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Sustainable in-well vapor stripping: A design, analytical model, and pilot study for groundwater remediation

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ABSTRACT

A sustainable in-well vapor stripping system is designed as a cost-effective alternative for remediation of shallow chlorinated solvent groundwater plumes. A solar-powered air compressor is used to inject air bubbles into a monitoring well to strip volatile organic compounds from a liquid to vapor phase while simultaneously inducing groundwater circulation around the well screen. An analytical model of the remediation process is developed to estimate contaminant mass flow and removal rates. The model was calibrated based on a one-day pilot study conducted in an existing monitoring well at a former dry cleaning site. According to the model, induced groundwater circulation at the study site increased the contaminant mass flow rate into the well by approximately two orders of magnitude relative to ambient conditions. Modeled estimates for 5 h of pulsed air injection per day at the pilot study site indicated that the average effluent concentrations of dissolved tetrachloroethylene and trichloroethylene can be reduced by over 90% relative to the ambient concentrations. The results indicate that the system could be used cost-effectively as either a single- or multi-well point technology to substantially reduce the mass of dissolved chlorinated solvents in groundwater.

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1. Introduction

Groundwater remediation technologies that depend on fluid flow (e.g., pump and treat, air sparging, and chemical oxidation) can remove contaminant mass from the transmissive zones of an aquifer, but are generally ineffective at directly removing contaminant mass from low permeability zones (U.S. DOE, 2000). Following the remediation of a transmissive zone, contaminant mass stored in low permeability media can slowly diffuse out at concentrations exceeding low-level cleanup goals for up to decades (Chapman and Parker, 2005; Seyedabbasi et al., 2012). This slow process of back diffusion is common at chlorinated solvent release sites and emphasizes the need to consider cost-effective remedial strategies for long-term remediation (ITRC, 2004; Sale et al., 2008).

Here we report on the design, modeling, and testing of a sustainable in-well vapor stripping (SIVS) system as a cost-effective alternative or supplement to other remediation technologies for long-term remediation at chlorinated solvent release sites. SIVS is an energy-efficient technology that can be operated by conventional or solar power; a solar-powered design is presented here. The SIVS system uses a solar-powered compressor to inject air bubbles into a monitoring well at a relatively low flow rate and pressure. As the air bubbles rise through the water column, solute volatile organic compounds (VOCs) are transferred (or "stripped") from the aqueous to vapor phase, while the bubbles simultaneously induce groundwater circulation around the well screen. The stripped VOCs can either be ventilated directly to the atmosphere or treated with a granular-activated carbon unit in accordance with local air quality permitting requirements. SIVS can either be installed as a single-well point technology or as a reactive barrier when installed in an array of monitoring wells along the downgradient edge of a source zone (Fig. 1).

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A simplified and closed-form mathematical model is developed for SIVS under simplifying assumptions of homogeneous media and complete mixing in the borehole. The model is used to estimate the rates of contaminant mass flow and removal in application to data collected from a one-day pilot test.

A pilot study is conducted at a former dry cleaning site in Sonora, California, to calibrate and evaluate the reliability of the SIVS model estimations. The study was conducted in an existing source area monitoring well and included a mechanical slug test, in-well air injection, groundwater sampling, and vapor sampling.

1.1. Basic elements of system design

In a shallow aquifer, a 20 watt air compressor can be used to inject air near the bottom of a monitoring well screen at flow rates up to about 10 LPM and at pressures less than about 9 kPa above the hydrostatic pressure. At these low pressures, air would not likely penetrate into the surrounding aquifer materials and rising bubbles would thereby be limited to the well casing (Suthersan, 1999). Depending on the availability of solar energy, a pole-mounted solar photovoltaic panel equipped to a charge controller, battery, and inverter can be designed to power a 20 watt air compressor for at least 5 h per day. A 12 V direct current timer switch can be used to automate at least 8 air injection events per day. The air can be injected through high density polyethylene tubing and controlled with a rotameter. The capital cost of such a SIVS system installed in a single existing monitoring well within a shallow aquifer is on the order of $2500.

1.2. Remedial concepts

SIVS applies principles used by existing vapor stripping and groundwater circulating well technologies. Vapor stripping technologies for groundwater remediation are generally described as either "air sparging" systems or "in-well vapor stripping" systems (Katz and Gvirtzman, 2000). Air sparging has been used to remove VOCs from groundwater as early as the mid 1970s (Lenzo et al., 1990) and became more common in the late 1990s when coupled with a soil vapor extraction system (Nyer, 1998). Air sparge systems inject air into a well at a high pressure to penetrate bubbles or air channels into the surrounding aquifer materials (U.S. NFESC, 2001).

In-well vapor stripping systems inject air into a well at a low pressure to contain the rising bubbles and stripped solute VOCs within the well casing (USACE, 2013). There are a variety of proprietary in-well vapor stripping technologies that integrate the use of groundwater circulating wells. In general, a groundwater circulating well has two hydraulically separated screens that are used to create vertical groundwater recirculation around the well. While the methods of recirculation vary, air is generally injected into the wells to strip solute VOCs and displace the casing water, causing groundwater to draw into the lower well screen and discharge out of the upper well screen. Groundwater discharged through the upper well screen then flows vertically downward through the aquifer and can be recaptured for additional treatment by flowing into the lower well screen (U.S. EPA, 1998).

SIVS is designed to be installed in an existing or new monitoring well(s) with only one screen. The injected air bubbles in the water column create inter-phase momentum transfer that induces mixing around the plume of injected air (i.e., induced circulation). The generalized flow patterns for induced groundwater circulation and regional advection that would be expected around a SIVS system in a homogenous aquifer are shown in Fig. 2; the induced flow patterns are based on long-term averaging of fluid flow measured in previous bubble column experiments using computational fluid dynamics (Díaz et al., 2009).

For the purpose of modeling SIVS, portions of the saturated-borehole sand pack and well column are characterized as an ideal completely mixed flow reactor (CMFR). It is assumed that the volume V [L^3] of the CMFR can be approximated as the casing water volume and the liquid volume of the borehole sand pack surrounding the wetted well screen above the air

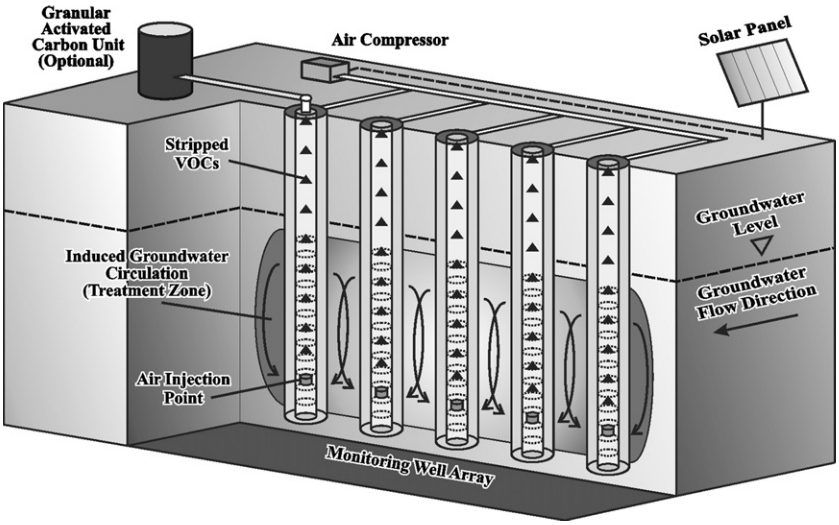

Fig. 1. A generalized overview of a multi-well point SIVS installation used to create a reactive barrier.

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