where $AF_{measured}$ is the ratio of the measured indoor air concentration to the measured groundwater concentration, C_{bk} is the indoor air concentration from sources other than groundwater, C_{gw} is the concentration in groundwater, and AF_{true} is the true groundwater-to-indoor-air attenuation factor.

the database (characterized by shallow groundwater overlain by high-permeability soils), site measurements show that affected groundwater has had no observable impact on indoor air quality at petroleum release sites. For chlorinated solvent sites, where a moderate correlation between groundwater and indoor air is

observed, the data indicate that indoor air concentrations have been elevated above typical background levels at only a limited number of sites. These findings highlight the difficulty of identifying vapor intrusion impacts through the use of indoor air measurements.

Although the indoor air concentration at the petroleum hydrocarbon sites did not correlate with the groundwater concentration, the measured indoor air concentrations typically exceeded the risk-based air limits recommended by USEPA. For example, the indoor air benzene concentration was greater than the USEPA Region 3 RBC (USEPA, 2003) for benzene ($0.22 \mu\text{g}/\text{m}^3$) at all 15 sites where it was measured. However, as discussed previously, the indoor air benzene concentration at these sites was consistent with the national average indoor air concentrations reported in a variety of studies. This analysis indicates that a failure to consider background sources of volatile chemicals when evaluating the results of direct indoor air measurements can lead to false positive indications of indoor air impacts by affected groundwater.

Effect of Background on Pathway Evaluation

At a corrective action site where volatile chemicals in groundwater are causing an indoor air impact, the total measured concentration in indoor air will be equal to the background concentration plus the contribution from the groundwater. Although the relative contribution from background and from groundwater cannot readily be determined for an individual site, the average contributions from each source can be evaluated for the population of sites in the database as described below.

The relationship between the groundwater and indoor air concentration is commonly expressed in terms of an attenuation factor as follows:

$$AF_{measured} = \frac{C_{ia}}{C_{gw}} \quad (1)$$

Where $AF_{measured}$ is the measured attenuation factor, C_{ia} is the measured indoor air concentration, and C_{gw} is the measured groundwater concentration. Note that the attenuation factor is not defined in the same way as that commonly used by the USEPA and others (i.e., $AF = C_{ia}/C_{sg}$, where C_{sg} is the soil gas concentration). When using the USEPA-defined attenuation factor, C_{sg} is typically estimated as $C_{sg} = C_{gw} \cdot H'$ (Johnson, 2002). However, several studies have indicated that Henry's Law is not useful for predicting soil vapor concentration from measured groundwater concentration (Barber et al., 1990; McCarthy and Johnson, 1993; McHugh et al., 2003), thus we have chosen to define the attenuation factor as the direct ratio of indoor air to groundwater concentration.

The measured indoor air concentration in Eq. (1) is the sum of the background concentration and the contribution from groundwater:

$$C_{ia} = C_{bk} + C_{gw-to-air} \quad (2)$$

where C_{bk} is the background indoor air concentration in the absence of a contribution from groundwater and $C_{gw-to-air}$ is the indoor air concentration due to migration from groundwater in the absence of a contribution from background. The indoor air

concentration due to groundwater can be expressed as a function of groundwater concentration as

$$C_{gw-to-air} = C_{gw} \cdot AF_{true} \quad (3)$$

where AF_{true} is the true groundwater-to-indoor-air attenuation factor. Substituting Eqs. (2) and (3) into Eq. (1) yields

$$AF_{measured} = \left(\frac{C_{bk}}{C_{gw}} \right) + AF_{true} \quad (4)$$

Equation (4) has the standard form of a linear slope-intercept equation (i.e., $y = m \cdot x + b$). As a result, regression analysis of the measured attenuation factor versus $1/C_{gw}$ can be used to estimate the relative contribution of background (C_{bk}) and groundwater (AF_{true}) on the measured indoor air concentrations in the database using the least squares method (see Figure 1).

The regression analysis indicates that background is the primary source of petroleum hydrocarbons in indoor air at corrective action sites, while affected groundwater may be a contributing source at chlorinated solvent sites. As shown in Table 3, the average background concentration for individual petroleum hydrocarbons for this data set is $10.7 \mu\text{g}/\text{m}^3$, consistent with the background concentration values reported in the literature (i.e., a range of 2.24 to $62.08 \mu\text{g}/\text{m}^3$ for BTEX compounds; see Table 1). Based on the regression analysis, the average background indoor air concentration for individual chlorinated solvents is $0.33 \mu\text{g}/\text{m}^3$, a value at the lower end of the range of average background indoor air concentrations reported in the studies reviewed by USEPA (e.g., 0.16 to $69.70 \mu\text{g}/\text{m}^3$ for TCE and PCE; see Table 1). The average true attenuation factors are 1.4×10^{-5} and 6.9×10^{-5} for petroleum hydrocarbons and chlorinated solvents, respectively. For both chlorinated solvents and petroleum hydrocarbons, analysis of variance for the regression indicates that the true attenuation factor is not significantly different from zero ($p > 0.05$), indicating that, for this data set, the groundwater-to-indoor-air pathway does not contribute to a statistically significant increase in indoor air concentrations over background conditions.

For both petroleum hydrocarbons and chlorinated solvents, the regression analysis yields poor R^2 values (0.49 and 0.07 in Figures 2a and 2b, respectively). These poor fits are expected, because the regression model used to determine the average background and true attenuation factor values does not account for the site-specific variations in the parameter values. Therefore, the regression model can account for only a limited amount of the variability in the data set.

Evaluation of Existing Groundwater-to-Indoor-Air Screening Models

The Johnson and Ettinger Model (JEM; Johnson and Ettinger, 1991) is the most common model in use today to evaluate the potential for indoor air impacts associated with environmental

Table 3. Best-fit estimates of background and true attenuation factor

Chemical class	Average background concentration ^a	Average true attenuation factor ^a	Regression coefficient (R ²)
Petroleum hydrocarbons (59 Cases)	10.7 ± 2.9 μg/m ³ (p < 0.001)	1.4 × 10 ⁻⁵ ± 2.5 × 10 ⁻⁵ (p = 0.30)	0.49
Chlorinated solvents (211 Cases) ^b	0.33 ± 0.16 μg/m ³ (p < 0.001)	6.9 × 10 ⁻⁵ ± 2.4 × 10 ⁻⁴ (p = 0.56)	0.07

^aBest fit parameter values shown with 95th percentile confidence intervals. Regression analysis performed on individual chemical concentration measurements within the chemical class. The p value is the statistical probability that the estimated parameter values are not different from zero (i.e., p ≤ 0.05 is considered statistically significant).

^bRegression analysis for chlorinated solvents does not include one site (three measurements) determined to be an outlier within the dataset.

contamination. The JEM is a one-dimensional analytical model for convective and diffusive vapor transport into indoor air. This model provides an estimated attenuation factor that relates the vapor concentration in the indoor air to the vapor concentration at the source of contamination. The model is typically run with a steady-state solution to vapor transport (i.e., infinite or nondiminishing source). Inputs to the model include chemical properties of the contaminant, saturated and unsaturated zone soil properties, and structural properties of the building.

Critical input parameters for the JEM have been identified in Johnson (2002). Although originally developed as a tool for evaluation of soil contamination, the JEM has been adapted by the USEPA for the evaluation of groundwater contamination and is commonly known as the JEM spreadsheet model or the GW-Screen model (USEPA, 2000). The input defaults for JEM spreadsheet model are presented in Table 4. In addition to this model, the USEPA has developed a simplified model, which is presented in USEPA Vapor Intrusion Guidance (USEPA, 2002)

Table 4. Default input parameters for the USEPA Johnson-Ettinger spreadsheet model

Parameter	Symbol	Unit	Sand (S)	Clay (C)	Loamy sand (LS)	Silty clay loam (SICL)
Soil parameters						
Fractional organic carbon content	foc	g-C/g-soil			0.002	
Dry soil bulk density	ρ _s	g/cm ³			1.5	
Total soil porosity	θ _T	cm ³ /cm ³ -soil			0.43	
Vadose zone, volumetric water content (or water-filled porosity)	θ _{ws}	cm ³ /cm ³			0.3	
Vadose zone, volumetric air content (or air-filled porosity)	θ _{as}	cm ³ /cm ³			0.13	
Thickness of capillary fringe	h _c	cm	17.05	81.52	18.75	133.93
Capillary fringe, volumetric water content (or water-filled porosity)	θ _{wcap}	cm ³ /cm ³	0.253	0.412	0.303	0.399
Capillary fringe, volumetric air content (or air-filled porosity)	θ _{acap}	cm ³ /cm ³	0.177	0.018	0.127	0.031
Foundation/wall crack, volumetric water content (or water-filled porosity)	θ _{wcrack}	cm ³ /cm ³			<i>a</i>	
Foundation/wall crack, volumetric air content (or air-filled porosity)	θ _{acrack}	cm ³ /cm ³			<i>a</i>	
Enclosed space parameters						
Enclosed area of building foundation	A _b	cm ²			923,521 or 1,692,321 ^b	
Enclosed space air exchange rate, residential	ER	1/s			0.000125	
Enclosed space volume/infiltration area ratio, residential	L _B	cm			488 or 267 ^c	
Enclosed space foundation or wall thickness	L _{crack}	cm			15	
Enclosed space foundation perimeter	X _{crack}	cm			3,844	
Depth to base of enclosed space foundation	Z _{crack}	cm			15 or 200 ^b	
Differential pressure, Q _s > 0	Δp	g/cm-s ²			40	
Areal fraction of cracks in foundation/walls	η	cm ² /cm ²			0.00042 or 0.00023 ^d	
Soil vapor permeability	k _v	cm ²	2.00E-08	1.00E-09	1.00E-08	1.00E-09

Notes: ^aUSEPA sets D_{crack,eff} = D_{s,eff}, making this parameter unnecessary.

^bLarger value used when basement present.

^cNot specified directly; calculated from a specified default building volume of 451 m³ and the listed values for A_b; smaller value corresponds to basement presence.

^dNot specified directly; calculated assuming a constant crack of 0.1 and the listed values for A_b and X_{crack}; smaller value corresponds to basement presence.

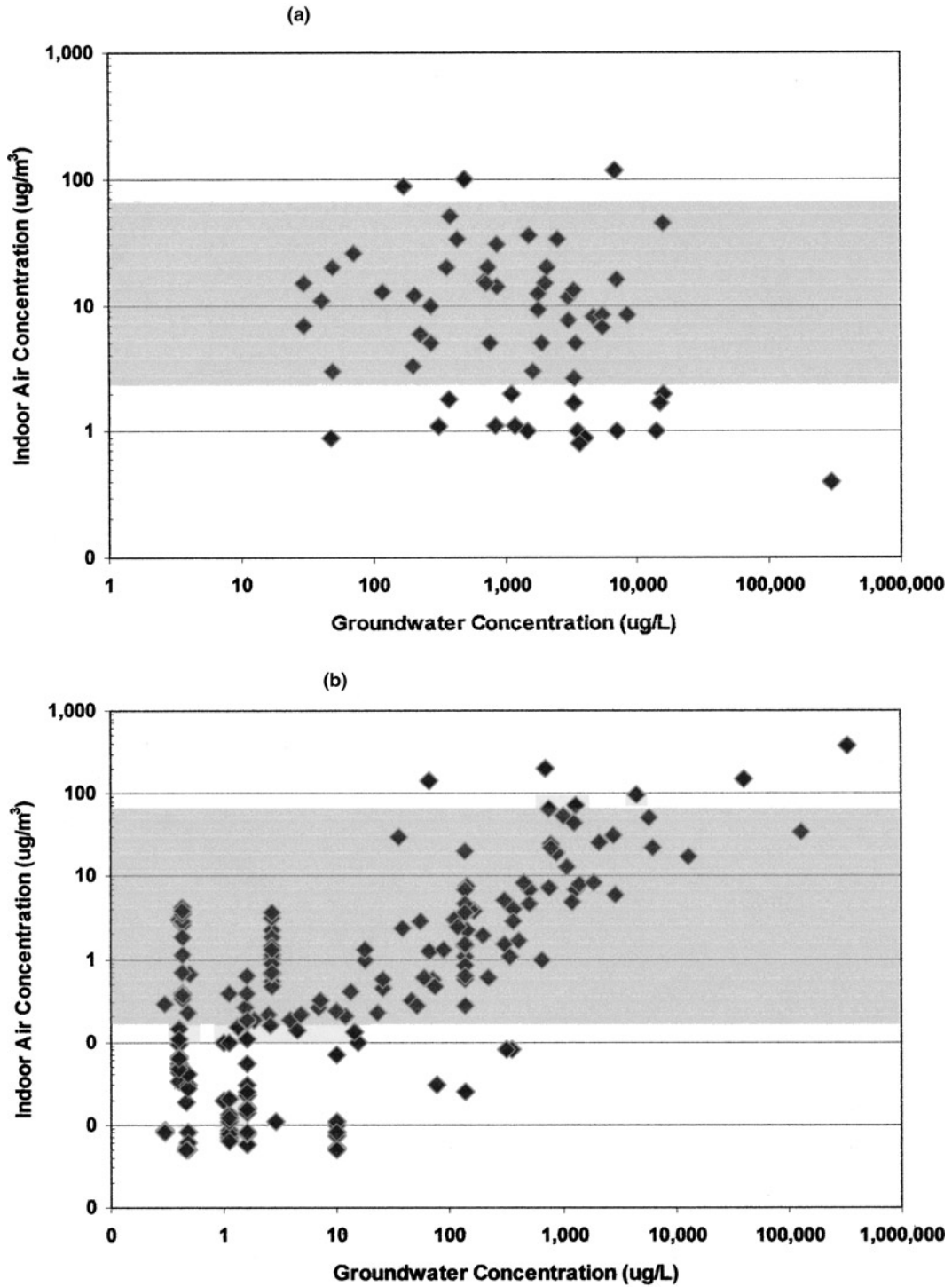


Figure 2. Indoor air concentration versus underlying groundwater concentration. Graphs show average groundwater and indoor air concentrations for individual (a) petroleum hydrocarbons and (b) chlorinated solvents at 31 corrective action sites. Shaded area represents the range of background indoor air values reported for average BTEX concentrations (petroleum hydrocarbons) and average PCE or TCE concentrations (chlorinated solvents) at sites without an impacted subsurface.

and was used for the development of groundwater-to-indoor-air screening values:

$$C_{ia} = C_{gw} \cdot H' \cdot AF_{sg-air} \quad (5)$$

where C_{ia} is the predicted indoor air concentration, C_{gw} is the measured groundwater concentration, H' is the dimensionless Henry's Law constant, and AF_{sg-air} is the soil-gas-to-indoor-air attenuation factor.

Based on the results presented above, neither the JEM spreadsheet (USEPA, 2000) nor the USEPA Vapor Intrusion Guidance model (USEPA, 2002) would be useful for predicting the observed relationship between groundwater and indoor air concentrations for petroleum hydrocarbon sites in the database because they fail to reflect the observed relationship between petroleum

hydrocarbons in groundwater and indoor air (see Figure 2). For petroleum hydrocarbon sites in the database, no correlation between groundwater and indoor air concentrations was observed. However, both models predict that the indoor air concentration will be a linear function of the measured groundwater concentration (see Figure 3). For chlorinated solvents, both models

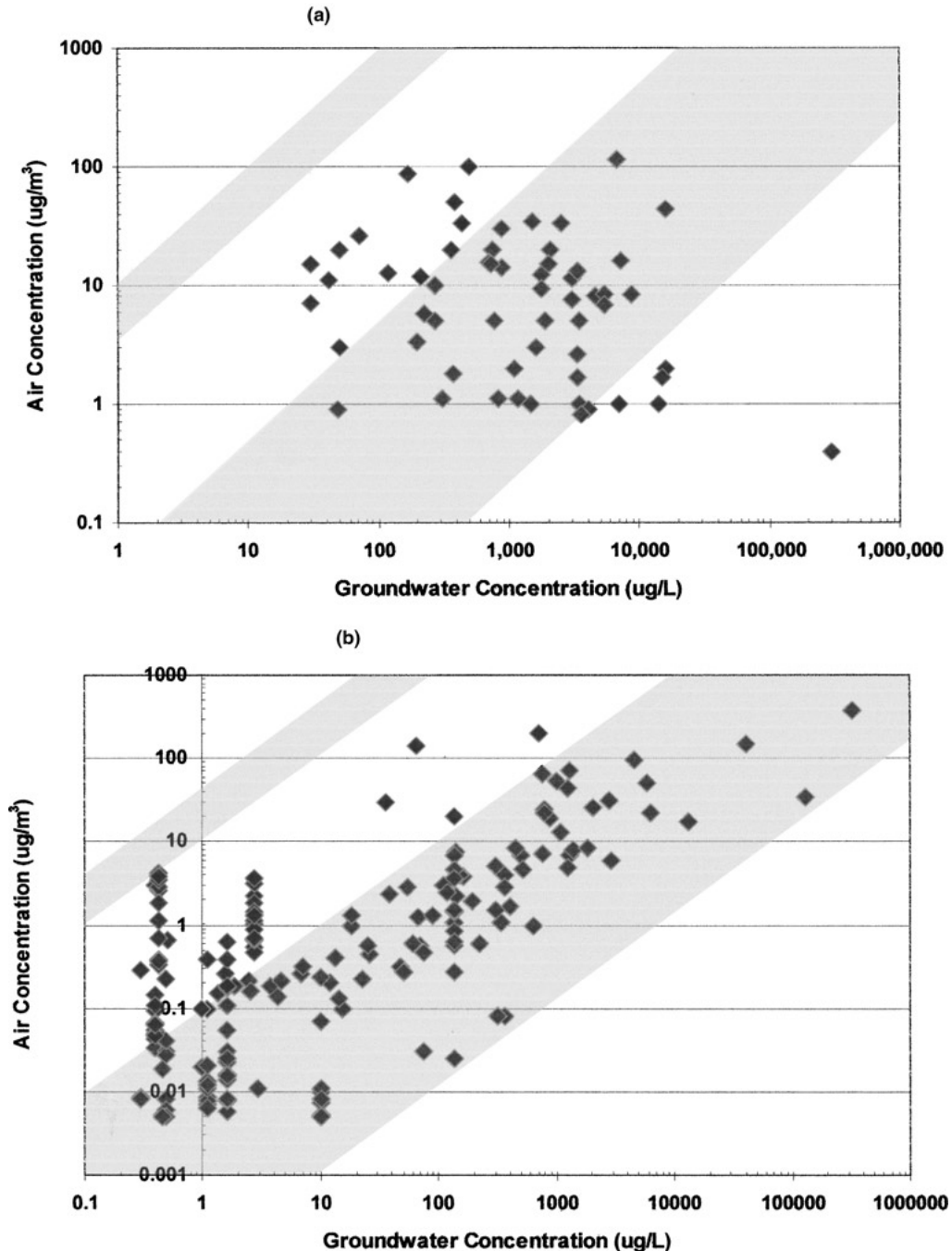


Figure 3. Observed and predicted relationships between indoor air and underlying groundwater concentrations. Graphs show measured groundwater and indoor air concentrations for individual (a) petroleum hydrocarbons and (b) chlorinated solvents at 31 corrective action sites. The shaded band represents the range of possible relationships that can be obtained between indoor air and groundwater using the USEPA Vapor Intrusion Guidance Model (USEPA, 2002) based on the allowed range of attenuation factors (0.001 to 0.0001) and the Henry's Law constant (a) benzene (0.23) or (b) trichloroethene (0.43). The USEPA Johnson and Ettinger Spreadsheet Screening Model (USEPA, 2000) predicts a similar linear relationship between groundwater and indoor air concentrations, with a broader range of possible concentration ratios based on the selected input parameter values.

predict the observed relationship between groundwater and indoor air concentrations, i.e., increasing indoor air concentrations with increasing groundwater concentrations; however, the USEPA Vapor Intrusion Guidance model, Eq. (5), appears likely to overpredict indoor air concentrations.

In order to evaluate the utility of these two models for screening the groundwater-to-indoor-air pathway for chlorinated solvents, model-predicted indoor air concentrations and attenuation factors (indoor air concentration/groundwater concen-

tration) were determined for each paired measurement in the database using site-specific values for soil type, building foundation type, and depth to groundwater. Figure 4 presents plots of measured versus predicted attenuation factors for the JEM Spreadsheet and the USEPA Vapor Intrusion Guidance model. As shown in Table 5, both models did a poor job of predicting the measured groundwater-to-indoor-air attenuation factors for the sites in the database. The JEM spreadsheet tended to underpredict the measured indoor air concentration, while the

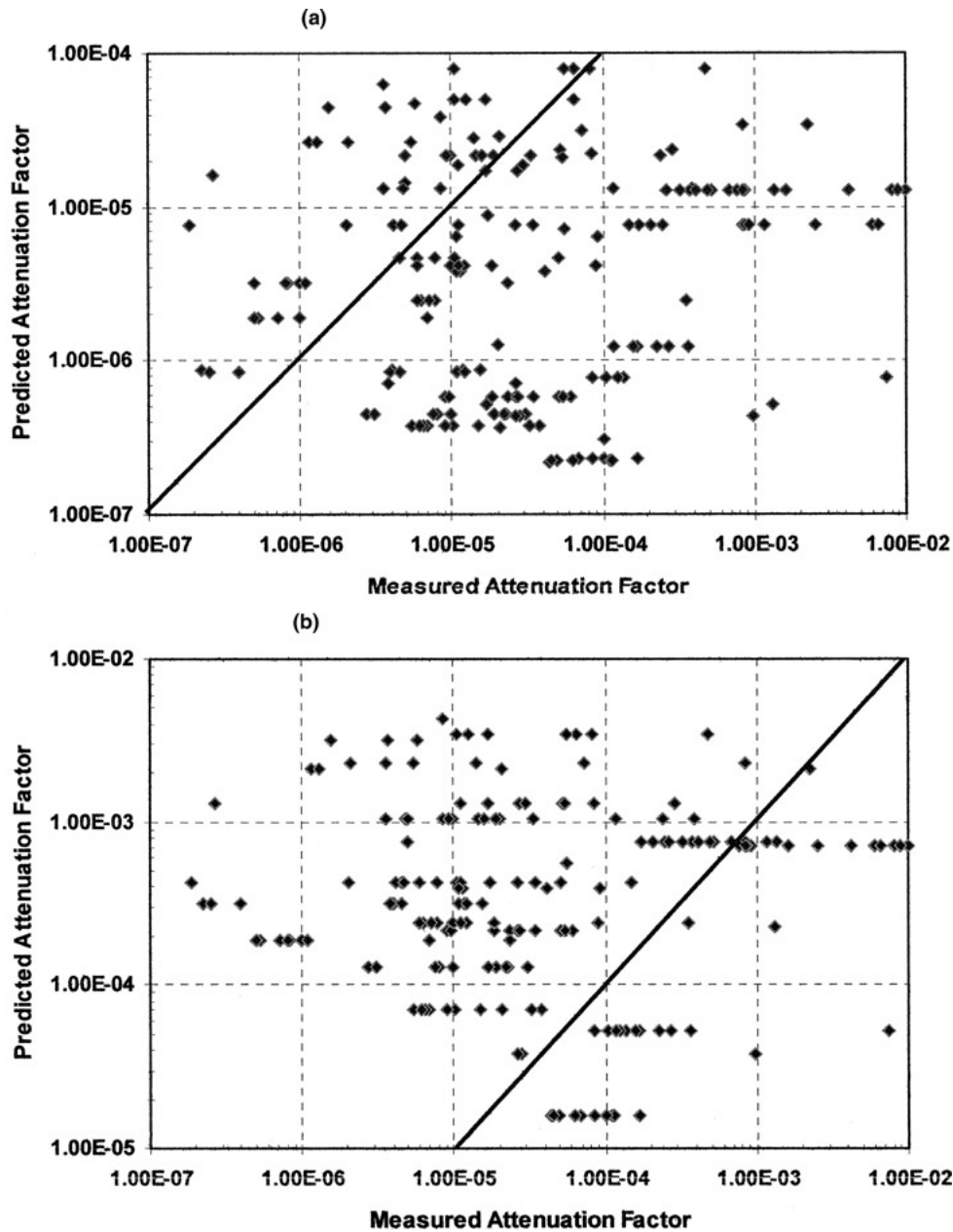


Figure 4. Measured versus predicted groundwater-to-indoor-air attenuation factors. Measured versus predicted groundwater-to-indoor-air attenuation factors for chlorinated solvent cases in the database. Predicted attenuation factors were determined from site-specific soil type and depth to groundwater using the (a) USEPA Johnson-Ettinger Spreadsheet Model (USEPA, 2000) and (b) the USEPA Vapor Intrusion Guidance Screening Model (USEPA, 2002). The line across each graph separates the points where the model overpredicts vapor intrusion (points above the line) from points where the model underpredicts vapor intrusion (points below the line).

Table 5. Comparison of measured and model-predicted attenuation factors for chlorinated solvents

Model	Number of over-predictions ^a	Number of under-predictions ^a	Average error versus measured attenuation factor ^b	Correlation coefficient ^c (R ²)
JEM spreadsheet	52	159	14×	0.00003
Vapor intrusion guidance	167	44	15×	0.00008

^aNumber of cases where the model overpredicts or underpredicts the measured attenuation factor.

^bThe average difference between the predicted and measured attenuation factors.

^cThe correlation coefficient between the measured and model-predicted attenuation factors.

USEPA Vapor Intrusion Guidance tended to overpredict the measured indoor air concentration. Although site-specific input values were used for the commonly measured model parameters, the use of default values for other parameters may have affected the model performance for chlorinated solvent sites. The currently available database does not provide sufficient information to support the use of site-specific values for all input parameters. Additional work would be required to evaluate model performance in cases where detailed site investigation data would support the use of all site-specific input parameters.

Background indoor air sources may explain some of the underpredictions for both models. Neither model accounts for the contribution of background sources to the measured indoor air concentration. As a result, the models would be expected to underpredict the measured attenuation factors at sites with significant background sources. Without knowing the local background indoor air concentration at a site, it is not possible to conclude that either model underpredicted the contribution from groundwater for these cases. However, for cases where the models overpredict indoor air concentrations, consideration of background contributions would only serve to increase the magnitude of the model error. Thus, it is clear that the USEPA Vapor Intrusion Guidance model significantly overpredicts the groundwater-to-indoor air impacts associated with chlorinated solvents for most sites in this database.

Conclusions

Failure to account for the background concentration of volatile chemicals in indoor air will result in false positive indications of indoor air impacts caused by groundwater. The background concentrations of volatile chemicals in indoor air that is not impacted by affected soil or groundwater often exceed risk-based limits applied at corrective action sites. As a result, the direct measurement of indoor air concentrations at corrective action sites will not provide an accurate indication of groundwater-to-indoor-air impacts.

Because background concentrations of volatile chemicals are highly variable from building to building, average background concentrations cannot be used to correct accurately for site-specific indoor air background. As an alternative, indoor air investigation methods are needed that can distinguish subsurface vapor intrusion from other sources of volatile chemicals. For example, real-time analyzers can be used to understand chemical concentration gradients within a building in order to facilitate the identification of the volatile chemical source. As an alternative, for sites with multiple volatile chemicals present in the subsurface, variations in measured attenuation factors between chemicals that cannot be explained by differences in fate and transport characteristics may indicate background indoor air contributions for specific chemicals. Finally, differences in stable isotope ratios (i.e., C-13 or Cl-37) between may prove useful for identifying the sources of some volatile chemicals found in indoor air.

After correcting for the contribution background sources, the average true attenuation factor for chlorinated solvents at a population of corrective action sites most likely to have groundwater-to-indoor-air impacts was 2.0×10^{-5} . For petroleum hydrocarbons, there was no indication that affected groundwater caused any increase in indoor air concentrations. Based on these findings, a groundwater-to-indoor-air attenuation factor of 2.0×10^{-5} would represent a conservative basis for development of groundwater screening values for chlorinated solvents. For petroleum hydrocarbons sites, no observable impacts would be anticipated at corrective action sites with deeper groundwater or less permeable soils compared to those sites included in this database.

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