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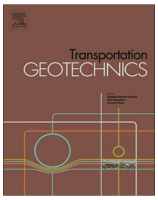

Contamination of roadside soils by runoff pollutants: A numerical study

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ABSTRACT

Roadway runoff contains multiple pollutant species that can contaminate roadside water, pose risks to aquatic organisms, and cause health problems for human beings. Roadside soils, mostly in their unsaturated states, constitute the first receiving entity for runoff water as the water flows off roadway surfaces. Considering the time-consuming and sophisticated procedures required for experimentally characterizing the soil–water characteristics of unsaturated soils, a finite element analysis (FEA) model was developed in this study and used to predict the contaminating process of variably saturated soils by the pollutants carried in runoff. The governing equation for the transport of multiple pollutant species was formulated based on the mass transport equation for porous media and the Richards' Equation for characterizing variably saturated soils. FEA formulation of the governing equation was accomplished by implementing a linear interpretation function in three-node triangular elements. The FEA model was validated using a miniature laboratory model. The validated FEA model was then implemented to analyze the contamination of a roadside ditch by studying different configurations of soil stratum. The FEA model developed in this work allows the prediction of pollutant distributions in soils at any time of interest, which will greatly facilitate the management of contamination problems caused by roadway runoff.

Introduction

Highway operations produce huge amounts of waste materials such as tire-wear materials, suspended solids and various petroleum and chemical products from sources including exhaust emissions, winter maintenance activities, pesticides, and herbicides (Guo et al., 2012; Kumata et al., 2011; Kayhanian et al., 2012). These waste materials can accumulate on road surfaces and be carried by runoff on rainy days to the roadside environment. Such roadway runoff in general is not treated before discharging to the receiving water bodies (Stagge et al., 2012). Roadway runoff discharges typically contain thousands of chemical species, among which the inorganic salts, heavy metals, and phenolic compounds are three major categories. Inorganic salts used in routine deicing activities in the northern regions of America can cause high sodium and chloride concentrations in roadside soils. When transported to rivers or lakes, they can impair water quality, pose risks to aquatic organisms, and even cause health problems for human beings. The growth and survival of organisms such as Hyalella Azteca were found to be highly sensitive to the high concentrations of chloride in water (Bartlett et al., 2012). Runoff, especially that from highways, also contains high concentrations of metals such as zinc, lead, mercury, iron, and copper due to wear of tires and other vehicular components. When reaching the receiving water and ecosystems, aquatic organisms can

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be intoxicated by many of such metallic species (Ikem and Adisa, 2011; Karlsson et al., 2010). The phenolic compounds from vehicular emission constitute another major source of pollutants carried by highway runoff. Research has shown that a dinitrophenol content over one millimolar (1 mM) in water can significantly change the living styles of algae and fish (Grynkiewicz et al., 2002).

Roadside soils are the first receiving entity for highway runoff as the water flows off the pavement surface. Soils are also frequently used to build the containers for receiving water in many treatment plants of runoff. In the United States, the remediation goals established by the US EPA are among the many standards for controlling the levels of particular contaminant species in soils. The EPA limits, for example, the accumulation of phenolic compounds in the top soil of Pacific Southwest to prevent potential risk on human health, since any above 270 mg/kg 2-Phenylphenol content in residential soil can be carcinogenic (US EPA, 2014). From this standpoint, the transport behavior of runoff and the carried pollutants in soils plays an important role in the contamination of roadside environments.

Contamination of roadside soils, especially in their unsaturated state, is a complex process that can take years to complete, depending on the level of saturation and the geometries of soils. Frequently, it is desirable to have a convenient tool that can be used to quickly determine the transport behavior of pollutants (each being a solute species) in common roadside soils. Such a tool is especially useful for unsaturated soils in which the determination of solute transport is more difficult than in saturated soils. More importantly, unsaturation constitutes the most common state for many field soils. Considering the time-consuming and laborious procedures for experimentally characterizing unsaturated soils, in this study the method of finite element analysis (FEA) is adopted for modeling the transport behavior of runoff-carried pollutant species in soils. Numerical simulation has been used as a powerful alternative for studying solute transport in variably saturated media (Pan and Lu, 2012; Pan and Wang, 2011). Through FEA modeling, the distribution of pollutants in soils can be predicted at any interested time, which provides a useful tool for managing runoff-related contamination problems.

Although convenient to use, the targeted FEA model for analyzing pollutant transport in a variably saturated soil cannot be easily developed. Successful development of the model entails overcoming multiple challenges such as determining a variety of parameters for soils, for example, the unsaturated hydraulic conductivity K, and controlling the convergence of the highly nonlinear governing equation. Pioneering efforts were made in these areas by Van Genuchten (1980) on formulating the soil–water characteristic curves that can be easily implemented for numerical analysis and by Fredlund for accurately describing the hydraulic properties of unsaturated soils (Fredlund, 2006). The Richards' Equation is among the most commonly used formulas for numerically characterizing the water retention curve of soils (Richards, 2004; Selle et al., 2011; Weill et al., 2009). Being a nonlinear partial differential equation, Richards' Equation gives analytical solutions only for a few special boundary and initial conditions (Miller et al., 1998). The FEA-based numerical method, however, is capable of solving Richards' Equation for general boundary and initial conditions. The Richards' Equation thus is used in this study for modeling pollutants in variably saturated soils.

FEA formulation

FEA modeling of the transport of multiple pollutant species in a variably saturated soil starts with the mass transport equation per Eq. (1), by which the concentrations of each included pollutant can be obtained at any interested time. It is noteworthy that the mass transport equation is a nonlinear partial differential equation that includes coefficients to be determined before the equation can be solved.

$$\frac{\partial \phi_i}{\partial t} = -\nabla \cdot (V_w \phi_i - D_i \nabla \phi_i) \qquad (1)$$

In Eq. (1), ϕ_i is the concentration of the pollutant (or solute) species i in soil, and the two terms on the right-hand side of the equation represent the two transport mechanisms of the species i. The first term $V_w\phi_i$ describes the transport flux of the species i with the moisture movement in soil by multiplying the velocity V_w of moisture or water to the species concentration. The second term on the right-hand side of Eq. (1), $D_i\nabla\phi_i$, describes the transport flux of the species i by the mechanism of diffusion in the pore water or moisture of the soil. The diffusion coefficient D_i can be determined experimentally in the laboratory condition. It can be seem from Eq. (1) that the changing rate of a species' concentration in a soil stratum depends on the gradient of the overall flux related to the species. To obtain the solution of this equation, these two mechanism equation need be solved in advance. Notably, while the diffusion field can be easily derived from the species' concentration ϕ_i, the determination of moisture flux in a soil stratum, by the term V_w, is a more challenging endeavor.

As stated before, Richards' Equation is used in this work to characterize the relationship between the moisture content θ and water head h in a variably saturated soil. The transient-state form of the Richards' Equation is given in Eq. (2) in terms of the water head h, where the symbol t denotes time. The other coefficient parameters included in Eq. (2) are explained in Table 1.

$$[C + S_e S]\frac{\partial h}{\partial t} + \nabla \cdot \left[-Kk_r \nabla\left(\frac{h}{\rho g} + e\right)\right] = 0 \qquad (2)$$

Table 1
Coefficient parameters included in Richards' Equation.

Symbols	Meaning of symbol
C	Specific moisture capacity of soil
S_e	Effective saturation of soil
S	Storage coefficient of soil
K	Saturated hydraulic conductivity of soil
k_r	Relative permeability of soil
g	Gravity acceleration
e	Vertical elevation