Virus Transport through Heterogeneous Unsaturated Zone in Guwahati city in Assam under Transient state condition

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ABSTRACT: Virus present in the groundwater is considered to be an important agent for water borne diseases in India. In order to predict how far viruses can be transported and how long they can remain infective in soil and groundwater is desirable for proper management of the placement of sources of contamination so that they will not have an impact on drinking-water wells. With respect to that, a one dimensional virus fate and transport model is developed for transient heterogeneous unsaturated flow to identify the transport parameters in the unsaturated zone. Simulation of virus transport in groundwater aquifer is necessary for predicting the vertical movement of virus in an aquifer and to implement remedial measures to inactive the virus present in the groundwater. The model involves solution of the advection–dispersion equation, which additionally considers virus inactivation rate in the solution. In case of unsaturated porous media the transport of virus are responsible for some of the parameters such as linear distribution coefficient, hydrodynamic dispersion co-efficient and inactivation coefficient for both aqueous and sorbed virus. As there is often changes in the state and content of soil water during flow so it is considered to be a highly nonlinear problem and for such it becomes necessary to solve the flow equation before solving the virus transport equation. In this study finite element scheme computer coded software, HYDRUS-1D is used to simulate the one dimensional flow equation and virus transport equation. This study is mainly carried out for a particular location of Guwahati city, Assam, India. The viruses that is been employed in this study were the male specific RNA coliphage MS2, and the Salmonella typhimurium phage, PRD1. For simulating the partial differential equation of virus transport equilibrium solute transport model is selected with Crank-Nicholson as time weight scheme and Galerkin finite elements as space weight scheme. The purpose of this research is to determine the role that unsaturated flow conditions play in virus sorption and inactivation during transport through different soil type. The effects of the moisture content variation on virus transport in unsaturated porous media were also investigated. The results obtained after several simulations indicates that the concentration of virus is affected by the moisture content and the heterogeneity of the soil profile during its flow through unsaturated zone. The model developed in this study can successfully simulate the virus transport through heterogeneous unsaturated columns.

KEYWORDS: Virus, heterogeneous, transient, HYDRUS, unsaturated, Crank-Nicholson, Galerkin. advection, dispersion.

1 INTRODUCTION:

Hazardous wastes, sewage sludge, fertilizers and pesticides from the ground surface are removed by filtering action of the unsaturated zone. This may result in high contents of organic matters and clay, which undergoes biological degradation, transformation of contaminants and sorption. Therefore, the unsaturated zone can be considered as a buffer zone for protecting the groundwater. Virus that is present in waste water and sewage sludge are mainly the pathogenic microbial organisms which may lead to waterborne diseases. In order to understand spatial and temporal movement of these microorganisms one has to simulate the fate and transport processes. These two processes are mainly governed by four processes: advection, hydrodynamic dispersion, inactivation process and adsorption onto the soil matrix. In this zone the virus sorption and inactivation are influenced by the soil moisture content and subsurface temperature fluctuations (Vilker and Burge, 1980; Vilker, 1981; Thomson and Yates, 1999), so the flow equation is solved before solving the transport equation.

Several mathematical models are developed for predicting the movement of viruses in porous media. (Tim and Mostaghimi, 1991) developed a numerical model, VIROTRANS for simulating vertical movement of water and virus through soil treated with waste water effluents and sewage sludges. (Yates and Ouyang, 1992) developed a predictive model of virus fate and transport, VIRTUS which studies the effect of temperature-dependent inactivation rate, inactivation rates for sorbed versus free virus and the effect of soil type. (Sim and Chyrysikopoulos, 2000) developed a one dimensional numerical model to investigate the effect of moisture content variation on virus transport on a homogeneous unsaturated porous media. They found that at low moisture content the transport of virus is highly affected by the irreversible sorption of virus onto air-liquid interfaces. (Anders and Chyrysikopoulos, 2009) conducted laboratory-scale virus transport experiments in columns packed with sand under saturated and unsaturated condition. They found that the liquid to liquid-solid and liquid to air-liquid interface mass transfer rates increases as the saturation level were reduced. A mass conservative fully implicit finite difference model simulating moisture flow in the unsaturated zone with the hybrid finite volume model for virus transport is developed (Ojha et al., 2012).The accuracy of the numerical scheme is tested for both advection and dispersion dominated transport.

This work provides a numerical model of virus fate and transport process through heterogeneous unsaturated porous media. The viruses employed in this study are MS2, the male specific RNA coliphage and the Salmonella typhimurium phage, PRD1. In order to solve the moisture flow and virus transport equation, a one dimensional computer code software HYDRUS-1D is used that is based on finite element scheme. This study is carried out in a 'Parbatkha' location of Guwahati city,Assam,India.

2 MODEL DEVELOPMENT:

2.1 Governing Equation:

The mass conservation equation for the transport of water and virus through variably saturated media under transient flow condition can be written as-

Richard's flow equation (Tim and Mostaghimi, 1991):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial \psi}{\partial Z} + 1\right)\right] \qquad (1)$$

Virus transport Equation (Sim and Chrysikopoulos, 2000):

$$\frac{\partial}{\partial t}(\theta C) + \frac{\partial}{\partial t}(\rho C^*) + \frac{\partial}{\partial t}(a_v C^0) = \frac{\partial}{\partial Z}(D^W \frac{\partial C}{\partial Z}) + \frac{\partial C}{\partial Z}(D^g \frac{\partial C}{\partial Z}) - q(\frac{\partial C}{\partial Z}) - \lambda\theta C - \lambda^*\rho C^* - \lambda^0 a_v C^0 \qquad (2)$$

From Eqn. (1) and (2), ψ is the pressure head; θ is the volumetric moisture content; K is the hydraulic conductivity; Z is the vertical coordinate, t is the time in days. C is the virus concentration in liquid phase, C^* is the virus concentration at liquid-solid interface, C^0 is the virus concentration at air- liquid interface, ρ is the bulk density of the soil, $a_v$is the air content, D^w and D^g is the dispersion coefficient of liquid and gaseous state, q is the water flux, λ is the first order inactivation rate co-efficient in aqueous virus, λ^* is the first order inactivation rate co-efficient of sorbed viruses at liquid-solid interfaces, λ^0 at air-liquid interfaces.

From eqn. (1) it is clear that the equation is nonlinear as both the hydraulic conductivity and moisture content depends on the pressure head. So the constitutive relation given by Van Genuchten (1980) is considered in this study.

Constitutive Relationships

The relationship proposed by van Genuchten's (1980) gives the relationship between $\theta - \psi$ and $K - \theta$ as follows

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha\psi|^n)^m} \qquad (3)$$

$$K(\psi) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m\right]^2 \qquad (4)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (5)$$

Where, θ_r is the residual water; θ_s is the saturated water content; n and m (= 1 – 1/n) are unsaturated soil parameters, l is the pore connectivity parameter ; K_s is the saturated hydraulic conductivity ; and S_e is effective saturation.

2.1.1 *Initial and Boundary condition for moisture flow:*

$$t=t_0, \quad \psi = \psi_0 = -1000\text{cm} \quad 0 \le z \le L \qquad (6)$$

$$t > 0, \quad (\frac{\partial \psi}{\partial z} = 0), \qquad z = L \qquad (7)$$

$$\left|-k\frac{\partial \psi}{\partial z} - k\right| \le E \qquad (8)$$

Where, ψ_0 is the initial pressure head potential and E is the maximum potential rate of infiltration or evapotranspiration under the current atmospheric conditions. Eqn. (6) indicates that the initial pressure head potential is uniformly distributed within the medium. Whereas, Eqn. (7) gives an atmospheric boundary condition with surface runoff and Eqn. (8) implies a free draining bottom boundary.

2.1.2 *Initial and Boundary condition for virus transport:*

$$C(0,z) = C^*(0,z) = C^0(0,z) = 0 \quad (9)$$

$$\frac{\partial C(t,\infty)}{\partial z} = 0 \quad (10)$$

$$C(0,t) = C_0 \quad (11)$$

$$-D_z\frac{\partial C}{\partial z} + qC = qC_0 \quad (12)$$

Where, the initial condition given by Eqn. (9) establishes that there is no initial liquid phase and adsorbed virus concentrations within the porous medium. The lower boundary condition given by Eqn. (10) preserves concentration continuity for a vertical soil profile. For the upper boundary condition Eqn. (11) represents the case of constant concentration at inlet, while Eqn. (12) represents the case of constant flux at inlet.

2.2 Input data:

Table 1: The different soil parameters that are considered in this study are given below.

Type of soil	loam	Silt clay
θ_r	0.078	0.07
θ_s	0.43	0.36
K_s (cm/day)	24.96	0.48
l	0.5	0.5
n	1.56	1.09
α(cm^{-1})	0.036	0.005
ρ(g/cm^3)	1.43	1.24

Table 2: Solute Transport parameters used in this study:

Parameter	Value	units	Reference
α_z	15	cm	HYDRUS-1D tutorial
D_z^w	0.825	cm^2/day	-do-
D_z^w	7128	cm^2/day	-do-
H	0.066		-do-
	PRD1		
K_d	0.041	ppm	Anders and Chrysikopoulos, 2009
λ	0.0021	day^{-1}	-do-
λ^*	0.00204	day^{-1}	-do-
λ^0	0.12	day^{-1}	-do-
	MS2		
K_d	0.137	ppm	Anders and Chrysikopoulos, 2009
λ	0.06	day^{-1}	-do-
λ^*	0.066	day^{-1}	-do-
λ^0	0.0708	day^{-1}	-do-

3 MODEL SIMULATION:

The flow and transport model for a heterogeneous soil profile upto a depth of 160 cm (upto 100cm it is loamy soil type and after that it consist of silt clay soil till 160cm)from the ground surface is developed. This model is simulated for 300 days of the year 2013. The soil profile is divided into ten equal zone such that Δz = 16 cm and at the centre of each zone a node (Ni) is considered. The node N1 is at 8cm, N2 at 24 cm, N3 at 40 cm respectively from the ground surface. The result obtain will give the variation of pressure head, water content and concentration of both the virus with time. In this model the source of virus MS2 and PRD1 is assumed to be active with concentration unit (C_0=1) for 200 days and after that it is been considered as inactive (C_0=0) for the remaining 100 days.

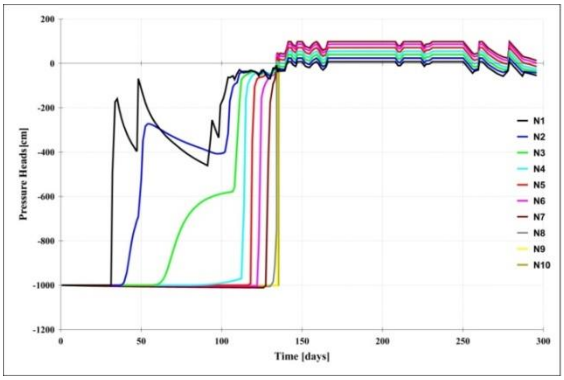

Fig.1: Variation of nodal pressure head(ψ) for different time period (days).

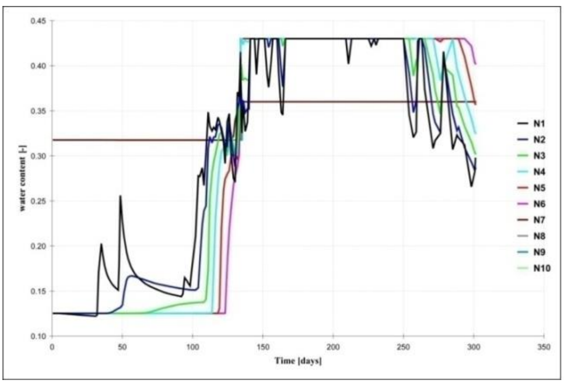

Fig.2: Variation of nodal water content(θ) for different time period (days).

Figure 1 and 2 provides the variation of pressure head and water content for different observation node with respect to its depth. The important observation from the figure is that there is a increase in water content and pressure head in loamy soil type as compared to the silt clay soil type. The reason may be as the rate of infiltration in silt clay is less than the loam soil so more amount of water remains onto the loamy soil profile.

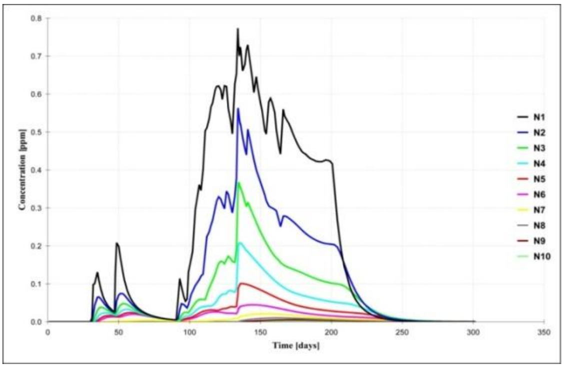

Fig.3: Variation of concentration MS2 virus at different observation node and time period.

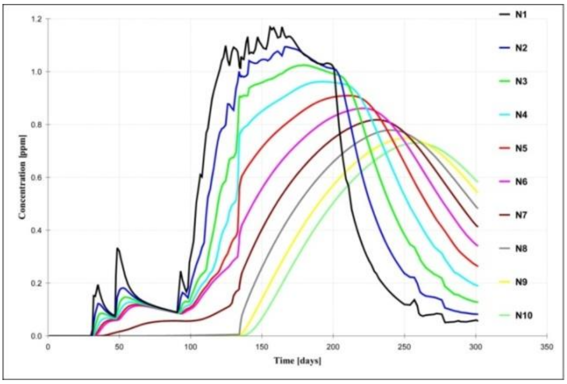

Fig.4: Variation of concentration PRD1 virus at different observation node and time period.

Figure 3 and 4 shows the concentration variation of virus MS2 and PRD1 for different observation nodes. The figure indicates that decrease in the aquifer moisture content leads to a substantial reduction in the liquid phase virus concentration. Thus, moisture content is one of the relevant parameter for both aqueous and sorbed virus.

4 SUMMARY:

In case of heterogeneous soil, a change in all the flow parameters and concentration are observed when the soil layer changes from loamy soil to silt clay soil type. It is observed that the viruses were transported more rapidly and in higher concentrations in loamy soil than the silty clay soil. The reason is that, the hydraulic conductivity is higher in loamy soil than the silt clay soil so water and contaminants gets transported faster in loamy soil. Powelson and Gerba (1994) suggested that size of the viruses may be considered as another important parameter if the porous media is highly hetergeneous, where virus may move faster than conservative tracers. From the result, it is observed that the virus MS2 is found to be transported faster than the virus PRD1.Since the size of MS2 virus is small (≈ 25nm) compared to the PRD1 virus (≈ 62nm) so the virus MS2 will get transported faster than the PRD1 virus.

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