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Assessing performance and closure for soil vapor extraction: Integrating vapor discharge and impact to groundwater quality

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ABSTRACT

Soil vapor extraction (SVE) is typically effective for removal of volatile contaminants from higher-permeability portions of the vadose zone. However, contamination in lower-permeability zones can persist due to mass transfer processes that limit the removal effectiveness. After SVE has been operated for a period of time and the remaining contamination is primarily located in lower-permeability zones, the remedy performance needs to be evaluated to determine whether the SVE system should be optimized, terminated, or transitioned to another technology to replace or augment SVE. Numerical modeling of vapor-phase contaminant transport was used to investigate the correlation between measured vapor-phase mass discharge, MF_r, from a persistent, vadose-zone contaminant source and the resulting groundwater contaminant concentrations. This relationship was shown to be linear, and was used to directly assess SVE remediation progress over time and to determine the level of remediation in the vadose zone necessary to protect groundwater. Although site properties and source characteristics must be specified to establish a unique relation between MF_r and the groundwater contaminant concentration, this correlation provides insight into SVE performance and support for decisions to optimize or terminate the SVE operation or to transition to another type of treatment.

1. Introduction

Soil vapor extraction (SVE) has been the presumptive remedy for volatile organic compounds (VOCs) in the vadose zone for approximately 15 years (U.S. EPA, 1996a). While initially SVE tends to be a highly effective method, it is recognized that SVE operational efficiency typically becomes limited over time primarily due to mass-transfer constraints associated with contaminant mass residing within lower-permeability portions of the vadose zone (Brusseau et al., 2010; Carroll et al., 2009; DiGiulio et al., 1998; Hoier et al., 2009; Oostrom et al., 2010; Switzer et al., 2004; Truex et al., 2009; U.S. EPA, 1996b; Yoon et al., 2009). For most SVE systems, a decision point eventually develops regarding whether to continue under the reduced-efficiency conditions, to adjust the extraction protocol, or to cease operations and potentially switch to other remediation methods. The U.S. Army Corps of Engineers (US Army Corps of Engineers, 2002) and the U.S. Environmental Protection Agency (EPA) (U.S. EPA, 2001) provide guidance for assessing transition and closure of SVE systems. A key analysis in this process is the determination of contaminant mass flux, or mass discharge, to groundwater and the resultant groundwater concentration at monitoring locations of interest. SVE closure/transition decisions related to meeting groundwater goals must consider the impact of persistent vadose-zone contaminant sources remaining after SVE termination.

The contaminant mass flux/discharge, also referred to as source strength, for a source zone is now recognized for groundwater as a primary metric for assessing risk and

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remediation performance, because it relates source-zone and plume dynamics (Brusseau et al., 2007, 2008, 2011; Carroll and Brusseau, 2009; DiFilippo and Brusseau, 2008; DiFilippo et al., 2010; DiGiulio et al., 1999; Einarson and Mackay, 2001; Falta, 2008; Falta et al., 2005a, 2005b; Freeze and McWhorter, 1997; ITRC, 2002; Schwarz et al., 1998; Suthersan et al., 2010; U.S. EPA, 2003). Contaminant mass discharge, rather than contaminant mass or concentration, is most directly related to the impact of vadose-zone contaminant sources on groundwater contaminant concentrations. However, to date, only a few studies have evaluated mass-discharge behavior for persistent sources in the vadose zone (Brusseau et al., 2010; DiGiulio and Varadhan, 2001; DiGiulio et al., 1998, 1999; Truex et al., 2009).

Recently, a vadose-zone characterization method was developed to quantify the overall vapor-phase contaminant mass-discharge rate emanating from persistent (e.g., diffusion controlled) VOC sources within the SVE treatment volume using data collected from cyclic SVE operations (Brusseau et al., 2010). Vapor-phase concentrations tend to increase during the no-flow period, or rebound time, due to diffusive mass transfer from persistent sources. The mass-transfer-limited discharge during rebound is analogous to conditions that would persist if the SVE system were to remain shut off (i.e. after SVE closure). Thus, it is of interest to predict the groundwater contaminant concentration that would result over time from this type of persistent, vadose-zone contaminant mass discharge. With this type of prediction, a relatively short-term measurement of vadose-zone source mass discharge could be used to evaluate the impact of the source on the groundwater contaminant concentration, for instance, at a down-gradient compliance well, as part of remedy decisions for the SVE system.

A numerical model was used to investigate the correlation between vapor-phase mass discharge from a persistent, vadose-zone contaminant source and the resulting groundwater contaminant concentrations. The study also evaluated how uncertainties in the vadose-zone source characteristics (e.g., size, location, and concentration) and different values for groundwater flow rate, sorption characteristics, and recharge rate impact this correlation. A waste site contaminated with carbon tetrachloride (CT) at the Department of Energy Hanford Site was used to demonstrate the methodology.

2. Methodology and case study

2.1. Case study site

At the Hanford Site in Washington State, dense nonaqueous phase liquids (DNAPL) consisting of carbon tetrachloride (CT) mixed with lard oil, tributyl phosphate, and dibutyl butyl phosphonate were disposed at the 216-Z-9 Trench (Rohay, 2007; Rohay and McMahon, 1996). A recent conceptual model developed based on multifluid flow simulations (Oostrom et al., 2007a) showed that CT in the DNAPL migrated primarily in a vertical direction below the disposal site and that some CT DNAPL likely migrated into the regional aquifer. Over time, the CT contamination within the more permeable sediments has been removed due to active SVE remediation. Initial vapor concentrations of CT (1993) measured from the SVE system discharge had an annual average of 15,939 ppmv (35,520–168 ppmv), which decreased to an average of 38 ppmv (66–11 ppmv) in 1996 (1 mg/L = 159 ppmv CT at 25 °C). Starting in 1996, SVE was operated in repeating, annual-operation cycles of about 6 months of SVE extraction followed by 6 months of no extraction. Rebound concentrations of CT in the SVE extraction system have decreased over time, and ranged from approximately 3 to 11 ppmv in 2011. This rebound behavior of CT concentrations following the periods of no flow, and its persistence despite active remediation, suggests that sources of CT mass remain in a mass-transfer-limited region of the vadose zone (Brusseau et al., 2010). The persistent source of this CT contamination has been interpreted to be located within the Cold Creek Unit (hereafter termed CCU), which is an approximately 5 m thick lower-permeability silt layer located mid-depth in the 70 m thick vadose zone. Groundwater was also contaminated with CT from the Z-9 Trench Site and other disposal areas, and has been undergoing active remediation via extraction and treatment at the land surface. Beneath the Z-9 Trench Site the groundwater CT concentrations in 2011 varied between 2 and 0.43 mg/L with expectations that concentrations will remain high for decades until the groundwater is treated. Thus, the groundwater contaminant concentration is not a direct indicator for the impact of vadose-zone contaminant conditions at the Z-9 Trench Site on the groundwater.

Fig. 1 illustrates the conceptual model for the case study site subsurface, representing the major sedimentary units, the general source location, and pertinent mass-transfer processes. The approximately 70-m-thick vadose zone consists of the permeable Hanford Formation at the top and the permeable Ringold Formation at the bottom, which are separated by the lower-permeability CCU. The configuration shown in Fig. 1 may be generally applicable to other sites with persistent contaminants located within lower-permeability zones, surrounded by cleaner, high-permeability sediments. Contaminants within the lower-permeability zones are likely to be persistent even with continued SVE operations, and represent a long-term source to groundwater (or vapor intrusion) that needs to be considered for closure or transition decisions.

2.2. Measuring mass discharge

An analysis of contaminant mass discharge at the Z-9 Trench Site was presented by Brusseau et al. (2010) for the cyclic operations of the SVE system, where periods of no flow (typically 0.5 to 1 year "rebound" time) were imposed to allow diffusive mass flux to occur between periods of active SVE operation. An example of typical CT concentration rebound during flow interruption and decreases during vapor extraction at the Z-9 Trench Site is shown in Fig. 2. Using data such as those presented in this figure, Brusseau et al. (2010) derived several source zone mass-discharge values (M/T), including the average rebound mass discharge (MF_r), calculated as the total mass of contaminant (M_{PV}) released from the source zone during rebound divided by the rebound time.

The MF_r term is determined based upon the assumption that the mass transferred from the lower permeability source zone into the higher permeability vadose zone during a rebound period is the same mass that is collected from the vadose zone pore space when the SVE system is restarted. So, the mass discharge during the rebound period can be