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Evaluation of deep vadose zone contaminant flux into groundwater: Approach and case study

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ABSTRACT

For sites with a contaminant source located in the vadose zone, the nature and extent of groundwater contaminant plumes are a function of the contaminant flux from the vadose zone to groundwater. Especially for thick vadose zones, transport may be relatively slow making it difficult to directly measure contaminant flux. An integrated assessment approach, supported by site characterization and monitoring data, is presented to explain current vadose zone contaminant distributions and to estimate future contaminant flux to groundwater in support of remediation decisions. The U.S. Department of Energy Hanford Site (WA, USA) SX Tank Farm was used as a case study because of a large existing contaminant inventory in its deep vadose zone, the presence of a limited-extent groundwater plume, and the relatively large amount of available data for the site. A predictive quantitative analysis was applied to refine a baseline conceptual model through the completion of a series of targeted simulations. The analysis revealed that site recharge is the most important flux-controlling process for future contaminant flux. Tank leak characteristics and subsurface heterogeneities appear to have a limited effect on long-term contaminant flux into groundwater. The occurrence of the current technetium-99 groundwater plume was explained by taking into account a considerable historical water-line leak adjacent to one of the tanks. The analysis further indicates that the vast majority of technetium-99 is expected to migrate into the groundwater during the next century. The approach provides a template for use in evaluating contaminant flux to groundwater using existing site data and has elements that are relevant to other disposal sites with a thick vadose zone.

1. Introduction

Contamination in the deep vadose zone, defined by Dresel et al. (2011) as "the sediments or rock below the zone of practicable excavation and removal but above the water table" is a significant issue in most regions of the United States, although most of the research focus has recently been on the arid regions regarding contaminant transport (Seaman et al., 2007) or groundwater recharge (Walvoord and Scanlon, 2004; Rimon et al., 2007). A large number of contaminated deep vadose zones are at the U.S. Department of Energy (DOE) sites, such as Yucca Mountain (Robinson et al., 2011), Idaho National Engineering and Environmental Laboratory (Nimmo et al., 2004), the Los Alamos National Laboratory (Birdsell et al., 2004) and the Hanford Site (Gee et al., 2007). Although radionuclides are of interest at many deep vadose zone sites, behavior of other contaminants such as metals (Hua et al., 2007), organics (Oostrom and Lenhard, 2003; Oostrom et al., 2007) and excess fertilizer (Onsoy et al., 2005) has been investigated in the unsaturated area below the root zone.

Due to its distance to the surface, a deep vadose zone may pose serious problems for characterization, monitoring, and remediation. Dresel et al. (2011) pointed out that remediation options for the deep vadose zone are often less developed than for the shallow zone or for saturated groundwater and that only few have been implemented as full remedial actions. They

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also provided a review of available mass reduction, stabilization, and hydraulic control remedial techniques and identified soil desiccation of sediment layers, in combination with surface barriers, as one of the few potentially effective methods to reduce contaminant flux to groundwater. Recently, Truex et al. (2012) conducted a successful soil desiccation field implementation at the Hanford Site.

The nature and extent of groundwater contaminant plumes are often a function of the contaminant flux from the vadose zone to the groundwater. Contaminant movement is typically relatively slow through a deep vadose zone and it is difficult to directly measure contaminant flux in these systems. Instead of directly measuring vadose zone contaminant concentrations and fluxes, theoretical conceptual models are often developed to improve the understanding of deep vadose zone transport (Birdsell et al., 2004; Khaleel et al., 2007; Nimmo et al., 2004; Oostrom et al., 2007, 2013; Robinson et al., 2011). These conceptual models typically provide characterization information and discussions of plausible subsurface flow and transport processes. Most of these models lack a comprehensive approach to evaluate potentially controlling features and processes, such as recharge, contaminant source characteristics, and lithography, on contaminant flux to groundwater.

In this paper, an integrated approach is presented for estimating future contaminant flux to groundwater at deep vadose zone sites. The approach is initiated by gathering available data and information to develop a baseline conceptual site model. An important part of this step is a consideration of the lines of evidence provided by different types of data and any limitations for use of the data. The baseline conceptual model is then refined considering the effects of potential controlling features and processes and relevant boundary conditions in the context of water and contaminant flux through the vadose zone into the groundwater. This refinement takes place based on results from a quantitative analysis using the STOMP flow and transport model (White and Oostrom, 2006) to investigate the role of different driving forces for contaminant flux at the site.

The integrated approach was applied to the SX Tank Farm at the U.S. Department of Energy Hanford Site (Fig. 1). As a result of previous tank leaks, the vadose zone beneath this site has become contaminated and some of the nonsorbing technetium-99 (Tc-99), originating from one of the tanks, has begun to migrate into the groundwater, creating a groundwater plume. However, a large fraction of the contaminant inventory is still present in the unsaturated vadose zone. A predictive analysis, supported by SX Tank Farm site characterization and monitoring data, was applied to estimate future contaminant flux to groundwater in support of remediation decisions for the vadose zone and groundwater. The current work builds on the SX Tank Farm analyses by Zhang et al. (2005) and Khaleel et al. (2007) by considering flow and transport in three dimensions and by

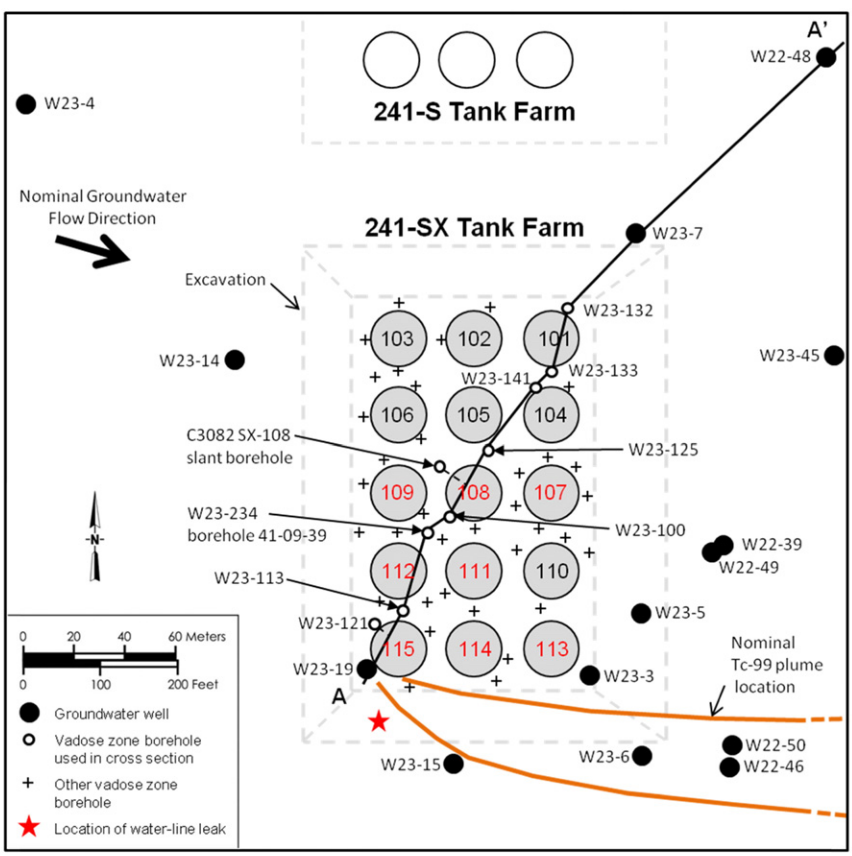

Fig. 1. Location map of the Hanford SX Tank Farm, including observation wells, water-line leak location, and the Tc-99 plume originating from SX-115 tank waste (after Serne et al. 2008a,b and Johnson and Chou, 2002).