MIGRATION OF POLLUTANTS IN GROUNDWATER. VI. FLUSHING OF DNAPL DROPLETS/GANGLIA

SATOSHI KAYANO and DAVID J. WILSON
Departments of Chemistry and of Civil and Environmental Engineering, Vanderbilt University,
Nashville, Tennessee 37235, U.S.A.

(Received: March 1992)

Abstract. Models for describing the flushing of DNAPL from contaminated aquifers are developed, and the dependence of the calculated cleanup times on the model parameters is explored. Diffusion transport from isolated DNAPL droplets, from low-permeability porous spherical domains containing distributed DNAPL droplets, and from low-permeability porous planar lamellae containing distributed DNAPL is analyzed, and the resulting expressions then coupled with the equations for advective transport of dissolved VOC by means of natural uniform flow and a system of injection and recovery wells generating a two-dimensional flow field. The models are readily run on currently available microcomputers. The results of computations with the models are consistent with the severe tailing and slow rates of remediation which are generally observed when DNAPLs are removed by flushing.

1. Introduction

Pump-and-treat operations generally play a central role in the remediation of hazardous waste sites, since groundwater is usually involved. Many such pump-and-treat operations are yielding very slow rates of remediation if dense nonaqueous phase liquids (DNAPLs) are present, indicating that kinetic limitations on the rates of solution of these compounds can be severe.

Feenstra and Cherry (1987) have provided an introduction to the subject of DNAPLs in groundwater. Schwille’s (1988) experiments have established that such liquids (generally chlorinated hydrocarbons) move quickly down through most aquifers, leaving behind substantial quantities of DNAPLs which are trapped in the aquifer medium. These may amount to 5–50 L m⁻³. Remediation of sites contaminated with heavy solvents in the zone of saturation thus requires the removal of significant quantities of DNAPL of low water solubility. In conventional pump-and-treat operations the only mechanism for the removal of this material is solution, which is severely limited kinetically by the small values of diffusion constants in condensed phases.

Although the work of Miller, Poirier-McNeill and Mayer (1990) indicated that equilibration in the transfer of toluene between the NAPL and aqueous phases in a glass bead matrix was virtually complete within 0.01 to 0.05 days, under field conditions the rate of equilibration of DNAPL or LNAPL is very much slower. Volatile organic compound (VOC) concentrations rarely exceed 10% of saturation even in LNAPL- or DNAPL-containing regions in the aquifer. Evidently in porous media in the field solution of VOC is limited either by substantially reduced water–
NAPL interfaces or by appreciable distances across which the VOC must diffuse before it reaches mobile groundwater.

Mutch et al. (1992), among others, have explored this point in connection with removal of DNAPL from fractured porous bedrock. Weber and his coworkers (Powers et al., 1991) have carried out a rather detailed theoretical and experimental investigation of the nonequilibrium considerations involved with the solution of ‘blobs’ of NAPL trapped in saturated porous media. They ascribed the slow rates of mass transfer to: (1) rate limited mass transport between the nonaqueous and aqueous phases; (2) the bypassing of advecting aqueous phase around contaminated regions of low aqueous permeability; and (3) nonuniform flow due to aquifer heterogeneities. They found that the mass transport of VOCs from NAPL ‘blobs’ in soils was very much slower than it was in highly regular media, such as glass beads. One can evidently expect that diffusion and desorption kinetics considerations will frequently be the limiting factor in the movement of VOCs in aquifers after the initial gravity-driven dispersal.

We recently published some simple phenomenological models for the flushing of DNAPL droplets in lab columns, in aquifers with a one-dimensional radial flow field, and in quiescent aquifers in which a single well screened at the bottom is used to bring about the flushing (Wilson, 1992). In the following sections we pursue these matters further. Initially we examine mass transport of VOC: (1) from a spherical droplet of DNAPL through a thick surrounding boundary layer to the mobile advecting water; (2) from a spherical domain of porous medium which is of low permeability to water and which is permeated with DNAPL; and (3) from a planar lamella of porous medium which is of low water permeability and which is permeated with DNAPL. The resulting equations are then coupled with equations describing the advective transport of the dissolved VOC by the flow field generated by superimposing the flow resulting from a set of injection and recovery wells upon a constant uniform natural flow. The aquifer is assumed to be uniform and isotropic with respect to fluid flow, with the domains of low permeability sufficiently small in size as to not disrupt the overall flow patterns. Two-dimensional flow is assumed in order to obtain models which can readily be run on currently available microcomputers.

2. Analysis

2.1. Diffusion Mass Transport

We consider here three models. In the first, VOC must diffuse from the surface of a trapped spherical droplet through a boundary layer much thicker than the droplet radius to the mobile water, where it is removed by advection. In the second, droplets of DNAPL are initially distributed uniformly through a sphere of porous material of low permeability to water. They dissolve, and VOC diffuses out through the porous material to the mobile water, which carries it away. In the third, the configuration of the porous material permeated with DNAPL is assumed to be