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Research paper

Numerical analysis of virus transport through heterogeneous porous media

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Abstract

Virus transport through two-dimensional heterogeneous porous media at field scale is simulated using an advective dispersive virus transport equation with first-order adsorption and inactivation constant. An increasing exponential dispersivity function has been used to account for heterogeneity of the porous media. Implicit finite-difference numerical technique is used to get the solution of two-dimensional virus transport equation for virus concentration in suspension. The numerical model is used to investigate the effect of inactivation and mass transfer rate constants on the relative concentration profile in two observation wells. The effect of correlation length and ln K variance on movement of virus through heterogeneous porous media has been studied. It is found that the higher values of mass transfer rate constant and inactivation constant lead to reduced virus concentration in both observations wells. An increase in the variance of conductivity field or its correlation length was found to result in an earlier arrival of the virus at the observation wells as well as a higher virus concentration.

Keywords: Virus transport; Heterogeneous porous media; Concentration profiles

1. Introduction

The transport of colloids (including viruses and bacteria as well as abiotic colloids) in groundwater has long been recognized as a serious hazard to human health. It has been identified that most of the viruses in groundwater originate from human and animal sewage from nearby municipal wastewater discharges, septic tanks, sanitary landfills and agricultural practices. As wastewaters including bacteria and viruses are released into the subsurface environment, they infiltrate through the vadose zone, and upon reaching the water table continue to migrate in the direction of groundwater flow. It is generally seen that the groundwater is often consumed without prior conventional water treatment. It is also seen that pathogenic bacteria and viruses travel a large distance at field scale. Therefore it is necessary to understand the mechanisms governing the transport and fate of these viruses in subsurface groundwater systems at field scale, so that health risk owing to groundwater pollution by viruses can be evaluated. It has been suggested (Robertson et al., 1991) that the main source of ground water pollution is septic tank as shown in Fig. 1. Most of the country's population is using septic tanks for wastewater disposal and these represent the largest volumetric source of contaminant discharge to the ground water-zone. Previous field observations have demonstrated that in some aquifers septic tank viruses and bacteria can travel on the order of several hundred meters. A field scale study (Masciopinto et al., 2008) suggests that for the case of municipal wastewater injection into fractured aquifers, the required most conservative set back distance for drinking wells should be more than 8000 m. There are several mathematical models available in literature for virus transport in porous media, which describe the virus attachment onto the solid matrix and inactivation constants (Vilker et al., 1978; Tim and Mostaghimi, 1991; Powelson et al., 1993; Redman et al., 2001). It is generally recognized that two processes occur during virus transport through porous media. The first process is the nonequilibrium reversible adsorption, which represents the rate of approach to

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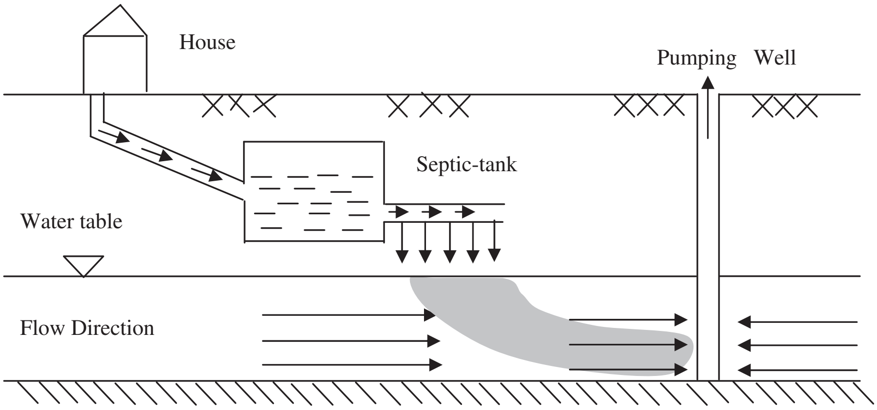

Fig. 1. Contamination of groundwater due to septic tank.

equilibrium between adsorbed and liquid phase virus concentrations. The second is the filtration process, which is used as colloids for models describing virus transport through porous media. Sim and Chrysikopoulos (1995) developed analytical solution for virus transport in one-dimensional homogeneous, saturated porous media for the case of both constant flux as well as constant concentration boundary condition. The effect of model parameters on virus transport was investigated. Espinoza and Valocchi (1997) used perturbation approach to study the effect of chemical heterogeneity on one-dimensional transport of kinetically adsorbing pollutant in a porous media. Rehmann et al. (1999) used numerical stochastic approach to study the effect of spatial variability of hydraulic conductivity and virus transport parameters (attachment, detachment, and inactivation) on virus transport through heterogeneous porous media. Sim and Chrysikopoulos (1999, 2000) developed analytical and numerical models to examine the effect of soil moisture variation on virus adsorption and inactivation in unsaturated porous media. The model accounts for virus sorption onto the liquid—solid and air—liquid interfaces as well as inactivation of viruses suspended in the liquid phase and virus attached at both interfaces. Jin and Flury (2002) reviewed the current research work done on fate and transport of viruses in porous media which include (a) mechanisms and modeling of virus sorption, (b) virus survival and factors affecting virus inactivation in the natural environment, and (c) mechanisms of virus transport in porous media and available modeling approaches. Bhattacharjee et al. (2002) used the numerical approach to solve a two-dimensional mathematical model for virus transport in physically and geochemically heterogeneous porous media. They studied the effect of subsurface-layered geochemical and physical heterogeneity on the movement of virus through porous media. Bradford et al. (2003) carried out experimental work for colloid transport in saturated porous media and predicted various breakthrough curves. These breakthrough curves can be fitted by using attachment and detachment models. This study is very useful for controlling deposition mechanisms. Anders and Chrysikopoulos (2005) conducted field-scale experiment to investigate the fate and transport of viruses during artificial recharge. Measured virus concentrations were fitted using a mathematical model to simulate virus transport in one-dimensional, homogeneous saturated porous media accounting for virus sorption, virus inactivation, and time-dependent source concentration. According to Han et al. (2006) retention and transport of colloids and microorganisms are complex processes in the vadose due to more complicated water flow regime and additional interfacial reactions involved. They also studied the retention and transport behavior of two bacteria phases MS-2 and ϕX174 in homogeneous and chemically heterogeneous media under variable saturated conditions. Anders and Chrysikopoulos (2006) conducted experiment to examine the effect of temperature and the presence of sand on the inactivation of bacteriophase MS-2 and PRD1. The experimental data suggested that the inactivation process can be represented by a pseudo-first-order expression with time-dependent rate coefficients. Further, Anders and Chrysikopoulos (2009) conducted experiment to investigate the factors that control virus inactivation as well as transport in saturated and unsaturated porous media.

In this work we study the virus transport in heterogeneous porous media and evaluate the effect of rate constant and inactivation constant on subsurface virus transport. It is assumed that porous media is saturated and heterogeneous. The implicit finite-difference technique has been used to solve the governing equations for the case of two-dimensional virus transport in heterogeneous porous media. The model is used to simulate the field experimental data of spatial moments.

2. Governing equations

The two-dimensional virus transport in homogeneous, saturated porous media with first-order adsorption and inactivation is governed by the following equation (Sim and Chrysikopoulos, 1995).

$$\frac{\partial C}{\partial t}+\frac{\rho}{\theta}\frac{\partial C^{*}}{\partial t}=D_{\mathrm{L}}\frac{\partial^{2}C}{\partial x^{2}}+D_{\mathrm{T}}\frac{\partial^{2}C}{\partial y^{2}}-V\frac{\partial C}{\partial x}-\lambda^{**}C-\lambda^{*}\frac{\rho}{\theta}C^{*} \qquad (1)$$

where, C is the concentration of virus in suspension [M/L^3], $C^*$is the mass of virus adsorbed on the solid matrix [M/M], D_{L} is the