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EVALUATING UNCERTAINTY IN *E. COLI* RETENTION IN VEGETATED FILTER STRIPS IN LOCATIONS SELECTED WITH SWAT SIMULATIONS

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Abstract. Vegetated fulter strips (VFS), as a best management practice, have become an important component of the water quality improvement in watersheds. The SWAT model allows for a comprehensive description of agricultural practices, and has proven to be efficient in applications to watershed with a substantial agricultural component. The REMM, KINEROS, and other models have recently been suggested to use SWAT output to evaluate the VFS retention capacity with respect to nutrient and sediment loads. The concern about the manure-borne pathogens in waterways and water bodies has to be addressed in more details by estimating the efficiency of VFS in pathogen retention. The existing knowledge base shows that the functioning of VSF as barriers for manure-borne pathogens to the large extent depends on vegetation status, soil infiltration capacity in VFS, and rainfall intensity and duration. The effect of these factors on the pathogen breakthrough in VFS needs to be researched at the time scales smaller than the computation interval of one day that SWAT uses. The downscaling of the SWAT output to the smaller time scales, however, introduces an uncertainty. We have developed the model STIR to simulate the overland transport and loss to infiltration of manure-borne pathogens in VFS. This model was used in Monte Carlo simulations to evaluate the possible variability in pathogen breakthrough in VFS with inputs from SWAT. The simulations show that probabilistic characterization of the VFS efficiency with site-specific soil and weather properties can be useful in making decisions on VFS placement with respect to manure-borne pathogens.

Keywords. SWAT, water quality, pathogens, indicator organisms, vegetated buffer strip, STIR model, uncertainty

INTRODUCTION

Vegetation filter strips (VFS) are commonly used to decrease the pollutant loads from manured fields and pastures. Using SWAT simulations has been suggested to make decisions about the VFS placement. One needs to select parameters of a particular VFS and assess its reliability after a decision about the VFS location is made. The REMM, the KINEROS, the VFSMOD and other models have recently been suggested to use SWAT output to evaluate the VSF retention capacity with respect to nutrient and sediment loads (Allison et al., 2006; EPA, 2005, Goodrich et al., 2006).

By the frequency of being the cause of water quality impairment, pathogens rank first and second among five leading pollutants in estuaries and rivers, respectively, in the United States (EPA, 2004). A wide range of opinions exists on the VFS efficiency with respect to pathogens and/or indicator organisms (Pachepsky et al., 2006). Tools to evaluate the efficiency of VFS and select its parameters with respect to manure-borne pathogens have been developed in 80th. They include the Agricultural Runoff Management II: Animal Waste Version (ARM II) model (Overcash et al., 1983), the Utah State (UTAH) model (Springer et al., 1983), the MWASTE model (Moore et al., 1988), and the COLI model (Walker et al., 1990).

Recent interest to the fate and transport of manure-borne pathogens has generated a substantial increase in data on fate and transport of pathogens and indicator organisms in VFS. Several excellent reviews have been published (Jamieson et al., 2002, Ferguson et al., 2003, Tyrrel and Quinton, 2003, Unc and Goss, 2004, Oliver et al., 2005). The existing knowledge base shows that the efficiency of VFSs as barriers for pollutants depends to large extent on soil infiltration capacity in a VFS and soil moisture content before the rain event, vegetation status and microtopography, and rainfall intensity and duration (Munoz-Carpena et al., 1999; Helmers et al., 2006). The effect of these factors on the pathogen breakthrough in VFS needs to be researched at time scales smaller than the computation interval of one day that SWAT uses. The downscaling of daily values of weather variables and SWAT outputs to the smaller time scales inevitably introduces an uncertainty. Another source of uncertainty for the VFS evaluation is the spatial scale of information about VFS soil and vegetation properties, and its management.

The objective of this work was to research the opportunities for the VFS evaluation in the uncertainty framework using the model STIR (Solute Transport with Runoff and Infiltration) that we have under development (Kouznetsov et al., 2006).

MODEL STIR

The STIR model has several components to handle flow and transport. In this work, we have employed fairly common overland flow and transport components.

Model parameters

The overland flow component uses the kinematic wave equation for the runoff flow and the Green-Ampt equation for infiltration. The selection of empirical formulas in these two equations has been based on the availability of look-up tables for the empirical parameters in these formulas. In particular, the depth-discharge relationship is used the form

$$q = \alpha h^{\frac{3}{2}} , \tag{1}$$

where q is the water flux cm^3 h^{-1}, h is the water depth along the slope cm, the parameter α is computed according the Manning hydraulic resistance law and depends on the slope and Manning's roughness coefficient n.

The matric suction at the wetting front in the Green-Ampt infiltration equation ψ_m is estimated from van Genuchten soil water retention parameters θ_s, θ_r, n_{VG}, α_{VG} and initial soil water content θ_0 as

$$\psi_m = \left[\left((\theta_s - \theta_r)/(\theta_o - \theta_r)\right)^{n_{VG}/(n_{VG}-1)} - 1\right]^{1/n_{VG}} / \alpha_{VG} \tag{2}$$

The transport component simulates the convective-dispersive transport in overland flow with the reversible attachment of microorganisms to surface layer and straining of microorganisms from the infiltrating water in the surface soil layer. The dispersive solute flux Q in the overland flow is proportional to the water flux:

$$Q = -\lambda q \frac{\partial c}{\partial l} \tag{3}$$

where λ is the dispersivity, cm. The attachment rate A, cell cm^{-2} h^{-1}, is given as

$$A = \rho d \frac{K_s c - s}{\tau} \tag{4}$$

where ρ is the topsoil bulk density, d is the thickness of the topsoil layer that actively interacts with the overland flow, K_s is the bacteria partitioning coefficient, g cm^{-3}, τ is the attachment rate constant, h^{-1}, c is the cell concentration in runoff water, cell cm^{-3}, s is the attached amount of cells, cell g^{-1}. The lumped attachment-detachment term (4) includes adsorption of cells to soil and to plant litter as well as the temporary retention in surface microponds and stagnant zones of the overland flow.

The straining rate B is assumed to be proportional to the infiltration rate I:

$$B = I K_{str} c \tag{5}$$

where I is the infiltration rate, cm h^{-1}, K_{str} is the proportion of infiltrating cells that are strained.

Example of calibration study

We are using six-meter long instrumented runoff plots with slopes of 5%, 10%, and 20% that we have instrumented in Beltsville, MD. Paired similar plots are set on sandy loam and on clay loam soils in triplicate. The extremes are represented by bare plots and by plots under the established grass mixture cover. A 30-min one year return rainfall event is simulated to collect the background concentrations of Cl, fecal coliforms and *E. coli*. A solution of KBr or $CaCl_2$ is added in fresh bovine manure to have Br^- or Cl^- as a tracer, the 30-cm wide strip of that manure is laid on the top of the plots and the rainfall simulations are performed for 1 h at bare plots and for 2 h at the vegetated plots. Runoff samples are taken each 5 minutes from the gutter at the bottom of the slope and analyzed for the tracer, fecal coliforms and E. coli concentrations. Surface roughness, biomass concentration, and ground cover are measured before each runoff experiment. Soil moisture contents, soil water retention, bacteria concentrations in soil are measured after experiments. The release of bacteria and tracer is studied at separate plots (Guber et al., 2006) and the developed release models are used in all STIR model runs.

The only parameter of the hydraulic component of the STIR model to calibrate was the soil saturated hydraulic conductivity. The Manning roughness coefficient n was set to 0.09 for the grass plots and 0.035 for bare plots. The hydraulic component of the STIR model after the calibration performed satisfactorily as shown in Fig. 1.

The transport component was first calibrated with Cl^- or Br^- data to obtain the value of the dispersivity λ in (3) as no attachment or straining was considered for the tracers. Then the attachment and the straining modules were calibrated with data on fecal coliforms using the dispersivity value found from the tracer data.

The model abstraction methodology of Pachepsky et al. (2006) has been used in the calibration process. The complexity of the model has been progressively decreased until the parameter set became robust.

The performance of the calibrated model is shown in Fig. 2. It is generally satisfactory except the simulations of concentrations in the very first portions of runoff which indicate the presence of the concentrated flow. Simulating attachment was essential for both bare and vegetated plots whereas simulating surface straining was not needed at vegetated plots.

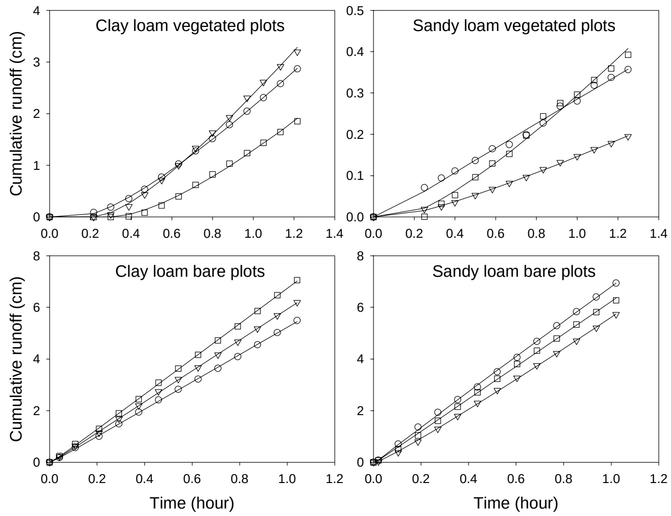

Figure 1. Results of the runoff and infiltration module calibration. Different symbols show replications in measurements, lines show simulation results.

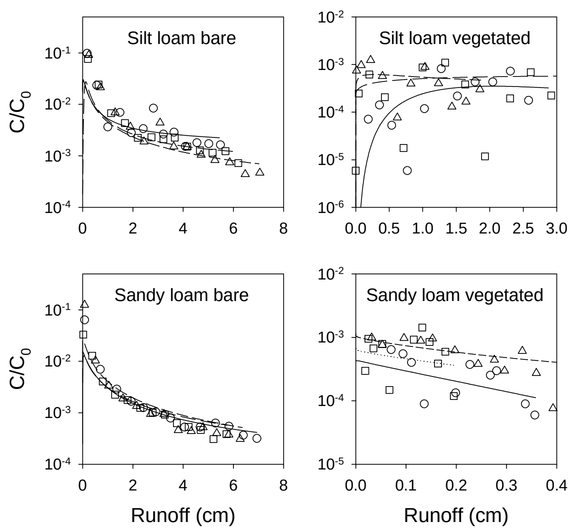

Figure 2. Results of the bacteria transport module calibration. Different symbols show replications in measurements, lines show simulation results.

SENSITIVITY AND UNCERTAINTY OF THE VFS EFFICIENCY

The VFS efficiency has been defined as the percentage of bacteria that exited the strip in runoff after entering the strip.

Sensitivity of the VFS Efficiency

The effect of model parameter values on the simulated VFS efficiency was assessed in a set of simulations in which bacteria were released from manure applied on a 200-m field under the simulated rainfall and moved with runoff through a 6-m long vegetated buffer strip set at a homogeneous clay loam soil profile.. The base set of model parameters and initial and boundary values were as follows. The rainfall intensity was 2.5 cm h-1, the rainfall duration was 1h, the van Genuchten parameters were θ_s=0.447, θ_r=0.085, n_{VG}=1.42, α_{VG}= 0.0125 cm^{-1}, the initial water content θ_0=0.35, the saturated hydraulic conductivity K_{sat}=0.467 cm h^{-1}, Manning's *n*=0.035 for the field and 0.090 for the vegetated buffer strip, the dispersivity λ=65000 cm, the partitioning coefficient K_s=1 cm^3 g^{-1}, the attachment rate constant τ=0.5 h^{-1}, the straining parameter K_{str}=0, and the thickness of the active soil layer *d*=5 cm. The sensitivity to a parameter was assessed by running the model with the parameter of interest varying in a reasonable range and all other parameters taken constant at or close to the base set values.

The results of simulations are shown in Fig. 3. The efficiency of the filter strip decreases after the rainfall intensity exceeds 2.6 cm h^{-1} (Fig 3a). Long rainfall can exhaust the filtering capability of the trip (Fig. 3b). High initial soil water contents cause the decrease in the efficiency (Fig. 3c). The increase in the roughness of the soil surface in the filter strip improves its efficiency (Fig. 3d). Low soil saturated hydraulic conductivity and or large van Genuchten parameters n_{VG} tends to decrease the efficiency (Fig. 3e and 3f). The increase in the partitioning coefficient and/or the decrease in the attachment rate constant generally increase the efficiency of the strip (Fig. 3g and 3h). Increase in dispersivity causes the decrease in the strip efficiency (Fig. 3i).

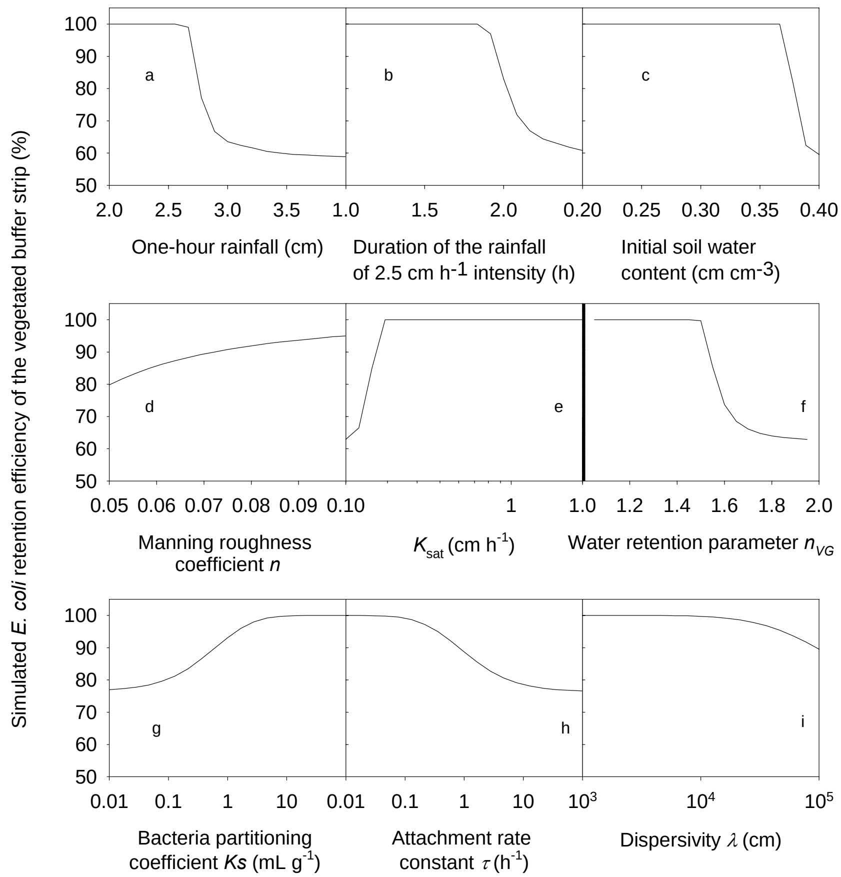

Figure 3. Sensitivity of the vegetated filter strip efficiency to model parameters and rainfall characteristics.

<u>Estimating Uncertainty in Model Inputs and Parameters</u>

The correct interpretation of the sensitivity results depends on the statistical distributions of parameters and weather-dependent inputs of the model. For example, if the 2.5 cm h^{-1} rainfall is rarely longer that 1.6 hours, the VFS will be efficient most of the time (Fig. 3). The NOAA National Weather Service has documented regional rainfall "intensity-duration-frequency" relationships. Local data can be used to fit an "intensity-duration-frequency" equation, for example, $R = A*T^m/(d+b)^n$ where R is the rainfall intensity, d is the duration, and T is the return period as discussed by Koutsoyiannis et al. (1998). Using local data is preferable if the efficiency of the VFS is of interest for a specific period of time within a year, e.g. after manure application. The distribution of initial water contents should be obtained from soil water simulations with a crop or grassland model. Ranges of the Manning roughness coefficient are given for specific vegetation types in multitude of published tables. We have used the uniform distribution within these ranges when no other data are available.

Distributions of soil water retention and soil hydraulic conductivity parameters have been summarized by Meyer et al. (1997) and by Rawls et al. (1998), respectively (Table 1). With limited data on the overland transport parameters, we have used the lognormal distributions L(-0.291,0.760), L(-1.13,0.345), and L(10.46,1.111) for the bacteria partitioning coefficient K_s, the attachment rate constant τ, and the dispersivity λ, respectively.

Table 1. Statistical distributions of soil parameters by soil textural classes

Soil textural class	Parameters of the van Genuchten's soil water retention parameters (Meyer et al., 1997)				Ksat (cm h^{-1}) after Rawls et al. (1997)		
	θ_s cm^3cm^{-3}	θ_r cm^3cm^{-3}	α_{VG}, cm^{-1}	n_{VG}	P= 0.25[#]	P= 0.50	P= 0.75
Sand	N(0.430, 0.060)[§]	L(-3.09, 0.224)[§]	N(0.147, 0.025)	L(0.978, 0.099)	9.6	18.2	26.6
Loamy sand	N(0.410, 0.090)	N(0.057, 0.015)	N(0.125, 0.04)	L(0.816, 0.091)	8.4	12.3	19.5
Sandy loam	N(0.410, 0.090)	B(2.89, 2.30, 0.017, 0.102)[§]	B(1.82, 4.41, 0.008, 0.202)	L(0.634, 0.082)	3	5.6	13
Sandy clay loam	N(0.390, 0.070)	B(2.20, 2.01, 0.086, 0.114)	L(-3.04, 0.639)	L(0.388, 0.086)	0.2	0.77	5.05
Loam	N(0.430, 0.099)	B(3.64, 2.65, 0.037, 0.107)	B(1.58, 3.62, 0.003, 0.113)	L(0.442, 0.073)	0.16	0.39	2.8
Silt loam	N(0.450, 0.080)	B(3.35, 2.57, 0.024, 0.099)	L(-4.10, 0.554)	L(0.343, 0.085)	0.76	1.44	3.71
Clay loam	N(0.410, 0.090)	N(0.095, 0.010)	L(-4.22, 0.72)	N(1.32, 0.097)	0.22	0.42	1.31
Silty clay loam	N(0.430, 0.070)	N(0.088, 0.009)	L(-4.72, 0.56)	N(1.23, 0.060)	0.23	0.37	1.04
Sandy clay	N(0.380, 0.500)	B(4.00, 1.49, 0.056, 0.117)	L(-3.77, 0.56)	L(0.241, 0.065)	0.03	0.09	0.25
Silty clay	N(0.360, 0.070)	N(0.071, 0.023)	L(-5.66, 0.58)	L(0.145, 0.043)	0.05	0.18	0.75
Clay	N(0.380, 0.090)	B(1.50, 1.58, 0.001, 0.14)	L(-5.54, 0.89)	B(0.80, 1.55, 1.04, 1.36)	0.09	0.2	0.6

[§]N(a,b), L(a,b), and B(a,b,A,B) denote the normal distribution, the lognormal distribution, and the beta distribution with the probability density functions $f(x)=\frac{1}{\sqrt{2\pi}b}\exp\left[-\frac{1}{2}\left(\frac{x-a}{b}\right)^2\right]$, $f(x)=\frac{1}{\sqrt{2\pi}bx}\exp\left[-\frac{1}{2}\left(\frac{\ln(x)-a}{b}\right)^2\right]$, and $f(x)=\frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}\frac{(x-A)^{a-1}(B-x)^{b-1}}{(B-A)^{a+b-1}}$, respectively.

[#]Saturated hydraulic conductivities are given at three probability levels.

The Latin Hypercube sampling of soil, rainfall, and transport parameter space has been used to evaluate the probability of failure of the abovementioned vegetated clay loam plots to prevent the transport of pathogen indicator organisms from a 200-m stretch of a manured field in weather conditions of Beltsville, Maryland. No correlation was assumed in the random sampling of model parameter distributions.

The VFS efficiency was less than 100% in 5% of cases, and less than 75% in 2.5% of cases. Relatively long high-intensity rainfalls, low hydraulic conductivities, high soil moisture contents before the rainfall, and high dispersivities were the main sources of the strip partial failure.

DISCUSSION

The work with the model STIR has convinced us that some aspects of the bacteria transport in filter strips need further clarification.

- The controversy exists in literature on what proportion of manure-borne fecal coliforms or *E. coli* moves in the overland flow being attached to solids. The opinions range from full suspension in liquid (Edwards et al., 1996) to the up to 25% attachment to particulate matter (Schillinger and Gannon, 1985). Our data have shown a drastic decrease in E. coli attachment to soil-borne solids in presence of manure particulates (Guber et al.., 2005). Because vegetated buffers have been found to be most effective in trapping particulate pollutants (Dillaha et al. 1989, Schmitt et al., 1999; Helmers et al., 2006; Dabney et al., 2006), the model STIR may need to be amended by including some modules to simulate the sediment transport and the bacteria attachment to sediment.
- The VFS integrity may be compromised by the lack of vegetation, the vegetation patchiness, or other features that allow the bypass flow through the VFS and substantially decrease its efficiency. Although successful models of such flow and transport have been developed (Helmers et al., 2005), obtaining parameters for such models remains a challenge. The differences between velocities of different parts of the overland flow are represented as the hydrodynamic dispersion in the STIR model, but this may not be sufficient for cases with dominant bypass, or concentrated, flow.
- The VFS soils may be or may become rich in organic matter which can substantially affect soil hydraulic properties (Rawls et al., 2004). Relatively little is currently known about hydraulic properties of VFS soils as compared with soils in other land uses.
- The efficiency of the Monte Carlo simulations with the Latin Hypercube sampling substantially increases when the correlations among parameters are taken into account (Reckhow, 1994). Correlations among some of the STIR parameters are not known, correlations among others, e.g. hydraulic properties, are known in general but not for typical VFS conditions, and correlations among the rainfall parameters have to be defined locally. Also, the VFS efficiency analysis ought to be done for sequences of rainfall events during the period when the upland field remains a source of pathogenic microorganisms.
- Although a substantial uncertainty is found for the values of parameters that control efficiency of VFS, many parameter combinations provide the simulated VFS efficiency of 100%. Most of these parameters cannot be measured for a specific site but their statistical distributions can be estimated for the specific site using publicly available information.

CONCLUSION

The probabilistic characterization of the VFS efficiency in manure-borne pathogens retention with site-specific soil and weather properties can be useful in making decisions on the VFS placement and design.

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