MODELING TRANSPORT OF *CRYPTOSPORIDIUM PARVUM* OOCYSTS IN OVERLAND FLOW

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ABSTRACT

Cryptosporidium, a manure-borne protozoan parasite that is common in the environment, has recently been recognized as an important microbial contaminant of water. *Cryptosporidium parvum* (*C. parvum*) can cause infection and diarrhea in many mammalian hosts, including humans. Because cattle, particularly calves, are considered a major source of *C. parvum*, it is important to understand the movement of these pathogens from feedlots to water supplies. Vegetative filter strips (VFSs) are an established best management practice for sediment and nutrient removal from feedlots, but their influence on movement of microbial pathogens is not well understood.

The potential of *C. parvum* oocysts from feedlots entering surface water through overland flow is perceived as one of the major threats to drinking water quality. VFSs are often positioned between the feedlot and surface water to remove a portion of the oocysts exiting the feedlot. Transport and partitioning of *C. parvum* in soil and water systems have been evaluated by microplot studies and saturated column experiments. In field-scale systems, the dynamics are often quite complex. The simplest case of overland-flow transport of oocysts is one in which a VFS infiltrates all runoff inflow. In this case, retention of all water also means retention of all oocysts. When runoff occurs from a VFS, it has been found that the number of oocysts exiting during a runoff event depends on several factors: the extent of entrainment of oocysts from manure, transport characteristics of oocysts (e.g., advection, dispersion, diffusion, and settling in the runoff water), adsorption and straining of oocysts induced by interactions with plants substrates, and death and predation of oocysts.

This paper will describe the development and implementation of a model for simulating removal of *C. parvum* oocysts from overland flow. Transport of oocysts through a VFS is simulated mathematically by including terms for the concentration of the oocysts in the liquid phase (in suspension or free-floating) and the solid phase (adsorbed to the solid particles). Advection, adsorption, and decay processes are modeled. The model also accounts for the potential ranges of all hydraulic, transport, and die-off kinetic parameters. The hydrology and sediment deposition is determined using an existing VFS model (VFSMOD) that simulates the hydrology and sediment filtration in buffer strips, and generates output files containing values for water outflow and sediment trapping on the VFS. This paper describes the numerical solution of spatial and temporal changes in oocyst concentrations in two phases, and the development and implementation of the interface between the developed model and VFSMOD. Future work will compare the model results with field data.

Key words: *cryptosporidium parvum, overland flow, sediment filtration*

INTRODUCTION

Waterborne outbreaks of cryptosporidiosis have been reported from around the world associated with the consumption of contaminated drinking water or the ingestion of recreational waters contaminated with *C. parvum* (Mackenzie et al., 1994; Lisle and Rose, 1995; Hancock et al., 1997; Frey et al., 1998).

Overland transport of oocysts in feces and manure from domestic farm animals and infected wildlife into watercourses has been suggested as a possible source of oocysts in rural watershed areas (Madore et al., 1987; Ongerth and Stibbs, 1987; Rose, 1988; Rose 1990). Nonpoint-source surface water contamination results from infected animals defecating directly into streams or other bodies of water, from transport through subsurface drains, and from runoff of manure applied to fields or defecated in fields or feedlots.

Given the range of variables that affect pathogen concentrations at reservoir or river source points for drinking water, models for their survival and transport continue to be valuable tools for watershed management. Several modeling efforts have taken into account bacterial growth and/or death in both suspended (free-floating) and filtered (adsorbed) forms (Peterson and Ward, 1989; Klawitter, 1998). Their transport in overland flow is assumed to occur in two phases: free-floating in water, or attached to fecal matter or sediments. To predict transport of oocysts in both phases, the runoff volume and sediment yield in a watershed catchment due to a storm or a series of storms should be determined by models or actual field data. If the oocyst concentrations in both runoff and sediment can be predicted, the number of *C. parvum* oocysts in the flow could be estimated from the runoff volume and sediment yield.

MODEL DEVELOPMENT

Detached oocysts from the ground can migrate downslope in overland flow in two possible modes. First, oocysts can be transported free-floating in water. Second, they can migrate while being attached to sediment particles. Both modes of transport are subject to decay due to numerous factors. Such factors may include deposition of sediment particles to which oocysts are attached or the filtering out of free-floating oocysts by vegetation.

The deposition decay rate of oocysts in the attached phase is assumed to be proportional to the concentration of oocysts in the transported sediment. The possibility that previously deposited sediment particles are picked up again due to increased transport capacity of the flow will be lumped into the decay rate constant, *rs*. Similarly, the decay rate for free-floating oocysts is assumed to be proportional to the concentration of free-floating oocysts in the flow. The possibility that oocysts stuck to vegetation or adsorbed to sediment may get detached and resuspended in the flow due to increased shear stress of the flow will be incorporated into the lumped free-floating decay rate constant, r_f.

The transport of *Cryptosporidium parvum* (*C. parvum*) by overland flow can be considered to proceed in two phases. The total number of oocysts in the flow during runoff can be expressed as follows:

$$N = M_s \cdot C_a + V \cdot C_f$$

where N is the number of *C. parvum* oocysts in the flow after a runoff event (number); M_s is the mass of sediment load in the flow (M); C_a is the concentration of attached oocysts in the transported mass (number/M); V is the runoff volume from the field (L^3); and C_f is the concentration of free-floating oocysts in the runoff (number/L^3). Note that units for C_a and C_f are number of oocysts per unit sediment mass and number of oocysts per unit water volume, respectively. The sediment mass and runoff volume needed for calculating the total oocyst number will be determined by means of a suitable hydrological watershed model. The main task of the model developed here will be to determine the oocyst concentration in both sediment and water.

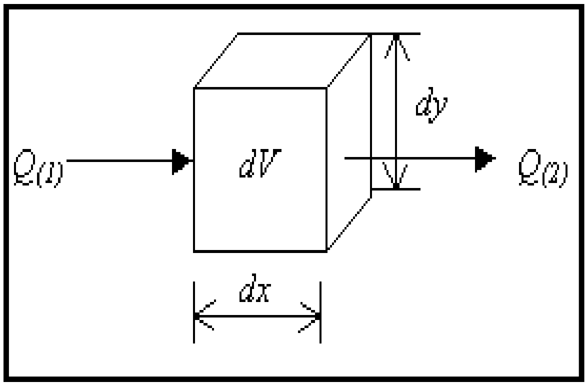

Figure 1. Element volume for mass balance of *C. parvum* oocysts.

Figure 1 is used to help describe the mass balance of *C. parvum* oocysts within an element volume of the overland transport path. This element volume has a unit width, a height of *dy,* and an incremental length of *dx* in the flow direction. It is used to develop a mass balance equation for oocysts in both free-floating and attached phases.

A mass balance on the oocysts in the attached phase yields

(2)

Here, dM_s can also be expressed as

$$dM_s = C_s \cdot dV$$

where *Cs* is the sediment concentration in the flow (M/L^3); *Q* is the flow velocity (L/T); *rs* is the lumped decay constant (first-order) in the sediment phase (T^{-1}); $dA = width \cdot dy$ (L^2); and $dV = width \cdot dx \cdot dy$ (L^3).

The equation for the number of free-floating oocysts is developed similarly.

$$\frac{\partial C_f}{\partial t} dV = \left(QC_f\right)_{(1)} dA - \left(QC_f\right)_{(2)} dA - r_f C_{f(2)} dV \qquad (3)$$

Here, r_f is the lumped first-order decay constant in the water phase (T^{-1}).

Equations (2) and (3) represent temporally and spatially dependent differential equations for the number of attached and free-floating oocysts, respectively, where all variables can be functions of both space and time. These equations need to have initial and boundary conditions. Since there is no flow at the start of an event, C_a and C_f in the VFS inflow are needed with time.

The aim of equations (2) and (3) is to calculate C_a and C_f. All other variables, such as M_s, *V,* and *Q*, need to be known prior to calculation. These variables will be obtained from the VFSMOD that simulates the hydrology and sediment filtration in buffer strips and generates outputs files containing data about water outflow and sediment trapping on the strip. The strength of the VFSMOD is its reasonable description of the hydrology within the filter area, which is essential for achieving good sediment outflow predictions or trapping efficiency. VFSMOD generates output files containing values for water outflow and sediment trapping on the VFS, which will then serve as the input files for the model developed in this work.

MODEL SOLUTION USING VFSMOD SIMULATION RESULTS

Equations (2) and (3) can account for different slope angles and surface roughness along the flow path, since parameters such as *V, Q,* M_s, and C_s are directly related to the watershed topography. This is important for hill slopes that are complex in shape and have a heavily varying vegetation density.

Equations (2) and (3) can be rewritten as:

$$\frac{\partial C_a}{\partial t} = \frac{1}{C_s}\left[-\frac{\partial(Q\cdot C_s\cdot C_a)}{\partial x} - r_s\cdot(C_s\cdot C_a) - C_a\frac{\partial C_s}{\partial t}\right] \quad (2')$$

$$\frac{\partial C_f}{\partial t} = -\frac{\partial(Q\cdot C_f)}{\partial x} - r_f\cdot C_f \quad (3')$$

Equations (2') and (3') can be solved numerically by an explicit finite difference solution scheme. Rewritten in finite difference form as

$$\frac{(C_a)^j_{i+1}-(C_a)^j_i}{\Delta t} = \frac{1}{(C_s)^j_{i+1}}\left[-\frac{(QC_s)^j_{i+1}(C_a)^j_{i+1}-(QC_s)^j_{i+1}(C_a)^{j-1}_{i+1}}{\Delta x} - (r_sC_s)^j_{i+1}(C_a)^j_{i+1} - (C_a)^j_{i+1}\frac{(C_s)^j_{i+1}-(C_s)^j_i}{\Delta t}\right] \quad (4)$$

$$\frac{(C_f)^j_{i+1}-(C_f)^j_i}{\Delta t} = -\frac{(QC_f)^j_{i+1}-(QC_f)^{j-1}_{i+1}}{\partial x} - (r_fC_f)^j_{i+1} \quad (5)$$

where i denotes a point in the time grid and j a point in the space grid. Therefore, as long as we know the data for Q, C_s, r_s, and r_f at a given time (i) and location (j) and assume that the conditions at $t = 0$ and $x = 0$ are known, the concentrations of oocysts in both the attached phase and the free-floating phase can be computed. Or, with available field data for C_a and C_s, we can estimate the parameters r_s and r_f.

Due to the fact that VFSMOD only provides water flow velocity and sediment particle concentration data at five individual points (i.e., the inflow, three intermediate points, and the outflow), we have only five data points for Q and C_s along the overland flow path. These five points divide the flow zone into four sub-zones. As described in the VFSMOD user manual, they are designated as zones A(t), B(t), C(t), and D(t). Within zone A(t), the depth of the sediment wedge is assumed to be constant. Starting from zone B(t), soil particles deposit and the load of sediment decreases.

The oocyst model can be applied to each sub-zone by assuming that the flow rate of water and the concentration of soil particles in the water phase are constant across each sub-zone. Thus, we can simplify Equations (4) and (5) into the following forms:

$$(C_a)^j_{i+1} = \frac{(C_a)^j_i - \frac{\Delta t}{\Delta x}(C_a)^{j-1}_{i+1}}{2 - r_s\Delta t + Q\frac{\Delta t}{\Delta x} - \frac{(C_s)^j_i}{(C_s)^j_{i+1}}} \quad (6)$$

$$(C_f)^{j+1}_{i+1} = \frac{(C_f)^j_i - \frac{\Delta t}{\Delta x}(QC_f)^{j-1}_{i+1}}{1 + \frac{\Delta t}{\Delta x}Q - r_f\Delta t} \quad (7)$$

MODEL IMPLEMENTATION

For the *C. parvum* transport model to make use of the values for water outflow and sediment trapping on the VFS generated by VFSMOD, we need to establish a connection between the VFSMOD output files and our simulation implementation. Therefore, an interface between the VFSMOD output files

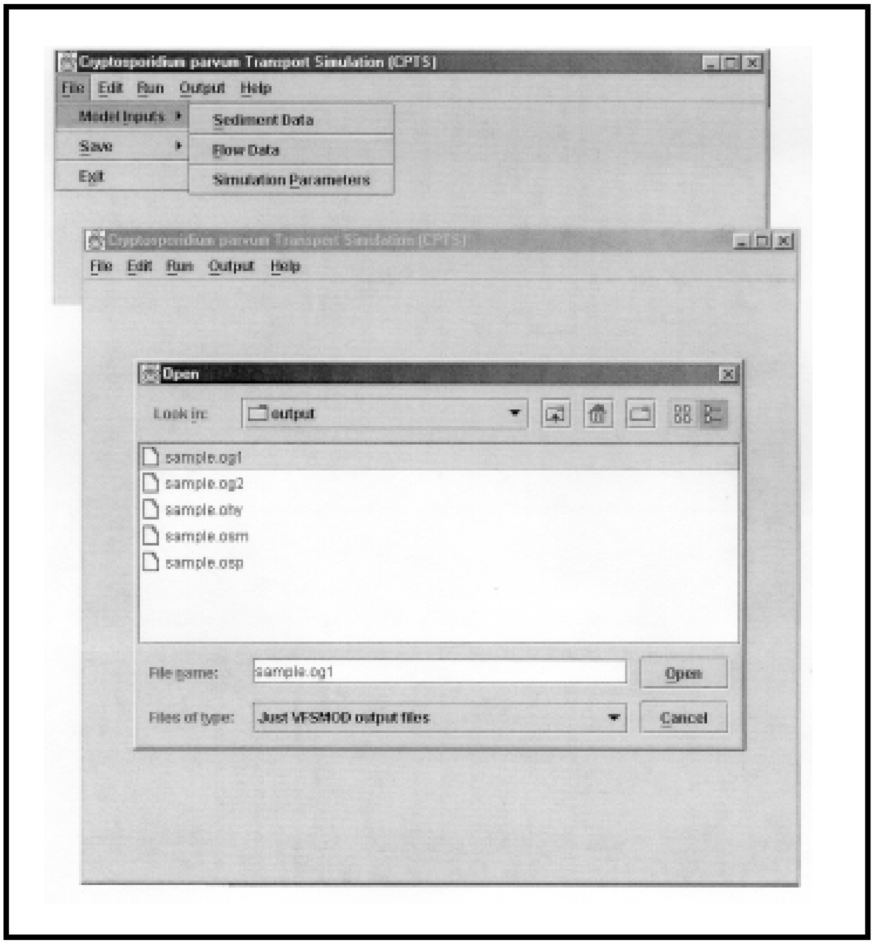

Figure 2. GUI for input water flow data and sediment load data from the output files generated by VFSMOD.

and the input of the *C. parvum* transport model was implemented. A graphical user interface was designed to allow the user to fetch data for water flow and sediment loads in overland flow, and to input decay parameters for the simulation. The interface is presented in Figure 2. Another window is designed to take input from the user for r_s and r_f. After reading in the flow and sediment data and the simulation parameters (r_s and r_f), the simulation can be started. The simulated concentrations of *C. parvum* oocysts in the attached and free-floating phases as functions of time and space can be saved and displayed by using the windows shown in Figure 3. The displaying program is still under development; hopefully it will be able to display free-floating and adsorbed oocyst results in the same manner as the current version of VFSMOD displays water balance and sediment balance results.

The *C. parvum* transport model only simulates transport during a rainfall-runoff event. Oocyst population dynamics between events may influence the pool of oocysts available for detachment and resuspension during the runoff event. Currently, these influences must be included in the lumped decay constants.

SUMMARY

A two-phase model was developed to

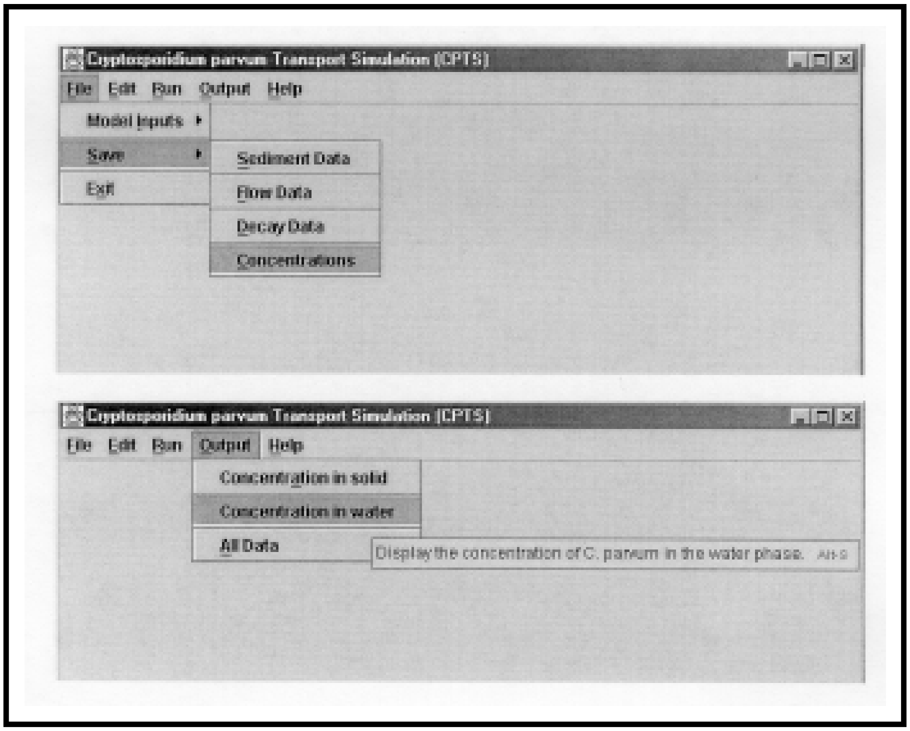

Figure 3. Saving and displaying the simulation results for the *C. parvum* oocyst concentrations.

simulate the transport of oocysts through a VFS. The model includes terms for the concentration of the oocysts in the water phase and the sediment particle phase. It also takes into account the potential ranges of values of all hydraulic, transport, and die-off kinetic parameters. The hydrology and sediment-deposition parameters were obtained from the simulation results of an existing VFS model (VFSMOD). An interface between the oocyst model and VFSMOD was implemented to allow data communication for the simulation. Due to the limited hydraulic and sediment data output by VFSMOD, water flow rates within each sub-zone were assumed to be constant. This assumption, however, may have resulted in unstable computation of the concentrations. Further work is underway to account for variable flow rates along each sub-zone length and to analyze parameter sensitivities.

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