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Design Guide for Vegetative Filter Strips Using VFSMOD

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Summary:

A front-end model, UH, was developed to generate the necessary source area inputs for VFSMOD. For each storm, UH generates a rainfall hyetograph, a runoff hydrograph, and sediment loss from the source area. The inputs are generated using a combination of the NRCS curve number method, the unit hydrograph, and the modified Universal Soil Loss Equation based on topography, land use and soil type. With these inputs, VFSMOD simulates overland flow and sediment dynamics within the VFS based on vegetation, soil type, and topography. The combined models, UH and VFSMOD, are used to begin development of a design guide for representative conditions in the Piedmont region of North Carolina. Simulations were conducted representing a vegetative filter width of 10 m representing a source area to filter width of 8%. Rainfall totals ranging from 16 mm to 150 mm were used to generate 6-hour storm hyetographs and runoff hydrographs from source areas with slopes ranging from 1% to 10%. VFSMOD was used to simulate these conditions using the outputs from UH. Analysis of VFS performance including graphs showing sediment delivery ratios are presented to demonstrate the utility of this approach.

Keywords: runoff, hydrograph, erosion, sediment, vegetative filter strip

Design Guide for Vegetative Filter Strips Using VFSMOD [1]

Abstract

VFSMOD is a field scale, mechanistic, storm-based model designed to route the incoming hydrograph and sedimentograph from an adjacent field through a vegetative filter strip (VFS) and to calculate the outflow, infiltration and sediment trapping efficiency. The model handles time dependent hyetographs, space distributed filter parameters (vegetation roughness or density, slope, infiltration characteristics) and different particle size of the incoming sediment. Any combination of unsteady storm and incoming hydrograph types can be used. The model has been field tested for different soil and climatic conditions in the uplands of the Piedmont and Coastal Plain areas of North Carolina.

A front-end model, UH, was developed to generate the necessary source area inputs for VFSMOD. For each storm, UH generates a rainfall hyetograph, a runoff hydrograph, and sediment loss from the source area. The inputs are generated using a combination of the NRCS curve number method, the unit hydrograph, and the modified Universal Soil Loss Equation based on topography, land use and soil type. With these inputs, VFSMOD simulates overland flow and sediment dynamics within the VFS based on vegetation, soil type, and topography.

The combined models, UH and VFSMOD, are used to begin development of a design guide for representative conditions in the Piedmont region of North Carolina. Simulations were conducted representing a vegetative filter width of 10 m representing a source area to filter width of 8%. Rainfall totals ranging from 16 mm to 150 mm were used to generate 6-hour storm hyetographs and runoff hydrographs from source areas with slopes ranging from 1% to 10%. VFSMOD was used to simulate these conditions using the outputs from UH. Analysis of VFS performance including graphs showing sediment delivery ratios are presented to demonstrate the utility of this approach.

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Introduction

Erosion continues to be a major nonpoint source of pollution for surface waters in many parts of the world. Chemicals and pathogens can be transported both in solution and attached to sediment. Phosphorus and some pesticides attached to sediment are a major pollution concern. Several land management practices targeted at the disturbed source area have been suggested to control runoff quantity and quality including conservation tillage contour plowing, and building terraces to reduce the length of slope. In addition, management practices such vegetative filter strips (VFS) have been suggested as potential erosion controls adjacent to the source area. Dillaha et al. (1989) defined these as areas of vegetation designed to remove sediment and other pollutants from surface water runoff by filtration, deposition, and infiltration. Vegetation at the downstream edge of disturbed areas may effectively reduce runoff volume and peak velocity primarily because of the filter's hydraulic roughness, and subsequent augmentation of infiltration. Decreasing flow volume and velocity decreases the transport capacity of the runoff thereby resulting into sediment deposition in the filter. Barfield et al. (1979) reported that grass filter strips have high sediment trapping efficiencies as long as the flow is shallow and uniform, and the filter does not become submerged during the storm event.

Unlike many other land conservation practices, performance and evaluation of vegetative filter strips should be done on a storm by storm basis. Muñoz-Carpena (1993) developed and tested a computer model (VFSMOD) to study hydrology and sediment transport through vegetative filter strips on a storm by storm basis. The model couples a hydrology submodel to describe overland flow and infiltration with a sediment filtration submodel developed at University of Kentucky by Barfield et al. (1979). The resulting model (VFSMOD) can handle complex storm pattern and intensity and varying surface conditions within the vegetative filter strip to evaluate runoff and sediment transport and deposition through the filter. One of the main drawbacks of VFSMOD is that the user must supply inflow hydrographs and sedimentographs from the source area in order to evaluate the filter strip performance.

In an effort to address this limitation to the application of VFSMOD, procedures to generate the source area inputs were implemented in a front-end program (UH). The main objective of the program was to use readily available algorithms and equations to generate inflow hydrographs and sediment for many expected source area conditions. The intent of this effort is to move to the concept of design storms to evaluate vegetative filter strip performance. This paper describes the development of UH to generate the necessary source area inputs for VFSMOD. An example suite of simulations for conditions in the Piedmont of North Carolina are presented to demonstrate how the combined UH-VFSMOD models can be used to evaluate vegetative filter strip performance on a storm by storm basis.

Design Guide Procedures

The procedure for developing a design guide for evaluating VFS performance on a storm by storm basis involves generating the source area inputs for VFSMOD for each design storm of interest. Using the inputs from the source area, VFSMOD simulates the transport and deposition of sediment within the VFS. The inputs from the source area are 1) a runoff hydrograph and 2) the sediment produced from the given storm. These inputs along with a rainfall hyetograph are generated with the model UH using readily available algorithms and equations, which are described in more detail below.

The development of the design guide for a particular area involves determining the size and duration of rainfall events, the range of source area conditions, and the lengths and types of vegetative composition of the VFS of interest. A matrix of inputs is prepared and the UH-VFSMOD models are used to simulate the combinations of inputs. The results are then developed into a graphical presentation to enable easy visual comparison. The resulting presentation can be used to assist users in determining the tradeoffs of management strategies such as increasing VFS length versus implementing improved land conservation practices in the source area.

Hyetograph Generation

Synthetic rainfall hyetographs were generated using equations based on the 24-hr rainfall storms and adjusted to the desired frequency. For storm types II and III, the best-fit approximation can be estimated by (Haan et al., 1994):

$$\frac{P(t)}{P_{24}} = 0.5 + \frac{T}{24}\left(\frac{24.04}{2|T| + 0.04}\right)^{0.75} \qquad [1a]$$

where T=t–12 with t in hours; and P_{24} = the 24 hour total rainfall (cm).

For storm types I and IA, a regression equation was obtained using tabulated data (Haan et al., 1994) as,

(type I):

$$\frac{P}{P_{24}} = \begin{cases} 0.4511 + (t-9.995)\left(\dfrac{-0.1617}{-3.0163|t-9.995|+0.013}\right)^{0.5853} & for \quad -3.0163|t-9.995|+0.013 < 0 \\ 0.5129 & for \quad -3.0163|t-9.995|+0.013 > 0 \end{cases} \qquad [1b]$$

(type IA):

$$\frac{P}{P_{24}} = 0.3919 + (t-7.960)\left(\frac{0.0843}{120.39|t-7.960|+0.3567}\right)^{0.4228} \qquad [1c]$$

with goodness-of-fit parameters of root mean square deviation of 0.0088 and 0.003, and χ^2=3.363 and 1.539, respectively.

For storm durations less than 24 hours, the ratio of $P(t)/P_{24}$ is used to derive the amount of rainfall at time t from the total rainfall for the period. To generate hyetographs for any duration, D in hours, and storm type, the equation of Haan et al. (1994) was modified to:

$$\frac{P(t)}{P_{24}} = \frac{P(t_{mid}+t-D/2)-P(t_{mid}-D/2)}{P(t_{mid}+D/2)-P(t_{mid}-D/2)} \qquad [2]$$

where t_{mid} is 9.995 for storm type I, 7.960 for storm type IA and 12.00 for storm type II and III.

Hydrograph Procedure

The source area hydrograph generation is based on the NRCS (SCS) Curve Number method to determine volume of runoff in a design storm event. This method was developed from many years of storm records for agricultural watersheds in many parts of the United States. The equation is (Haan et al, 1994):

$$Q = \frac{(P-0.2S)^2}{P+0.8S}, for\ P > 0.2S \qquad [3]$$

where Q = direct surface runoff depth (mm); P = storm rainfall (mm); S = maximum potential difference between rainfall and runoff (mm). The value of S can be determined by:

$$S = \frac{25400}{CN} - 254 \qquad [4]$$

where CN=curve number for the source area. The initial abstraction is assumed to be Ia=0.2 S.

CN is selected antecedent rainfall condition II and can vary from 0 to 100. Antecedent moisture condition II represents moderately wet antecedent moisture conditions. Different land use conditions are used to determine CN and have been tabulated by NRCS (1986). When a combination of different land uses are represented, a composite CN can be calculated as an area-weighted average of the CN for the different land uses.

Using the NRCS method for a triangular hydrograph, the time to peak can be estimated as:

$$t_p = \frac{D}{2} + 0.6t_c = \frac{D}{2} + t_l \qquad [5]$$

where t_p = time to peak (hr); D = duration of rainfall (hr); t_c = time of concentration (hr); and t_l = time of lag (hr).

The time of concentration equals $t_l/0.6$ and the longest travel time. This can be determined by:

$$t_c = L^{0.8}\frac{\left[\dfrac{1000}{CN}-9\right]^{0.7}}{4407{S_g}^{0.5}} \qquad [6]$$

where t_c = time of concentration (hr); L =longest flow length (m); CN= curve number; and S_g = average watershed gradient (m/m).

The TR55 method (USDA NRCS, 1986) is used to calculate the design peak flow:

$$q_p = q_u AQF_p \qquad [7]$$

where q_u = unit peak flow (m^3/s.ha.mm) ; A = watershed area (ha); Q = runoff volume (mm); and F_p = ponding factor that accounts for the percentage of the watershed with ponding or wetland condition that will delay the overland flow. The peak unit hydrograph is calculated as,

$$q_u = 4.3046x10^{C_o + C1\log(t_c) + C2(\log(t_c))^2 - 6} \qquad [8]$$

where Co, C1, C2 are coefficients obtained for each storm type and the value of the ratio Ia/P.

The source area hydrograph is then calculated from the NRCS unit hydrograph using the approximation (Haan et al., 1994),

$$q = q_p\left(\frac{t}{t_p}e^{1-t/t_p}\right)^{3.77} \qquad [9]$$

To couple the generated hydrograph with the storm hyetograph, the hydrograph is delayed t_I seconds. The delay is calculated as the time when initial abstraction (Ia) ends in the watershed, and thus rainfall excess is produced. The delay time is obtained from the hyetograph as the time the rainfall equals Ia.

Modified Universal Soil Loss Equation

Modified Universal Soil Loss Equation or MUSLE is used to compute soil loss for a single storm. MUSLE is a modification of USLE. This equation estimates soil loss from sheet and rill erosion. The equation for MUSLE is (Haan et al., 1994):

$$A = R_m \, K \, LS \, C \, P \qquad [10]$$

where A = computed soil loss per unit area; R_m = storm modified rainfall factor; K = soil erodibility factor; LS = slope length and degree factor; C = crop practice factor; and P = conservation practice factor.

The storm modified rainfall factor (R_m) is the potential of a rainfall event to cause erosion. The storm erosivity due to rainfall is found from the hyetograph by computing EI_{30}. The estimate of R_m for each storm event was done using the equation suggested by Foster et al. (1977) as a combination of the rainfall and runoff factors. The equation is:

$$R_m = 0.5R_{st} + 0.35V(q_p)^{1/3} \qquad [11]$$

where R_{st} is computed as EI_{30}, the rainfall erosivity, and V is the volume of runoff and q_p is the peak runoff rate.

K is the soil erodibility index, which is defined as the mean annual soil loss per unit of erosivity for a standard erosion plot with no conservation, 10% slope and 22 m in length. A smaller K value indicates that the soil is not easily eroded. The length (L) and slope (S) factors are calculated following the original USLE methods. C and P are estimated based on land use and any erosion control practices such as terracing from NRCS tables (see USDA NRCS, 1986).

Vegetative Filter Strip Model

The Vegetative Filter Strip Model (VFSMOD) is a field scale, mechanistic, storm-based model designed to route incoming hydrographs and sedimentographs from an adjacent field through a VFS and calculate the outflow, infiltration and sediment trapping efficiency. The model handles time dependent hyetographs, space distributed filter parameters (vegetation roughness or density, slope, infiltration characteristics) and varying particle sizes of incoming sediment. The model was field tested for soil and climatic conditions in the Piedmont and Coastal Plain of North Carolina (Muñoz-Carpena et al. 1999).

Two main submodels, one for hydrology and one for sediment transport and deposition, are linked together to produce a field-scale single storm model. The model routes the incoming hydrograph and sedimentograph from an adjacent field through a vegetative filter strip (VFS) and calculates the outflow, infiltration and sediment trapping efficiency for that event. Selected inputs for VFSMOD and the UH models are given in Table 1 (Muñoz-Carpena and Parsons, 1999).

Table 1. Input Parameters for UH and VFSMOD

Input Variable	*Description*	*Input Variable*	*Description*
P	amount of storm precipitation	RNA(I)	Manning's roughness for each segment (s.m-1/3)
CN	SCS curve number	SOA(I)	slope at each segment (unit fraction, i.e. no units)
A	area of upstream portion (m^2)	VKS	saturated hydraulic conductivity, K_s (m/s)
storm type	storm type = type (1=I, 2=II, 3=III, 4=Ia)	SAV	Green-Ampt's average suction at wet front(m)
D	storm duration	OS	saturated soil-water content, θ_i (m^3/m^3)
L	length of the source area along the slope (m)	OI	initial soil-water content, θ_s (m^3/m^3)
Y	slope of the source area (%)	SM	maximum surface storage (m)
FWIDTH	width of the strip (m)	SS	spacing of the filter media elements (cm)
VL	length of the plane (m)	VN	filter media (grass) Manning's n m (0.012 for cylindrical media) (s.cm-1/3)
NPROP	number of segments with different surface properties (slope or roughness)	H	filter media height (cm)
SX(I)	X distance from the beginning on the filter, in which the segment of uniform surface properties ends (m).	VN2	bare surface Manning's n for sediment inundated area and overland flow (s.m-1/3)

Example of the Design Procedure for North Carolina Piedmont Conditions

The combination of UH and VFSMOD was applied to North Carolina (NC) Piedmont conditions. Input variables such as rainfall amount and slope were selected to simulate conditions representative of the region. Table 2 shows the variables and their range for this study. The rainfall amounts were selected based on totals for 6-hour storms. For the NC piedmont, a 25 mm storm is fairly typical whereas a 6-hour storm total of 100 mm would have a longer return period (on the order of 10 years). Curve numbers of 78 and 85 were selected for the source area to represent moderate and higher erosion. The slope of the vegetative filter and the source area ranged from 1% to 10% with a filter length of 10 m and a ratio of filter to source area of 8%. The density of the grass in the filter was assumed to be dense (roughness coefficient of 0.45). Clay and clay loam were used to represent NC Piedmont conditions. Simulations were conducted with all combinations of the inputs to demonstrate the approach to develop relationships indicative of vegetative filter conditions over this range of conditions. It should be noted that these simulations represent a small portion of the range of conditions required for a complete design guide. These are intended to demonstrate the capabilities of the combined UH and VFSMOD models.

Table 2. Inputs Used to Simulate Conditions for the NC Piedmont

6-hour Storm Rainfall Amounts (mm)	*Curve Number*	*Slopes (%)*	*Soil Type*	*Filter Density (roughness coeff)*	*Buffer Length (m)*
16, 25, 50	78	1, 2, 4	Clay	Dense (0.45)	10
75, 100, 150	85	6, 8, 10	Clay loam		

Summary outputs from VFSMOD were used to examine the effectiveness of the vegetative filter. Comparisons of runoff inflow and outflow indicated that in most cases there was little difference for the clay and clay loam soils. This is due in part to the low infiltration rate in these soils. An example is given in Figures 1 (simulated hyetograph) and 2 (simulated runoff inflow and outflow) for CN=78, Rainfall=25 mm, Slope=4% and a buffer length of 10 m.

The primary function of the vegetative filters is the reduction of sediment. The sediment delivery ratio is defined as SDR = Sediment Out/Sediment In. This was computed for each simulation. An SDR near zero indicates that the filter trapped nearly all of the sediment whereas values approaching one indicate poor filter sediment trapping.

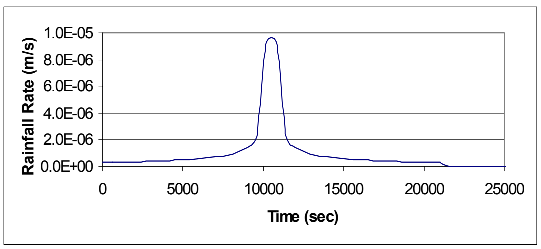

Figure 1. Simulated Hyetograph for the 6-hour Storm with Total Rainfall=25 mm**.**

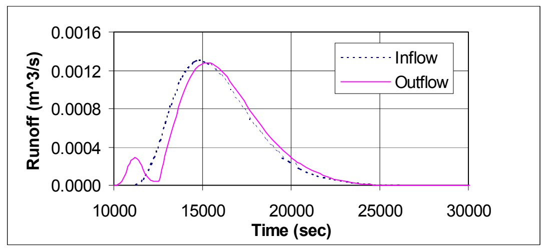

Figure 2. Runoff Hydrographs for CN=78, Rainfall=25 mm, Slope=4% and a buffer length of 10 m.

Table 2 shows the SDR along with the sediment mass in and out of the vegetative filter. For all simulations, the filter strips were effective for the 16 mm rainfall storm indicating that the 10 m buffer length would trap all sediment from this frequent storm size. The increase of the storm size to 50 mm indicated that the SDR increased to 0.49 or greater. To maintain high sediment trapping, an increase in filter strip length or better source area conservation would be required. In general, Table 2 shows that the SDR for the 10-m filter width increases with increases in rainfall and slope as would be expected.

Table 2. Sediment Input and Output (kg/ha) and Sediment Delivery Ratio (SDR) for Selected Simulations.

Rainfall vs. slope (CN=78)									
Slope (%)	*16 mm*			*50 mm*			*150 mm*		
	Input	*Output*	*SDR*	*Input*	*Output*	*SDR*	*Input*	*Output*	*SDR*
4	69	0	0	1129	549	0.49	13337	12544	0.94
10	297	0	0	4954	3992	0.81	58558	57452	0.98
Rainfall vs. slope (CN=85)									
Slope	*16 mm*			*50 mm*			*150 mm*		
	Input	*Output*	*SDR*	*Input*	*Output*	*SDR*	*Input*	*Output*	*SDR*
4	77	0.5	0.01	1453	899	0.62	14719	14028	0.95
10	338	28	0.08	6436	5569	0.87	64814	63773	0.98
Rainfall vs. CN (Slope=4%)									
CN	*16 mm*			*50 mm*			*150 mm*		
	Input	*Output*	*SDR*	*Input*	*Output*	*SDR*	*Input*	*Output*	*SDR*
78	69	0	0	1129	549	0.49	13337	12544	0.94
85	77	0.5	0.01	1453	899	0.62	14719	140278	0.95
Rainfall vs. soil type (slope 4%, CN=78)									
Soil	*16 mm*			*50 mm*			*150 mm*		

Soil type	*16 mm*			*50 mm*			*150 mm*		
	Input	*Output*	*SDR*	*Input*	*Output*	*SDR*	*Input*	*Output*	*SDR*
Clay	69	0	0	1129	549	0.49	13337	12544	0.94
Clay loam	90	0	0	1469	857	0.58	17409	16695	0.96

Figures 3 and 4 show the SDRs simulated for source areas with CN=78 and 85, respectively. In both cases, the simulations for source and filter areas with a slope of 1% were unable to handle 6-hour storms with rainfall amounts greater than 50 mm. This was due to the vegetative filters filling with sediment prior to the end of storm. For slopes greater than 1%, the SDR increased as 6-hour storm rainfall increased. For a slope of 2%, the 10-m vegetative filter strips reduced sediment outflow by nearly 80% (SDR=0.2) for a rainfall amount of 50-mm and a source area CN=78. For the 50 mm rainfall amount, SDR increased from less than 0.1 (S=1%) to about 0.8 (S=10%) indicating that better source area conservation practices are required with increasing slopes (Figure 3). As one would expect, increasing the CN from 78 to 85, increased SDR for each rainfall amount (Figure 4). Again, this indicates that better conservation practices in the source area would be necessary to keep SDR low.

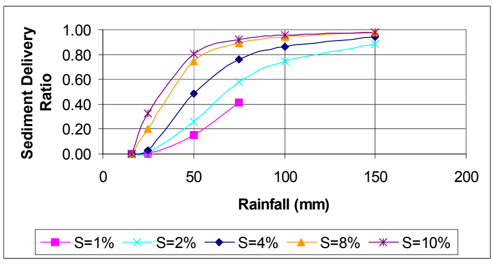

Figure 3. Comparison of SDR for Varying Source Area Slopes for 6-hour Storms (CN=78).

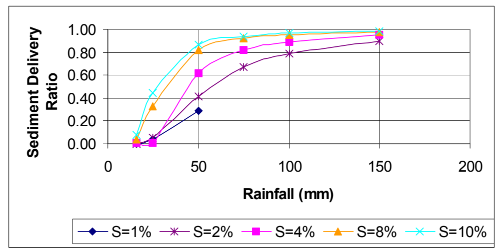

Figure 4. Comparison of SDR for Varying Source Area Slopes for 6-hour Storms (CN=85).

Summary

Simulations using the combined models UH and VFSMOD were done to represent conditions similar to that of North Carolina Piedmont area. The UH model generates rainfall hyetographs, runoff hydrographs and storm estimates of sediment loss from the source area using the NRCS curve number method, unit hydrograph method, and modified Universal Soil Loss Equation. These inputs are used by VFSMOD to simulate overland flow and sediment transport, based on vegetation, soil type, and topography in the vegetative filter strip. Rainfall and topographic factors of both the source area and the vegetative filter strip can be varied to simulate a wide range of conditions and model outputs enable analysis of VFS performance.

Examples representing conditions in the NC Piedmont were done using the UH and VFSMOD. A vegetative filter length of 10 m representing a ratio of source area to filter strip of 8% was used. Runoff hydrographs and storm based erosion losses using 6 hour storms ranging from 16-mm to 150-mm were simulated with source area CNs of 78 and 85. SDR results were analyzed to demonstrate the use of these models to evaluate vegetative filter strip performance on a storm event basis.

Future work with the combined models will include the development of a full procedure to utilize these models to evaluate the effectiveness of vegetative filter strips for erosion control in a variety of landscape settings.

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