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Examining the use of USEPA's Generic Attenuation Factor in determining groundwater screening levels for vapor intrusion

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Abstract

A value of 0.001 is recommended by the United States Environmental Protection Agency (USEPA) for its groundwater-to-indoor air Generic Attenuation Factor (GAFG), used in assessing potential vapor intrusion (VI) impacts to indoor air, given measured groundwater concentrations of volatile chemicals of concern (e.g., chlorinated solvents). The GAFG can, in turn, be used for developing groundwater screening levels for VI given target indoor air quality screening levels. In this study, we examine the validity and applicability of the GAFG both for predicting indoor air impacts and for determining groundwater screening levels. This is done using both analysis of published data and screening model calculations. Among the 774 total paired groundwater-indoor air measurements in the USEPA's VI database (which were used by that agency to generate the GAFG) we found that there are 427 pairs for which a single groundwater measurement or interpolated value was applied to multiple buildings. In one case, up to 73 buildings were associated with a single interpolated groundwater value and in another case up to 15 buildings were associated with a single groundwater measurement (i.e., that the indoor air contaminant concentrations in all of the associated buildings were influenced by the concentration determined at a single point). In more than 70% of the cases (390 of 536 paired measurements in which horizontal building-monitoring well distance was recorded) the monitoring wells were located more than 30 meters (and some up to over 200 meters) from the associated buildings. In a few cases, the measurements in the database even improbably implied that soil gas contaminant concentrations increased, rather than decreased, in an upward direction from a contaminant source to a foundation slab. Such observations indicate problematic source characterization within the dataset used to generate the GAFG, and some indicate the possibility of a significant influence of a preferential contaminant pathway. While the inherent value of the USEPA database itself is not being questioned here, the above facts raise the very real possibility that the recommended

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groundwater attenuation factors are being influenced by variables or conditions that have not thus far been fully accounted for. In addition, the predicted groundwater attenuation factors often fall far beyond the upper limits of predictions from mathematical models of VI, ranging from screening models to detailed computational fluid dynamic models. All these models are based on the same fundamental conceptual site model, involving a vadose zone vapor transport pathway starting at an underlying uniform groundwater source and leading to the foundation of a building of concern. According to the analysis presented here, we believe that for scenarios for which such a “traditional” VI pathway is appropriate, 10^{-4} is a more appropriately conservative generic groundwater to indoor air attenuation factor than is the EPA-recommended 10^{-3} . This is based both on the statistical analysis of USEPA’s VI database, as well as the traditional mathematical models of VI. This result has been validated by comparison with results from some well documented field studies.

Graphical Abstract

Introduction

For cases in which groundwater does not serve as a source of drinking water, vapor intrusion (VI) may be the major contaminant exposure pathway to volatile organic chemicals (VOCs) for residents living above VOC-contaminated groundwater. In such scenarios, a common objective during site investigations involves determining the critical groundwater contaminant concentration below which VI-associated adverse health risks can be considered negligible. To this end, the United States Environmental Protection Agency (USEPA) has recommended the use of a Generic Attenuation Factor for establishing such screening levels for VOCs in groundwater (USEPA 2015). This recommended screening level is calculated using a generic groundwater-to-indoor air attenuation factor (GAFG) of 0.001 (USEPA 2012, 2015) together with the appropriate USEPA Regional Screening Levels for indoor air contaminant concentration (USEPA 2017). This calculation also requires using the appropriate Henry’s law coefficient for the VOC of concern, which links the aqueous phase concentration to the vapor concentration at the groundwater source. This method for establishing the allowable groundwater contaminant concentration is important in many site investigations and a comprehensive understanding of its development is required for assuring its appropriate application.

As VI risk screening tools, Generic Attenuation Factors were originally proposed by USEPA (2002) based on statistical analysis of USEPA's VI database. Assembling this database was an important first step in beginning to develop a more rigorous understanding of the VI phenomenon. The statistical examination of this database, including its use for derivation of generic attenuation factors, was an important step in providing guidance in site investigation. Since the first publication of the Generic Attenuation Factor, there have been several studies examining their applicability and limitations. McHugh et al. (2007) used a Monte Carlo simulation to examine the GAFG and found that spatial variability in VOC concentrations can greatly affect the upper-bound of the attenuation factor. Brewer et al. (2014) reviewed the particular Generic Attenuation Factor for subslab-to-indoor air attenuation developed by USEPA and concluded that heterogeneity in subsurface vapor plumes leads to uncertainty regarding the representativeness of limited subslab data. They recommended development of generic (and site-specific) attenuation factors based on estimated subslab vapor entry rates, indoor air exchange rates and specific to different climate regions. Song et al. (2011) evaluated measurements in the USEPA's VI database and concluded that a large number of the empirical attenuation factors were likely to have been significantly affected by background sources. This study concluded that greater attenuation is expected if potential background contaminant levels in indoor air are accounted for. Moreover, the USEPA itself published a report (USEPA 2012) in which a source strength screen was used to minimize the influence of background sources, which showed that background sources could influence the observed apparent attenuation. Ultimately, however, the same GAFG value (0.001) as that proposed in the earlier draft VI guidance (USEPA 2002) was again recommended in the final VI guidance (USEPA 2015).

In this article, we first review the concept of a Generic Attenuation Factor and examine the implicit conceptual site model upon which it has been based. Then we examine the possible scenarios involved in the determination of the GAFG, keeping in mind that the generic attenuation factor focuses on the entire pathway from groundwater source to indoor air, and then compare such scenarios with the models used in developing a screening level for groundwater. Based on this comparison, we identify the limitations of the historically recommended GAFG for determining groundwater screening levels and validate our findings using data from a well-documented field study. Finally, based on these findings we make new recommendations for the determination of VI-relevant screening levels for VOCs in groundwater.

USEPA's Generic Attenuation Factor

Use of a value of 0.001 as a default GAFG was originally proposed in the USEPA's 2002 draft VI guidance and this value was again recommended in USEPA's final VI guidance released in 2015. In this study we shall focus on the basis for the 2015 recommendation. As described in USEPA's VI database report (2012), the database from which the agency developed its GAFG recommendation consists of measurements of contaminant concentrations in indoor air, subslab soil gas, exterior soil gas and groundwater. The database contains 2,929 paired observations, including paired groundwater and indoor air measurements (1,021), paired exterior soil gas (235) and indoor air measurements, paired subslab soil gas and indoor air measurements (1,582) and paired crawlspace and indoor air

measurements (91). Approximately 97% of the collected data involved chlorinated chemicals and the other 3% were petroleum hydrocarbons. Site information such as geologic settings, contaminant types and contaminant history was recorded in the database. It also should be noted that most buildings recorded in the database are residential structures with basements.

In order to obtain a value for the GAFG, the distribution of observed groundwater-to-indoor air contaminant concentration attenuation factors was examined following the application of a source strength filter to reduce the influence of indoor background sources (reducing the number of accepted paired observation from 1,021 to 774). Among the 774 paired groundwater and indoor air measurements (with groundwater source vapor concentrations greater than 1000 times the corresponding background concentration) the GAFG was selected as the 95th percentile value from the distribution of calculated attenuation factors (USEPA 2012). In other words, 95% of all real cases fell at or below this recommended GAFG value, and the USEPA recommended the use of this value as a conservative screening criterion when there are measured groundwater concentration data (USEPA 2015).

The consequence of incomplete source characterization in USEPA's VI database

Though the USEPA (2012) applied a source strength filter to reduce the influence of background sources on the GAFG, the recommended value still could have been affected by other factors. These include the possible existence in some cases of preferential pathways and in other cases, inaccurate groundwater source characterization (e.g., due to contaminant concentration heterogeneity in the groundwater), as illustrated in Figure 1. For example, due to the difficulty in measuring groundwater contaminant concentrations directly beneath a structure of concern, monitoring wells are normally located at some distance away from the building. In the USEPA's VI database (USEPA 2012a), the data from a single monitoring well were also often assumed to characterize the source for several nearby buildings, based on an assumption that the source plume was of very large size and of uniform concentration. However, such an assumption is open to question, as both lateral and vertical contaminant concentration gradients may be present. It should be noted that there might be yet other factors such as indoor sources and unidentified vadose-zone sources that also could cause bias in the database, and how these factors were addressed, if at all, in USEPA's screening process is unknown.

Considering the 774 paired groundwater and indoor air measurements used by USEPA for the determination of the GAFG (i.e. after application of the 1,000X "background" filter for CHCs in Residences Screen), Table 1 shows the count of independent indoor contaminant concentration measurements that correspond to the same groundwater concentration value. To understand this table, note that in one instance (at the Redfields, CO site), 73 data points for indoor air (i.e., different buildings) were linked to a single interpolated groundwater concentration value. In another instance (at West Side Corporation), 15 indoor air concentration measurements (i.e., different buildings) were linked to a datum from a single monitoring well. At the other end of the scale, 347 monitoring well results (186 interpolated

values and 161 values from a single monitoring well) were linked to only 1 indoor air concentration measurement. This table indicates that there are 427 paired sets of measurements (213 interpolated values and 214 values from a single monitoring well) for which the same groundwater concentration was used for analyzing the groundwater to indoor air attenuation in multiple buildings. This latter figure (214) represents about two sevenths of the paired measurements (774) used to generate the GAFG, and raises an obvious concern about how it might be weighting the analysis. Without further evidence to justify the assumption of homogeneity of the groundwater source plume in these cases, it is reasonable to raise a question regarding whether the single groundwater sample can accurately represent the source strength that applies to multiple houses in a wide area.

Even for cases with one-to-one groundwater-indoor paired measurements, there are many reported instances (Guo et al. 2015; Luo et al. 2009) in which field data warn against relying too strongly on a single monitoring well concentration and there is no reason to believe that the data in the USEPA database were immune to such issues. One aspect to consider carefully is the monitoring well to house distance. Figure 2 shows the distribution of horizontal distances between monitoring well and the respective assigned building for 536 paired measurements among the 774 sets used to generate the GAFG. The database also includes horizontal distances for other data points, i.e., those with interpolated groundwater values. This figure shows that in more than 70% of cases (390 of 536) the monitoring wells were located more than 30 meters away from the corresponding building. In one case (at the Redfields site, Residence 273), the groundwater data were obtained from a monitoring well over 200 meters from its paired building. It is probable that site investigators would have always reported the data from the closest monitoring well as the source, regardless of distance from the building, which implies that there were no closer monitoring well data. Such source-building separation distances, however, exceed the generally recommended 30 m lateral inclusion zone proposed by USEPA (2002, 2015). This distance is based upon a series of studies showing that soil gas concentration decays exponentially with lateral diffusion distance from the edge of a source, even in the absence of aerobic biodegradation (Lowell and Eklund 2004; Yao et al. 2013). This 30 m lateral distance represents the distance at which the influence of a groundwater source would be negligible, in terms of a VI impact on a building that far removed. A significant fraction of the points in the USEPA database are therefore outside of what is considered reliable for establishing a relevant subsurface source strength and included based only on the assumption of a uniform source. This is not to say that we believe that a large fraction of the groundwater concentration points happen to represent an edge of a plume, but only that the distances are great enough that questions do need to be raised regarding the applicability of the measured groundwater concentrations.

In practice, investigators often employ interpolation of interpolation of measurements from multiple monitoring wells to minimize the variation caused by source heterogeneity. Figure 3 compares the distribution of groundwater attenuation factors obtained using single interpolated groundwater values and those obtained using an actual single groundwater measurement to the distribution of all 774 attenuation factors used by USEPA to generate their GAFG. The comparison indicates that the 95th percentile value (5.5×10^{-4}) of the distribution of (399) calculated attenuation factors using interpolated groundwater values is

about one third of an order of magnitude less than the corresponding value (0.0016) of the (375) attenuation factors based on actual single groundwater measurements and the corresponding value (0.0012) using the entire database after source strength screen (774 paired measurements). This shows that interpolating groundwater values can slightly reduce the variability in attenuation factor compared to simply using a nearest groundwater sample value in the USEPA database. However, due to the potential source heterogeneity along the distance from building to monitoring well, particularly at the great separation distances shown in Figure 2, the uncertainty in attenuation factor due to inappropriate source characterization is not necessarily minimized by employing the paired measurements based upon interpolated groundwater values. Actually, the USEPA database report itself warned about the possible introduction of high or low bias in contaminant concentration if a nearby or interpolated value does not accurately represent conditions under the respective building (USEPA 2012).

Analysis of groundwater source to subslab attenuation data provide another reason for caution in assigning distant monitoring well data to a particular building. Among six subslab contaminant concentration measurements paired with a single groundwater source, the observed variations spanned up to more than four orders of magnitude (i.e., 0.26 $\mu\text{g}/\text{m}^3$ for building UA19 to 10,000 $\mu\text{g}/\text{m}^3$ for building UA03 at the LAFB site), suggesting the potential presence of significant source heterogeneity. Considering other data as shown in Table 2, the vapors at a few sites would have had to migrate through the vadose zone or building foundation slab in a direction opposite a contaminant concentration gradient for the VI pathway to be complete. Such observations of course violate established physical laws of chemical transport, as must be assumed in a conceptual site model based on a traditional VI pathway over a homogenous vapor source. In other words, such unreasonable observations must be associated with inappropriate source characterization, due to significant heterogeneity of a groundwater source plume or failure to identify all sources.

There is no guarantee that the groundwater concentration beneath any building would be the same as that measured in monitoring well(s) located tens of meters from the building (and this leaves aside the issue of the possibility of vertical contaminant concentration gradients in the groundwater). The real source vapor concentration directly beneath the building may be either higher or lower than the measurement from a nearby monitoring well, which manifests itself in uncertainty and variation of the measured groundwater-to-subslab and thus groundwater-to-indoor air concentration attenuation factors. It should be noted Table 2 shows just a few examples that are so obvious that there must have been inaccurate source characterization, for which the possibility of the presence of preferential pathways (see below) or other background sources must still also be considered. It is unknown if this problem might have also impacted other data in the USEPA database.

Potential influences of preferential pathways in USEPA's VI database

Other than inappropriate source characterization, preferential VI pathways could be a second and potentially equally important factor that can affect the interpretation of paired source-to-indoor air concentration data. Even if a vapor source is correctly characterized, a preferential pathway (a path other than diffusion through the vadose zone soil) might also play a role in

determining the subslab and indoor air concentration. Preferential pathways could account for cases showing little attenuation or even an increase in soil gas contaminant concentration with the decrease of depth below the ground surface. The presence of some paired measurements in the database which cannot be explained in a traditional conceptual site model (absent factors such as preferential pathways or improperly characterized sources) should not be included in the generation of the generic attenuation factor. For example, the USEPA's VI database (USEPA 2012) for the SCM - Cortlandville site (building 712006-H-048) reports a groundwater-to-indoor air attenuation factor of 0.07, while the corresponding groundwater concentration is 0.1 ug/L. Such a limited extent of attenuation in the presence of a very weak source is physically difficult to justify if the attenuation is caused by the usual diffusion of the contaminant vapor through the capillary and vadose zones when properly accounted for (Atteia and Hohener 2010; McCarthy and Johnson 1993; Shen et al. 2013; Yao et al. 2017b). The presence of subslab concentrations lower than corresponding indoor air concentrations, shown in Table 2, also indicates that there is more to the particular situation than the "traditional" VI pathway and likely flags the existence of an alternative VI pathway or other interior sources. In a now widely cited study, Guo et al. (2015) found that a subsurface land drain served as a preferential pathway by which contaminants could directly reach the subslab zone without the expected concentration attenuation associated with diffusion of contaminant through soil. Riis et al. (2010) identified sewer lines as preferential VI pathways and found that the sewer gas could impact indoor air contaminant concentrations in houses associated with the drain network. In another case study by Pennell et al. (2013) vapors from a sewer system increased an indoor air contaminant concentration by about 2 orders of magnitude over what was otherwise expected. In each case, a sewer line made a more significant contribution to the indoor air concentration than did the traditional VI pathway.

McHugh et al. (2017) reviewed many field reports and concluded that the measurements of sewer gas should be included as part of a routine vapor intrusion investigation. In particular, sewer lines that are submerged in contaminated groundwater can be a significant source of VOCs. In another study, McHugh et al. (2012) identified a telephone utility tunnel as a preferential pathway, showing that it is not necessarily sewer lines alone that can serve as preferential pathways. Thus, it is reasonable to suspect that measured subslab and/or indoor air concentrations can be affected by preferential pathways such as land drains, sewer lines and utility tunnels and this reality existed at the time of selection of data for inclusion in USEPA's VI database. Unfortunately, the widespread nature of such effects was not yet fully appreciated at the time the data for the database were collected and thus such information was not captured in the database. As a result, the upper limit of the distribution of the observed groundwater-to-indoor air concentration attenuation factors could well be significantly skewed towards the high side (i.e., excessively conservative), even in the absence of the source heterogeneity issue already discussed.

In summary, the variability of measurements in the USEPA's VI database could be partially caused by inaccurate source characterization and/or by the potential presence of preferential pathways that are not typically present for every building. Thus, the recommended GAFG value (0.001), which was obtained as the 95% percentile of the measured groundwater-to-indoor air attenuation factor, inherently includes the influence of such factors. This raises the

possibility that if the variability with these factors could be eliminated or reduced, the recommended GAFG value could be much less than 0.001. For example, interpolation of measurements from multiple monitoring wells could reduce the variability compared to using a single value from the a single nearest well. It was already seen in Figure 3 that this provided a lower GAFG value (0.00055), though if the nearest monitoring well is still tens of meters away from the concerned building there could be a high degree of uncertainty in the correct value of source concentration.

In the determination of groundwater screening level, little consideration related to source heterogeneity or the presence of a typical preferential pathways is included. The application of the recommended GAFG value (0.001) can cause unnecessary further investigation, mitigation or remediation. Therefore, to develop generally useful and realistic GAFG value, an improved method is required. This should be based on a self-consistent conceptual site model that presumes appropriate groundwater source characterization and the absence of preferential pathways.

The use of a VI screening model

Screening models, such as the Johnson-Ettinger model (JEM) (Johnson and Ettinger 1991), were formerly recommended by USEPA to calculate site-specific groundwater screening level (USEPA 2002 and 2015). Such an approach has also been employed by ASTM (2015) to calculate groundwater risk-based corrective levels. The EPA-JEM, a modified version of the Johnson-Ettinger model developed by USEPA, treats the capillary zone and unsaturated vadose zone soil as two separate, but uniform, layers (USEPA 2017b). The resulting model predicts attenuation factors that are up to two orders of magnitude higher (i.e., more conservative) than those predicted by more robust, three-dimensional numerical simulations and a corresponding two-dimensional analytical model (CVI2D) (Yao et al. 2017a). The latter model employs a continuous soil moisture content profile calculated using the van Genuchten equation (van Genuchten 1980), and this same approach is now routinely used in most three dimensional VI computational models. The use of an averaged “discrete” moisture content value, as employed in the EPA-JEM, underestimates the very significant contaminant vapor concentration attenuation that takes place during the transport of vapor through soil containing very high moisture. This is particularly critical in correctly predicting the attenuation of the vapor concentration through the vadose zone.

An equation was included in the spreadsheet implementation of CVI2D (CVI2D toolkit) to estimate the limiting concentrations in indoor air with respect to the emission rate from the groundwater vapor source. This equation (1), which was actually developed based on the JEM by approximating the subslab concentration as zero, simply states that the maximum rate of diffusive entry of contaminant from a groundwater source into a building equals the rate at which the contaminant is purged from the building by air exchange. This equation is also the steady state solution for the VI evaluation presented by Little et al. (1992). This analysis neglects any resistance of the foundation to entry of the contaminant, and so is the most conservative assumption that can be made regarding transport of the contaminant into the building.

$$\frac{D_{e,t} A_B c_s}{L_T} = c_{in} V_b A_e \quad (1)$$

$$\text{so } \frac{c_{in}}{c_s} = \frac{D_{e,t} A_B}{L_T V_b A_e} \quad (2)$$

where c_{in} and c_s is the indoor air and corresponding groundwater vapor concentration, respectively, L_T is the vertical separation distance between building foundation and groundwater source, V_b is the building volume, A_e is the indoor air exchange rate, A_B is the building foundation area. Thus, the entire mass of upward diffusing VOC beneath the building footprint enters the building in an unimpeded manner and impacts indoor air. The parameter $D_{e,t}$ is the total effective diffusivity and can be calculated from the following equation (Johnson and Ettinger 1991):

$$D_{e,t} = \frac{L_T}{\int_0^{L_T} \frac{1}{D_e(z)} dz} \quad (3)$$

where z is the vertical coordinate ($z = 0$ at the water table). The parameter $D_e(z)$ can be estimated using Millington and Quirk (1961) equation:

$$D_e(z) = D_g \frac{(\theta_t(z) - \theta_w(z))^{3.33}}{\theta_t(z)^2} + \frac{D_w \theta_w(z)^{3.33}}{H \theta_t(z)^2} \quad (4)$$

where D_g and D_w are the diffusivity of contaminant in gas and water phase, respectively, H is the Henry's law constant, $\theta_t(z)$ and $\theta_w(z)$ are the total and water-filled porosity in soil, respectively. Note that diffusivity through gas filled porosity takes place at a much faster rate as the diffusion coefficient of contaminant through gas (air) is 2–3 orders of magnitude higher than the diffusion coefficient of contaminant in water. In cases involving only one soil layer, $\theta_t(z) = \theta_t$ is a constant and $\theta_w(z)$ could be estimated using the van Genuchten (1980) equation:

$$\frac{\theta_w(z) - \theta_r}{\theta_t - \theta_r} = \left(1 + (\alpha_{vg} * z)^N\right)^{1/N - 1} \quad (5)$$

where α_{vg} is related to the inverse of the air entry suction [L^{-1}]; θ_r is the residual soil water content, dimensionless; N is the van Genuchten curve shape parameter. Note that the above equation explains why the capillary zone above the water table cannot be neglected in

transport analysis. The resistance of the portion which is primarily water filled is a very significant portion of the total diffusion resistance of the whole vadose zone. For steady state diffusion the overall rate of contaminant diffusion through both moisture-saturated soil and the unsaturated soil above it must be equal, so the fact that the diffusion coefficient is very low in the saturated soil means that the contaminant concentration gradient (i.e., attenuation) in that zone must also be large.

Consider now a sample calculation based upon the above model. Assume the contaminant is trichloroethylene (TCE), the soil type is sand and that there is a very shallow groundwater source such that $L_T = 0.5 \text{ m}$. Assume a typical $10\text{m} \times 10 \text{ m}$ house footprint with a 2.44 m height such that $V_b = 244 \text{ m}^3$. Further assume that the air exchange rate (A_e) is at the conservative end of the range recommended by the USEPA (2002, 2011) $A_e = 2.8 \times 10^{-5} \text{ s}^{-1} = 0.1 \text{ h}^{-1}$ and that we allow for not only the slab but the foundation walls to communicate vapor with soil (Johnson and Ettinger 1991), such that $A_B = 180 \text{ m}^2$. Applying equations (2) through (5) yields:

$$\begin{cases} D_{e,t} \approx 1.8 \times 10^{-9} \text{ m}^2/\text{s} \\ \frac{c_{in}}{c_s} \approx 10^{-4} \end{cases} \quad (6a) \quad (6b)$$

Unless the soil beneath the building is observed to be more porous than the classical sand type, or the area of foundation is larger than 180 m^2 , or the vertical building-groundwater separation distance is less than 0.5 m , or the volume of the building is less than 244 m^3 , or the indoor air exchange rate is less than 0.1 h^{-1} , as shown in Table 3, this figure (10^{-4}) basically represents the physical upper limit of groundwater attenuation factor of TCE based on a traditional VI pathway. In other words, the USEPA GAFG value of 10^{-3} is unrealistically high, implying greater risk than actually exists. The assumed values in our analysis were chosen to be very conservative and under a typical VI site scenario highly unrealistic. The USEPA recommended value of 0.001 appears to fall even further outside of the physically realistic realm. The USEPA's GAFG value cannot be obtained by any other models that employ more realistic assumptions regarding soil moisture profiles (and the important role of diffusive resistance of the capillary zone) to capture the transport of vapor through the soil (Atteia and Hohener 2010; McCarthy and Johnson 1993; Shen et al. 2013; Yao et al. 2017b). In fact, even in the USEPA database there are ten sites where the distributions of groundwater attenuation factors are below 0.001 (USEPA 2012). This simple limiting calculation provides additional evidence that the influences of preferential pathways or inaccurate source characterization were likely skewing the results in the database towards the unrealistically high USEPA recommended value of GAFG.

Validation of the new screening levels with field data

Figure 4 shows the comparison between the bounding attenuation factor estimate presented above using equations (2) through (5) and measurements from the CDOT-MTL Denver Site (Kurz 2000; Foster et al. 2004; Johnson et al. 2002, 2009), where an intensive study was performed involving collections of groundwater, soil gas, and indoor air samples.

Characterization of the dissolved ground water plume was based on a large number of data points and considered reasonably reliable. A review of the data indicates that the screening levels proposed in this study correspond with the upper (most conservative) limit of observed groundwater attenuation factors reasonably well, while the USEPA's GAFG of 0.001 overestimates the risk by at least one order of magnitude. It should be noted that the possible influences of preferential pathways were not addressed in that study. Incorporation of site-specific parameters for individual building in the screening models would provide a more accurate prediction.

Overestimation of potential indoor air impacts based on the USEPA's GAFG (0.001) was further examined using data from the well-documented field investigation at a residential house extensively studied by Arizona State University (Guo et al. 2015; Holton et al. 2013). In that field site, multiple groundwater samples were taken directly beneath an impacted building foundation to minimize any effects of lateral separation between monitoring well and the building. Figure 5 shows the comparison between measured indoor air contaminant concentrations and the predictions of three different screening models or criteria. One criterion was the USEPA GAFG value of 0.001. The second was the conservative screening value (10^{-4}) obtained using equations (2) through (5) and the third was the result of a calculation using the two-dimensional screening model (CVI2D). The parameters assumed in the CVI2D calculation are shown in Table 3.

In Phase "a" of the study (day 120 to 740), an active preferential pathway (the land drain) was present and the house was under natural indoor pressure conditions; in Phase "b" (day 780 to 1045), indoor depressurization was applied using the controlled pressure method (Guo et al. 2015; McHugh et al. 2012) with the land drain open and acting as an active preferential pathway; in Phase "c" (day 1071 to 1157), the preferential pathway was closed and the building remained depressurized; in section "d" (1157 to 1300), both the preferential pathway and the indoor depressurization system were turned off.

In Phases "a" and "b", with an active preferential pathway, the predicted potential indoor air concentration using USEPA's GAFG (0.001) was in good agreement with the upper limit of measured indoor air concentrations. This was true in both the presence and absence of indoor depressurization associated with the application of the controlled pressure method, while the "typical VI scenario" screening level of 10^{-4} and CVI2D underestimated the maximum indoor air contaminant concentrations by around 1 and 2 orders of magnitude, respectively. Note, however, that there was considerable variation associated with the influence of the preferential pathway, and that during the majority of the time, even with the pathway available, the indoor air concentrations did not exceed the estimates of the two model-based estimation methods. These results do suggest that, despite its general drawbacks, the USEPA GAFG of 0.001 is reasonably protective in a scenario involving a preferential VI pathway (i.e., a direct pathway from groundwater to indoor air in absence of a constraining capillary fringe and vadose zone). Soil gas profiling at this site suggests significant groundwater source heterogeneity in the vicinity of the house, but in this case the behavior was unquestionably dominated by the preferential pathway.

In Phases “c” and “d” of the study, when the preferential pathway was not present, the CVI2D predictions were generally above the upper limit of observations, while predictions using a screening level of 10^{-4} (equations 2–5) and 0.001 (GAFG) overestimate the indoor air concentrations by 1 and 2 orders of magnitude, respectively. These results confirm that screening models are better predictors of indoor air concentrations than the USEPA’s GAFG (0.001) in situations where preferential pathways are absent. The predictions using equations (2) – (5) are approximately an order of magnitude more conservative than the results of the more realistic CVI2D model.

Implications

This article has reviewed the use of USEPA’s VI database to make an estimate of GAFG. It examined scenarios involved in calculating groundwater attenuation factors and it has compared the recommended GAFG of 0.001 derived by the USEPA from its VI database with alternative more reliable methods for making estimates of vapor intrusion risk in “typical” VI scenarios.

We have found that the different approaches yield estimates of GAFG that are very different. Part of this may be because the purpose of the USEPA’s recommended GAFG is to offer a conservative value of attenuation in the absence of any gas-phase site investigation data. But this approach becomes less defensible when more is known about a potential site, particularly when good groundwater characterization is available and the existence of preferential pathways is not suspected. As a result of this analysis, we conclude that the GAFG value of 0.001 is not generally appropriate for use in determining groundwater screening. Moreover, it should be noted that though the determination of the current GAFG value of 0.001 was quite likely affected by inappropriate source characterization and preferential pathways, based on available studies it is not reasonable to conclude that 0.001 could be used to cover cases involving inaccurate source characterization or potential pathways, both of which may induce attenuation from groundwater to indoor air even lower than 0.001. On the other hand, VI screening models based upon well-established vadose zone vapor transport equations are more appropriate for use in the calculation of groundwater screening levels for sites where preferential pathways are not present, as they represent the conceptual site model that is usually presumed in any case. Such models and associated screening levels should, of course, continue to be verified in the field with site-specific groundwater, soil gas and, as appropriate, indoor air data.

In conclusion, if the groundwater source can be correctly delineated (in both horizontal and vertical directions) and the absence of preferential pathways can be confirmed, the use of VI screening models based upon vadose zone transport is more appropriate than use of the GAFG derived from the USEPA’s VI database. Poor agreement between indoor air concentrations and screening model calculations might indicate the presence of significant groundwater source heterogeneity and/or preferential pathways (Guo et al. 2015) for which additional characterization is warranted. Ultimately, this might lead to simpler risk management via methods such as shutting off of an identified preferential pathway as an alternative to aggressive and oftentimes ineffective groundwater remediation intervention. Finally, it is worth noted that the type of VOC does not significantly affect the observed and

modeled attenuation factors (excluding the effect of biodegradation), and that the conclusions drawn apply to all VOCs, and not just those discussed in the cited studies.

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FIGURE 1. Scenarios involving source heterogeneity or preferential pathways that may influence indoor air quality (Guo et al. 2015).

FIGURE 2.

Frequency plot showing the distribution of lateral separation distances between groundwater monitoring well(s) and assigned building (536 in total, including those with interpolated groundwater values) (USEPA 2012a).

FIGURE 3.

Frequency plot showing the difference of the groundwater attenuation factor distributions among the cases with interpolated groundwater measurements (399 paired), those using single groundwater measurement (375 paired, without interpolated groundwater values), and all paired datasets used to generate 0.001 (774 paired in total). (USEPA 2012a).

FIGURE 4.

Comparison of groundwater attenuation factors between screening values and measurements from the CDOT-MTL Denver Site (Johnson et al. 2009).

FIGURE 5.

Comparison of screening model calculations, GAFG and field measurements from ASU house (Guo et al. 2015) (points: observations; lines: predictions).

Counts of paired measurements with the same groundwater data (the number in the circle refers to the number of interpolated groundwater values) (USEPA 2017a)

TABLE 1

Number of indoor air measurements paired with a single groundwater measurement															
1	2	3	4	5	6	8	9	10	12	14	15	18	22	34	73
Number of unique groundwater measurements paired with multiple indoor air measurements															
347 (186)	28 (12)	13 (2)	5 (1)	5	10 (3)	1	1	1	2	1 (1)	1	1 (1)	1 (1)	1 (1)	1 (1)
Count															
347 (186)	56 (24)	39 (6)	20 (4)	25	60 (18)	8	9	10	24	14 (14)	15	18 (18)	22 (22)	34 (34)	73 (73)
774															

Note: Take the 2nd column for example: the number in the 1st line, 2, means that the same groundwater data were used as the source vapor concentration for 2 indoor measurements; the values in the 2nd line, 28 (12), indicate that there were 28 different groundwater data which were used as the source for 2 indoor measurements and among the 28 groundwater measurements, 12 are based on interpolation of multiple groundwater measurements (i.e., the rest, 16, groundwater data are based on a single groundwater sample); the values in the 3rd line, 56 (24), indicate that there were 56 (i.e., 56 = 2 × 28) paired measurements where the same groundwater data were used for 2 indoor measurements and 24 (i.e., 24 = 2 × 12) paired measurements where the interpolated groundwater data were used for 2 indoor measurements (i.e., the rest, 32, paired measurements are associated with a single groundwater measurement).

TABLE 2

Paired measurements with subslab concentration higher than that of groundwater source or indoor air concentration higher than subslab concentration (USEPA 2017a)

Site Name	Chemical	Building Name	c_s (ug/m ³)	c_{ss} (ug/m ³)	c_{in} (ug/m ³)
Hopewell Precision Site	Trichloroethylene	16	1639	3496	13
SCM - Cortlandville		712006-H-018	3030	0.86	5
		712006-H-015	3247	0.86	1
Harcros/Tri State	Tetrachloroethylene	1748 Sante Fe	5473	7458	20
West Side Corporation		241026-H-071	81843	750	1700

Note: c_s , c_{ss} and c_m represent the corresponding groundwater vapor concentration, subslab concentration and indoor air concentration, respectively.

TABLE 3

Parameter used in screening model calculations (Guo et al. 2015; Holton et al. 2013; Johnson et al. 2009; USEPA 2002)

Parameter	Symbol	Unit	Figures 5 and 7	Figures 6	Figure 7
Foundation airflow rate	Q_s	L/min			10
Volume of the enclosed space	V_b	m^3	244	244	177
Air exchange rate	A_e	h^{-1}	0.1	0.1	0.5
Foundation depth	d_f	m	2	2	0.3
Source depth	d_s	m	2.5	2.5	2.8
Soil type			Sand	Sand	Loamy Sand ^a (deep; 2.8–0.9 m) and Sand (shallow; 0.9–0 m)
van Genuchten parameters	α	m^{-1}	3.524	3.524	Loamy sand (3.475) sand (3.524)
	N		3.177	3.177	Loamy sand (1.746) sand (3.177)
Soil total water content	θ_t		0.375	0.375	Loamy sand (0.390) sand (0.375)
Soil residual water content	θ_r		0.053	0.053	Loamy sand (0.049) sand (0.053)
Soil permeability	k	m^2	1.02E-11	1.02E-11	Loamy sand (1.67E-12) sand (1.02E-11)
Foundation footprint length	L_B	m			11.4
Foundation footprint width	W_B	m			7.4
Foundation crack thickness	d_{ck}	m			0.1
Foundation crack width	w_{ck}	m			0.005
Partition coefficient	K_{ow}		0.403	1.07 0.703 0.403	
Contaminant			TCE	1,1-DCE 1,1,1-TCA TCE	
Source vapor concentration	C_s	ug/L	20.15		
Diffusion coefficient in air	D_g	m^2/s	6.9E-6	9E-6 7.8E-6 6.9E-6	
Diffusion coefficient in water	D_w	m^2/s	1E-9	1.04E-9 8.8E-10 1E-9	
Total effective diffusion coefficient	D^{eff}_T	m^2/s		8.15E-10 1E-9 1.79E-9	8.9E-9
Groundwater attenuation coefficient	α		10 ⁻⁴	4.8×10 ⁻⁵ 5.9×10 ⁻⁵ 10 ⁻⁴	1.4×10 ⁻⁵

Note:

^aLoamy sand was chosen based on the agreement between measured effective diffusivity and the calculated value based on Millington and Quirk (1961) equation and Van Genuchten (1980) equation.

TCE: Trichloroethylene; 1,1-DCE: 1,1-Dichloroethene; 1,1,1-TCA: 1,1,1-Trichloroethane