Assessing Soil Vapor Extraction Remediation Performance and Closure: A Review - 12188

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ABSTRACT

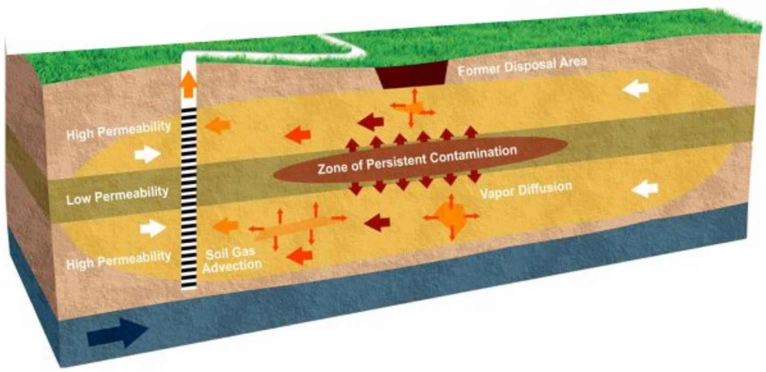
Soil vapor extraction (SVE) is a baseline remediation approach for volatile contaminants. While SVE is generally effective for removal of contaminants from higher permeability portions of the vadose zone, contamination in low-permeability zones can persist due to mass transfer processes that limit the removal effectiveness. Thus, a diminishing rate of contaminant extraction over time is typically observed, yet contamination may remain in low-permeability zones. Under these conditions, SVE performance needs to be evaluated to determine whether the system should be optimized, terminated, or transitioned to another technology to replace or augment SVE. Methodologies have been developed to quantify SVE performance over time and to evaluate the impact of persistent vadose zone contamination sources on groundwater quality. Recently, these methods have applied mass flux/discharge concepts to quantify contaminant source strength. Methods include field measurement techniques using the SVE system to quantify source strength and predictive analyses with analytical and numerical models to evaluate the impact of the contaminant source on groundwater.

INTRODUCTION

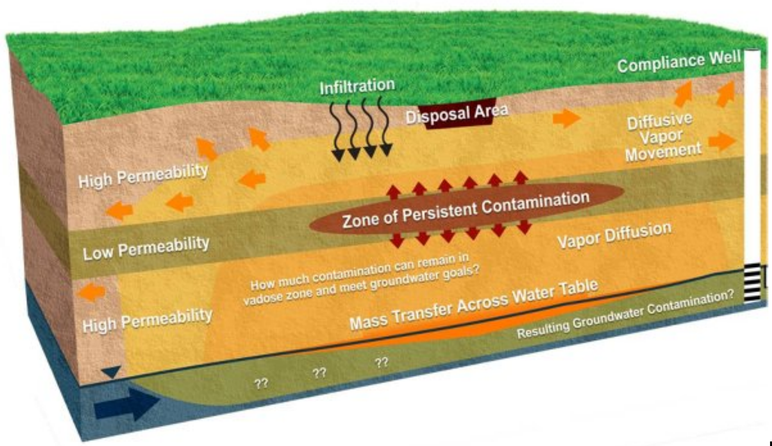
DOE-EM's Office of Technology Innovation and Development (EM-30) is investing in applied research to assist site operations by identifying scientifically defensible endstates for environmental remediation of volatile organic contaminants in the vadose zone. A key part of identifying an appropriate endstate is having a robust understanding of how contaminants in the vadose zone will impact groundwater, the primary pathway to potential receptors at DOE sites.

Soil vapor extraction (SVE) is a baseline remediation approach applied at many sites to remove volatile contaminants from the vadose zone. This process typically removes contamination from portions of the vadose zone readily accessible to induced soil gas movement and where vapor diffusion distances are small and not impeded by high moisture content. Some portions of the vadose zone are more slowly remediated due to low induced soil gas flow, large vapor diffusion distances, and/or presence of non-aqueous phase liquid contamination (Figure 1a). While SVE generally removes contaminants from most parts of the vadose zone, at some sites, contamination can persist in regions of the subsurface where properties and processes mentioned above decrease contaminant removal efficiency. Under these conditions, SVE performance needs to be evaluated to determine whether the system should be optimized, terminated, or transitioned to another approach. In many cases, the SVE system performance must be evaluated in the context of the groundwater remediation goals at the site (Figure 1b).

At some sites, vadose zone contamination may be initially present at low levels and the site must determine whether active, passive, or no remediation is needed.



a)



b)

Figure 1. Conceptual depictions of a) contaminant extraction during SVE operations with zones that release contaminants slower than other zones and b) post-SVE conditions and associated contaminant transport relevant to assessing the impact to groundwater.

Guidance documents are available from EPA, USACE, and AFCEE that address SVE design, operation, optimization and closure [1, 2, 3]. The AFCEE guidance [1] provides details for actions and considerations related to SVE system optimization, but has limited information related to approaches for SVE closure and meeting remediation goals. The existing EPA and USACE guidance established an overall framework for SVE design, operation, optimization, and closure decisions. The EPA [2] and USACE [3] approaches for SVE closure/transition decisions related to protecting groundwater can be summarized with the following elements using an organization based on the four steps outlined by the EPA [2].

1. Conduct site characterization so that the conceptual model of the site is defined and can be used as a context to support SVE data analysis relative to closure/transition (e.g., how is the contaminant distributed and how does this relate to SVE effectiveness)

2. Provide design information that shows how SVE was configured and operated to appropriately address the contamination.
3. Provide SVE performance monitoring to demonstrate mass extraction and decreases in the subsurface contamination.
4. Quantify mass flux to groundwater to define the impact on groundwater remediation goals.

Recent efforts have focused on developing specific approaches to conduct these steps with emphasis on quantifying SVE performance and setting an SVE remediation endpoint based on groundwater quality goals.

QUANTIFYING SVE PERFORMANCE

The contaminant mass removal rate during SVE operations provides a measure of the current contamination in relation to historical SVE operations. Contaminant removal rates typically decline over time due to SVE operation, but the rate of decline may diminish such that the removal rate approaches an asymptotic value. Asymptotic contaminant removal rate behavior is often attributed to the impact of rate-limited mass transfer. Rate-limited mass-transfer processes may comprise dissolution of trapped organic liquid, diffusive mass transfer between lower-permeability and higher-permeability domains, desorption, or some combination thereof. If the asymptotic value is high relative to initial removal rates, then a mass-transfer limitation may exist with respect to SVE removal effectiveness. Under these conditions, it will be useful to assess mass transfer constraints. Temporal extraction-concentration profiles (i.e., elution tails) can be analyzed to evaluate rate-limited mass transfer [3, 4]. Data from a single SVE rebound period can serve as an alternate or additional source of information to help characterize mass-transfer constraints [3, 5, 6, 7]. Data from cyclic operation of the SVE system (i.e., multiple rebound periods) can also be analyzed and evaluated in terms of vadose zone contaminant mass flux behavior and how it changes over time [8]. Using one or more of these techniques, data can be collected to describe the current SVE performance in terms of contaminant removal rate (mass/time for a specified time period) and how this rate changes over time. Compilation of this type of data, consistent with refinement of the site conceptual model, is of use to provide a context for assessing SVE system performance. Those systems where contaminant removal rates are still significantly declining over time are still operating effectively and are candidates for continued operation without change. If an asymptotic removal rate is being approached, additional analyses are warranted to evaluate the system in terms of optimization, closure, or transition to another technology.

The above analyses can be used to quantify the mass flux from the contaminant source under SVE conditions (induced soil gas flow) using the mass removed (product of SVE concentration and SVE extraction rate) per time period. Information from mass transfer rate limitation can be evaluated with respect to the presence and significance of contaminant sources that are resistant to SVE treatment. The contaminant mass flux of persistent sources should be quantified at sites where persistent sources are present and expected to be significant with respect SVE operational and closure decisions. In addition to the measurement under SVE operational conditions, the contaminant mass flux from these persistent sources can be estimated under conditions with no SVE-induced flow [8]. This measure of contaminant mass flux can be used to estimate the impact of the persistent remaining source on ground surface or the groundwater if the SVE system is shut down [9].

The method for quantifying the post-SVE mass flux from persistent sources described in Brusseau et al. [8] can be applied using the full SVE well network to quantify the overall mass flux. This type of method can also be applied to individual wells so that a spatial distribution of mass flux can be estimated based on the relative mass flux at different wells (locations). This type of spatial information may be important to provide input to SVE system optimization or to target application of other technologies to augment or replace SVE – if continued remediation is needed.

SETTING AN SVE REMEDIATION ENDPOINT BASED ON GROUNDWATER GOALS

The EPA [2] and USACE [3] outline processes for assessing closure/transition of SVE systems using several types of analyses, including estimation of contaminant mass flux to groundwater and the resultant groundwater contaminant concentration. Analysis of the contaminant mass flux/discharge to the groundwater and resultant groundwater concentration based on vadose zone conditions can provide input to setting a remediation target. Because near-term direct measurement of the impact of a vadose zone contaminant source on the groundwater may be difficult in some cases, methods to estimate the near-term and future impact on groundwater are needed. Additionally, if the groundwater is contaminated by sources within the groundwater (e.g., immiscible-liquid or sorbed-phase contamination), the groundwater concentration is not a direct indicator of the effect of the vadose zone source on groundwater concentrations. Numerical simulation and analytical solution techniques can be applied to estimate the mass flux/discharge to the groundwater. Other types of approaches can and have been applied, but the material below focuses on the mass flux/discharge efforts. Additionally, some sites must consider vapor intrusion in addition to groundwater impacts. Mass flux/discharge efforts may also be useful for these applications.

As outlined by Truex et al. [10], there are several methods to estimate the impact of volatile vadose zone contaminants on groundwater. The basic approaches include direct mixing, one-dimensional modeling, and multidimensional modeling methods. The suitability of each technique is dependent on the site setting and associated primary transport mechanisms from the vadose zone to the groundwater.

If the mass flux from the vadose source zone can be measured or estimated, a Direct Mixing Method (DMM) can be used to calculate a resultant groundwater concentration. This method requires selection of a cross sectional area in the groundwater that is representative of the assumed mixing depth and the cross sectional distance perpendicular to groundwater flow that is impacted by the vadose zone source. The DMM assumes that all of the contamination from the vadose zone source enters the groundwater and would likely be a reasonable estimating method for conditions where the cross sectional area can be effectively selected, such as when aqueous transport in the vadose zone dominates the mass flux to groundwater. The direct mixing method may provide a simple, yet reasonable method to compute the resultant groundwater concentration. However, if vapor-phase contaminant transport is a major portion of the mass flux to groundwater, it may be more difficult to select an appropriate cross sectional area and a larger portion of the mass flux from the source may not reach the groundwater. In these situations, other estimating methods should be considered.

Contaminant mass flux from the vadose zone to the groundwater and resultant groundwater concentrations may be estimated using one-dimensional (1D) modeling-based approaches [11, 12, 13]. One-dimensional solutions use concentration boundary or initial conditions for the source. Contaminant mass flux to the groundwater is controlled by these inputs and the lower boundary condition or function used to represent water table mass transfer. Similar to the DMM, these 1D methods will likely be a reasonable estimating method for conditions where aqueous transport in the vadose zone dominates the mass flux to groundwater. Truex et al. [10] demonstrated that these approaches using a specified water table boundary condition without consideration of groundwater processes are problematic for the vapor-phase transport component of the estimate.

Multidimensional numerical modeling provides a means to estimate contaminant transport in two or three dimensions to support selection of a remediation endpoint, although three-dimensional analysis is most appropriate for vapor phase transport [14]. Carroll et al. [9] recently conducted a predictive analysis demonstrating a correlation between vadose-zone volatile contaminant sources and groundwater contaminant concentrations. Their effort used a case study to evaluate the post-remediation relation between a persistent vadose zone source and groundwater contaminant concentrations, and was targeted for sites where SVE has been applied and has reached diminishing returns due to mass transfer limitations in some defined portion of the vadose zone. However, the method is applicable to other sites at this stage of SVE remediation that can be described using the general conceptual model shown in Figure 2 and basic hydraulic properties for the site. In the Carroll et al. [9] study, there was a linear function that described the groundwater contaminant concentration resulting from a vadose-zone volatile contaminant source as quantified by the vapor-phase mass discharge from the source. This vapor-phase mass discharge can be measured for an SVE system using the method described by Brusseau et al. [8]. The study demonstrated how variations in key parameters for the site impact the estimate of the resultant groundwater condition and identified those for which it is most important to reduce uncertainty to improve the quality of the estimate. Likely at many sites, a sensitivity analysis would be required to help support use of the predictive estimate in supporting a remediation decision such as to optimize, terminate the SVE operation, or to transition to another type of treatment.

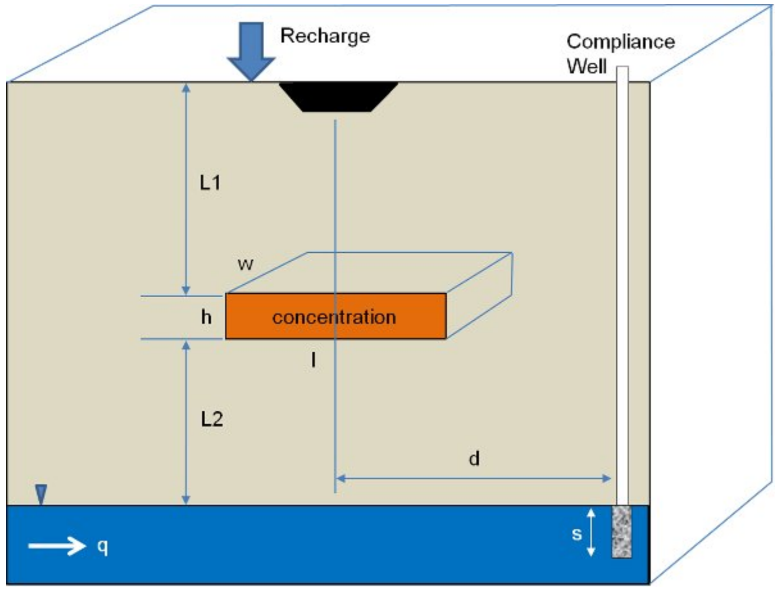


Figure 2. Generalized conceptual model elements used by Carroll et al. [9] for assessing the impact of a vadose zone contaminant source on groundwater. The figure shows generic symbols for the type of dimensional information important to estimating the impact at a compliance well.

When applying estimating techniques that relate vadose zone contaminant conditions to the groundwater, several overall considerations are important. For instance, Oostrom et al. [15] used numerical modeling to describe some key factors related to how vadose zone contaminants impact groundwater. As vapor-phase transport becomes more important (e.g., for arid sites with low aqueous recharge), three-dimensional gas transport and a coupled vadose zone – groundwater system need to be considered to effectively estimate the amount of contaminant mass transfer from the vadose zone to the groundwater. Under most cases, even with vapor concentrations up to 100 mg/L (about 15,000 ppmv for carbon tetrachloride), the effects of density-driven advection are relatively minor and diffusive vapor transport dominates in the gas phase. Truex et al. [10] demonstrated that for vapor-phase transport, analyses should consider that the ability of the groundwater to transport contaminants controls the vapor-phase mass flux from the vadose zone across the water table. For the vapor phase, contaminant mass transfer to the groundwater is dominated by diffusion in the aqueous phase, which makes this overall mass transfer process slow. Including vadose zone – groundwater mass transfer processes in transport estimates yields considerably lower contaminant mass fluxes to the groundwater than are obtained with single-phase one-dimensional approaches with imposed zero-concentration boundary conditions at the water table.

Oostrom et al. [15] also demonstrated that for sites with relatively low recharge rates, only a small amount of the contaminant emanating from the vadose zone source enters the groundwater. Most of the mass is transferred out of the domain into the atmosphere. At higher recharge rates, a higher percentage of the overall vadose zone source is transferred to the groundwater. In addition to mass transfer processes at the water table, the fate of vapor phase contamination at a specific site is a function of the three dimensional configuration of the site, especially elements such as the distance between the source and the land surface and the source and the water table. The nature of the capillary fringe also impacts the rate of vapor phase contaminant mass transfer to the groundwater [16].

Truex et al. [10], Oostrom et al. [15, 16], and Carroll et al. [9] demonstrated that the groundwater velocity has a large effect on vapor-phase contaminant mass flux across the water table and resulting groundwater contaminant concentrations. At high groundwater flow rates, the mass transfer rate to the groundwater is larger compared to lower flow rates; as a result, the overall contaminant mass flux into the groundwater is larger. However, the high groundwater flow rates cause increased dilution of the contaminants and vertically smaller plumes. The reverse situation occurs for lower groundwater flow rates; mass flux is low, but groundwater contaminant concentrations may be higher.

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