Modeling *E. coli* Retention in Vegetated Filter Strips

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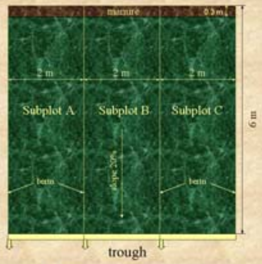
Abstract

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.

Objectives

1. To test the model STIR on the experimental data on fecal bacteria transport in VFS.
2. To assess effect of model parameters on simulated VFS efficiency.
3. To evaluate uncertainty in predicted VFS efficiency as related to the uncertainty in model inputs.

Plot Runoff Experiment



Layout of an experimental plot

Plot location: ARS Beltsville Agricultural Research Center

Soil texture: sandy loam, clay loam soils

Vegetation: bare, blue fescue (*Festuca ovina 'Glauca'*) and white clover (*Trifolium repens*)

Bovine manure application rate: 11.7 L m^{-2}

Irrigation rate: 7.22 ± 0.91 cm h^{-1}

Sample collection interval: 5 min

Measurements in runoff: volume of water, FC concentration

Measurements in sediment: FC content.

Rainfall simulation at the clay loam bare plot.

Model STIR

Overland flow: $q = \alpha h^{3/2}$ $\alpha = \sqrt{i}/n$

Dispersive solute flux: $Q = -\lambda q \dfrac{\partial C}{\partial l}$

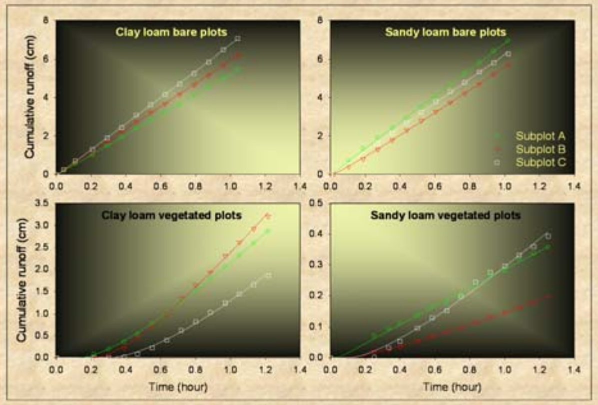
Soil-bacteria interaction: $A = \rho d \dfrac{K_s C - S}{\tau}$

Bacteria straining: $B = I K_{str} C$

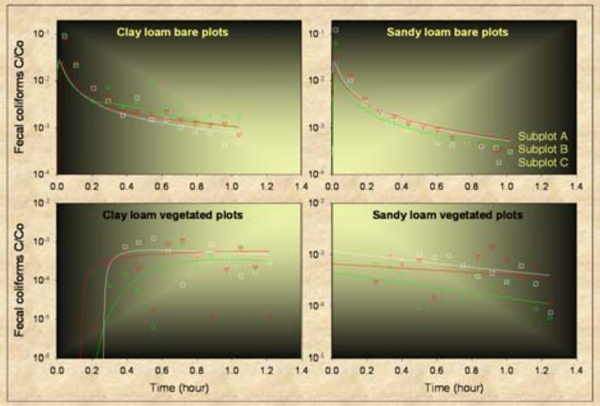
Infiltration: $I = K_{sat}\left[1 + \dfrac{\psi(\theta_s - \theta)}{F}\right]$

Soil-water retention: $\psi = \left[\left((\theta_s - \theta_r)/(\theta - \theta_r)\right)^{n_{VG}/(n_{VG}-1)} - 1\right]^{1/n_{VG}} / \alpha_{VG}$

h - water depth in the overland flow
n – Manning's roughness coefficient
i – surface slope
l – distance along the slope
λ – dispersivity
C - FC concentration in runoff water
S - FC amount attached to soil
ρ - topsoil bulk density
d - thickness of the topsoil layer
K_s - bacteria partitioning coefficient
τ – bacteria attachment rate constant
K_{str} - fraction of infiltrating cells that are strained
ψ – soil matric suction at the wetting front
θ_s, θ_r, n_{VG}, α_{VG} – van Genuchten parameters
θ - initial soil water content
K_{sat} – saturated soil hydraulic conductivity



Model fit (lines) to the measured runoff (symbols) data



Model fit (lines) to measured FC content in runoff (symbols)

Assessment of Vegetation Filter Strip 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 long 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:

Rainfall intensity - 2.5 cm h^{-1}; rainfall duration - 1h;

Initial water content θ = 0.35 cm^{3}cm^{-3}, thickness of the active soil layer d = 5 cm;

van Genuchten parameters: θ_s = 0.447 cm^{3}cm^{-3}, θ_r = 0.085 cm^{3}cm^{-3}, n_{VG} = 1.42, α_{VG} = 0.0125 cm^{-1};

Saturated hydraulic conductivity K_{sat} = 0.467 cm h^{-1};

Manning's n = 0.035 for the field and n = 0.090 for the vegetated buffer strip, dispersivity λ = 65000 cm;

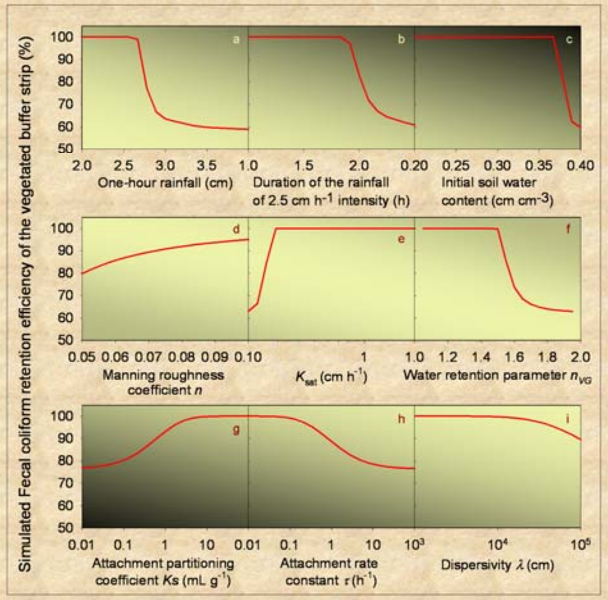
Bacteria partitioning coefficient K_s=1 cm^3 g^{-1}, attachment rate constant τ = 0.5 h^{-1}, straining parameter K_{str} = 0.

The efficiency of the filter strip decreases:

- after the rainfall intensity exceeds 2.6 cm h^{-1} (Fig. a);
- when long rainfall exhausted the filtering capability of the trip (Fig. b);
- with increase in initial soil water contents (Fig. c);
- for large van Genuchten parameters n_{VG} (Fig. f);
- with increase in the dispersivity (Fig. i).
- with increase in the attachment rate constant τ (Fig. h).

The efficiency of the filter strip increases:

- with increase in roughness of the soil surface in the filter strip (Fig. d);
- with increase in the soil saturated hydraulic conductivity (Fig. e);
- with increase in the partitioning coefficient K_s (Fig. g).



Model parameters effect on vegetation filter strip efficiency

Estimating uncertainty in model inputs and parameters

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.

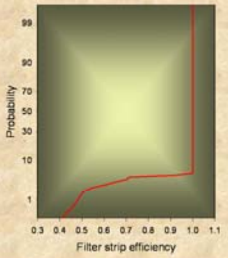


Table 1. Statistical distributions of soil parameters by soil textural classes

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^{3}cm^{-3}	θ_r cm^{3}cm^{-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.

Conclusions

1. The model STIR had a reasonable accuracy in fitting the experimental data on fecal bacteria transport in vegetated filter strips.
2. Statistical distributions of parameters of the STIR model can be estimated for a specific site using publicly available information.
3. Although a substantial uncertainty was found for the values of parameters that control efficiency of VFS, 95% of randomly chosen parameter combinations provided the simulated VFS efficiency of 100%.
4. 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.
5. 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. 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.
6. 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.
7. Overall, the probabilistic characterization of the VFS efficiency in manure-borne pathogens retention with site-specific soil and weather properties is possible and can allow one to quantify the uncertainty and risks associated with specific VFS placement and management.