Water Research 110 (2017) 313–320

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Modeling fecal bacteria transport and retention in agricultural and urban soils under saturated and unsaturated flow conditions

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ARTICLE INFO

Article history:
Received 5 January 2016
Received in revised form
8 December 2016
Accepted 14 December 2016
Available online 20 December 2016

Keywords:
Bacteria transport
Kinetic sorption model
Variably saturated flow
Attachment-detachment
HYDRUS-1D
Urban soil

ABSTRACT

Pathogenic bacteria, that enter surface water bodies and groundwater systems through unmanaged wastewater land application, pose a great risk to human health. In this study, six soil column experiments were conducted to simulate the vulnerability of agricultural and urban field soils for fecal bacteria transport and retention under saturated and unsaturated flow conditions. HYDRUS-1D kinetic attachment and kinetic attachment-detachment models were used to simulate the breakthrough curves of the experimental data by fitting model parameters. Results indicated significant differences in the retention and drainage of bacteria between saturated and unsaturated flow condition in the two studied soils. Flow under unsaturated condition retained more bacteria than the saturated flow case. The high bacteria retention in the urban soil compared to agricultural soil is ascribed not only to the dynamic attachment and sorption mechanisms but also to the greater surface area of fine particles and low flow rate. All models simulated experimental data satisfactorily under saturated flow conditions; however, under variably saturated flow, the peak concentrations were overestimated by the attachment-detachment model and underestimated by the attachment model with blocking. The good match between observed data and simulated concentrations by the attachment model which was supported by the Akaike information criterion (AIC) for model selection indicates that the first-order attachment coefficient was sufficient to represent the quantitative and temporal distribution of bacteria in the soil column. On the other hand, the total mass balance of the drained and retained bacteria in all transport experiments was in the range of values commonly found in the literature. Regardless of flow conditions and soil texture, most of the bacteria were retained in the top 12 cm of the soil column. The approaches and the models used in this study have proven to be a good tool for simulating fecal bacteria transport under a variety of initial and boundary flow conditions, hence providing a better understanding of the transport mechanism of bacteria as well as soil removal efficiency.

1. Introduction

Varieties of studies have been conducted over the last three decades on the survival, transport, mass balance, and simulation of various bacterial species in soil and groundwater systems. According to such studies, the survival times of bacteria in soil and groundwater systems have ranged from a few days to several months (Entry et al., 2000). There are many factors influence the survival and transport of bacteria in soil. These factors are mainly comprised of physical and chemical characteristics of soil including soil moisture content, soil type, temperature, pH, nutrient availability, competing microorganisms, and applied water quality (Franz et al., 2005). Soil moisture content appears to exert the greatest control on bacteria transport and retention in soil (Gargiulo et al., 2008; Mubiru et al., 2000; Tate, 1978). With soil moisture content linked to particle size distribution and organic matter content of the soil, Tate (1978) observed that the survival of *E. coli* in organic soil was threefold greater than the survival of *E. coli* in sandy soil. Furthermore, Hagedorn et al. (1978) showed that fecal bacteria moved faster in coarser soil materials. Mubiru et al. (2000) concluded that mortality is primarily influenced by type, matric potential, and fine particles content of soil. In recent years, lysimeter studies have been conducted to investigate the transport of fecal coliforms and bacteriophages through a variety of soils

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http://dx.doi.org/10.1016/j.watres.2016.12.023
0043-1354/

(Aislabie et al., 2001; McLeod et al., 2004). Pang et al. (2008) studied transport of fecal coliforms, Salmonella bacteriophage, and Br in undisturbed lysimeters soils. Their results indicated that soil structure plays the most important function in the transport of microbes and Br, while soil composition had the maximum influence on mass balance.

The mechanism of particle attachment is controlled by the rate of transport of colloid into pore spaces and the fixation capability of the solid surfaces. Attachment rate is a function of porous medium, as its behavior in a clean medium is different from those previously altered media. Attachment at the air-water interface under unsaturated flow conditions may not facilitate retention of bacteria (Chen and Flury, 2005). Many researchers have assumed a constant first-order attachment coefficient; consequently, an exponential distribution has been proposed for the retained colloids with space (Logan et al., 1995; Tufenkji and Elimelech, 2004). Instead, the exponential distribution becomes depth dependent when unfavorable attachment conditions occur between colloids and a porous medium (Balkhair, 2016; Bradford et al., 2006).

Soil textural classes are known to affect removal efficiency of bacteria in onsite wastewater treatment systems (Gerba and Goyal, 1985; USEP, 2002). Processes such as mechanical filtration, adsorption, desorption, and hydraulic properties which are influenced by soil texture and structure have a significant effect on the removal of pathogenic bacteria (Ausland et al., 2002; Canter and Knox, 1985; Sobsey and Shields, 1987). Previous studies have provided little experimental data on comparative studies between soil textural classes and their vulnerability in retaining and transport of bacteria under variably saturated flow conditions. For example, Gargiulo et al. (2007) used HYDRUS-1D to simulate bacteria transport in Sterile fused silica sand in which two kinetic adsorption sites were considered and first-order kinetic growth was assumed on the solid and liquid phases. Bradford and Bettahar (2005) used HYDRUS-1D to simulate transport and retention of oocyst in Ottawa sands (99.8% quartz) under saturated flow condition, in which straining, attachment, and detachment processes were investigated. In addition, the influence of sand grain size distribution on oocyst transport was explored. In an independent study of the same soil (Ottawa sands), Bradford et al. (2006) studied transport and deposition behavior of pathogenic *Escherichia coli* O157:H7 under saturated condition and different flow rates. They found that the deposition profile of *E. coli* was highly dependent on the sand grain size and flow velocity. Higher deposition was associated with fine sand grains.

Knowledge of soil textural class is insufficient information to adequately quantify the transport and deposition of pathogenic bacteria in porous medium. Noting that soil particle sizes and their percentages vary within textural class, determination of grain sizes especially fine grains such as clay is a key factor in the description and interpretation of bacteria deposition and transport through soil profile. Several studies have reported through simulation of bacteria and viruses transport and deposition a high variability in the estimation of transport parameters such as attachment/detachment rates for the same soil texture (Bradford and Bettahar, 2005; Bradford et al., 2006; Farrokhian Firouzi et al., 2015; Foppen et al., 2007; Gargiulo et al., 2007; Jiang et al., 2007; Morales et al., 2014; Pang et al., 2008; Pang and Šimůnek, 2006). The primary objective of this study is to evaluate the transport and retention of fecal bacteria in two field soils of different textural classes under saturated and unsaturated flow conditions. The evaluation was carried out by fitting bacteria transport and retention simulation results of two kinetic sorption models; one-site irreversible kinetic attachment model and one-site reversible kinetic attachment-detachment model, to experimental data using HYDRUS-1D.

2. Materials and method

2.1. Soil

The following two soils were used in the bacterial transport experiments: Hada Al-Sham Agriculture soil (HAAS) and Jeddah Urban Soil (JUS), both are in the western region of Saudi Arabia. The HAAS samples were collected from the Hada Al-Sham agriculture experimental farm located approximately 90 km to the northeast of Jeddah city. JUS samples were collected from the public gardens of Jeddah's costal city. Physical, chemical, and bacterial analyses were carried out on both soil types. The physical analyses included bulk density, particle size distribution, porosity, and hydraulic conductivity. The chemical analyses included Electric conductivity (Ec), pH, Total Nitrogen, Total Carbon, and Organic matter. The bacterial analysis included the detection of fecal coliform. The method of analysis of these parameters are given in Table 1.

Soil water retention parameters were determined by fitting the experimental data of matric potential and water content relationship with the empirical equation of (Van Genuchten, 1980):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} \tag{1}$$

Where θ is the water content ($cm^3\ cm^{-3}$); θ_r is the residual water content; θ_s is the saturated water content; h is the matric potential (kPa or cm of H_2O); α is an empirical parameter, often assumed to be related to the air-entry suction (L^{-1} or kPa^{-1}); and n and m ($m = 1 - 1/n$) are empirical parameters related to the pore-size distribution. RETC is a computer code used to analyze the soil water retention and hydraulic conductivity functions of saturated-unsaturated soils (Van Genuchten et al., 1991). This code uses the parametric models of van Genuchten to represent the soil water retention curve. Unknown parameters in Eq. (1), mainly α, n, θ_r, and m are estimated by the nonlinear least-squares parameter optimization method that is built in RETC.

2.2. Solute

The University Wastewater Treatment Plant (UWWTP) is a typical plant in Jeddah city. Its treated wastewater was used in all leachate experiments. The plant, which is located at the center of the city and receives its wastewater from neighboring households covering several districts, treats water up to the secondary stage. Prior to experiments, samples of the treated wastewater were collected from the effluent of UWWTP for chemical and biological analyses. The treated wastewater was transported from UWWTP to the experimental site. Due to the transfer of effluent and environmental bacterial growing conditions, water samples were collected for the evaluation of fecal coliforms. The bacterial counts were determined using Microfil S filtration devices (0.22-µm pore size; Millipore, Billerica, MA). A wide range of fecal coliform input concentrations (1.4×10^6–8.6×10^8 cfu/100 ml) was detected in all experiments. Fecal coliforms were not perceived in samples collected prior to the leaching experiments. Each leachate experiment had its own bacterial content which was determined at the beginning of the experiment. Leachate at the outlet of the soil column in all experiments is expressed in relative concentration (effluent concentration divided by influent concentration). A complete physical, chemical, and biological analysis of UWWTP effluent is available. Only concentrations of related parameters are presented here in mg/l (TDS = 794, TN = 27.5, P = 11.2, BOD = 338.6, SS = 631, COD = 592.4, TOC = 174) and pH of 7.8.