A Design Procedure for Vegetative Filter Strips Using VFSMOD−W

R. Muñoz−Carpena, J. E. Parsons

Abstract. *Although vegetative filter strips (VFS) are a common BMP used for runoff sediment control, there is currently no widely accepted objective design criteria available to select optimal construction characteristics (filter length, width, slope, vegetation) needed to achieve a desired sediment reduction. A design procedure for VFS using VFSMOD−W is presented. VFSMOD, the main component of VFSMOD−W, is a field−scale, mechanistic, storm−based model developed to route the incoming hydrograph and sedigraph from an adjacent field through a VFS and to calculate the resulting outflow, infiltration, and sediment trapping efficiency. A front−end model, UH, was developed and added to VFSMOD−W to generate the necessary source area design inputs for VFSMOD. For each design storm, UH generates a rainfall hyetograph, a runoff hydrograph, and sediment loss from the source area 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, a set of response curves, i.e., sediment and runoff reduction vs. filter construction characteristics, can be developed from VFSMOD−W outputs for a given design scenario. To illustrate this procedure, a design case was presented where the goal was to obtain a 75% runoff sediment reduction for conditions similar to those of the North Carolina Piedmont region. In addition to two soil types present in the area, the range of conditions used in the analysis included two design alternatives (one concentrating field runoff in a narrower filter), four design storms with 1 to 10 year return periods, and buffer lengths ranging from 1 to 100 m. For the range of design storms considered, the optimal filter lengths obtained were 1 to 4 m for the sandy clay soil and 8 to 44 m for the clay. The results show that in some cases current environmental regulations pertaining to filter lengths in the area will not be sufficient. This application case clearly illustrates the importance of using an objective design procedure based on the specific location characteristics when implementing VFS as an effective off−site BMP.*

Keywords. *Computer program, Hydrology design, Modeling, Sediment, TMDL, Vegetative filter strips, VFSMOD, Water quality.*

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 in surface runoff both in solution and attached to sediment. Phosphorus and some pesticides attached to sediment are a major surface water pollution concern, contributing to deterioration of water quality. 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, best management practices (BMPs) such as vegetative filter strips (VFS) adjacent to the source areas have been suggested as potential controls to help reduce erosion and offsite transport of sediment. Dillaha et al. (1989) defined VFS 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, resulting in 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.

As with many other BMPs, there are not readily available criteria for the optimal design of VFS. Many states and NRCS have established general guidelines for the construction and use of VFS (see for example Franti, 1997; Leeds et al., 1994; USDA−NRCS, 1999). However, these approaches do not quantify performance for specific cases or give much guidance on quantifying performance and effectiveness. This is especially critical in the context of the TMDL (total maximum daily load) effort. In principle, the objective of the design effort is to answer the question: what would be the optimal construction parameters for a VFS on a given area to meet certain regulatory standards (i.e., sediment reduction to achieve a TMDL)?

When implementing a vegetative hydrological structure, the designer faces a complex system where a large number of parameters and uncertainties need to be taken into account. Unlike many other land conservation practices, performance

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and evaluation of vegetative filter strips should be done on a storm−by−storm basis. Muñoz−Carpena (1993) developed and tested a field−scale, mechanistic 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 (Muñoz−Carpena et al., 1993a, 1993b) with a sediment filtration submodel based on one developed at the University of Kentucky (Barfield et al., 1978, 1979; Hayes et al., 1979, 1982, 1984; Tollner et al., 1976, 1977). The resulting model (VFSMOD) can handle complex storm pattern/intensity and varying surface conditions within the vegetative filter strip to evaluate runoff and sediment transport and deposition through the filter. VFSMOD was successfully tested with natural events using data from the North Carolina Piedmont (Muñoz−Carpena et al., 1999) and Coastal Plain (Muñoz−Carpena, 1993) experimental sites (Parsons et al., 1991). Researchers at the University of Guelph (Canada) tested the model against field experimental data (Abu−Zreig et al., 2001; Gharabaghi et al., 2001). They reported good agreement ($R^2 = 0.9$) with a highly significant ($p < 0.01$) linear relationship between model predictions (infiltration, outflow, and sediment trapping) and measured values when actual filter flow lengths (discounting concentrated flow segments) are used rather than total filter length. Factors affecting sediment trapping in VFS were also studied using VFSMOD in a follow−up study (Abu−Zreig, 2001). Recently the program has been used to model the effect of VFS in a small watershed (72 ha) (Kizil and Disrud, 2002), as well as a component to simulate fecal pathogen filtering from runoff (Zhang et al., 2001).

One of the main drawbacks of using VFSMOD in a design context is that the user must supply inflow hydrographs and sedigraphs from the source area to evaluate the filter strip performance. In an effort to address this limitation, this article describes the development of a program (UH) to generate the necessary source area inputs for VFSMOD, and proposes a VFS design procedure to meet sediment TMDLs based on the combined models. These models and procedures are incorporated into VFSMOD−W, a Microsoft Windows−based VFS modeling and design system, as described herein. The field testing of the new UH model in VFSMOD−W is reported elsewhere (Sadeghi et al., 2004). The intent of this effort is to use the concept of design storms (with associated return periods) to evaluate vegetative filter strip performance. An example application for conditions in the Piedmont region of North Carolina is presented to demonstrate how the combined models can be used to design a vegetative filter strip.

Materials and Methods

Design Procedure

The objective of the design procedure is to find optimal construction characteristics (length, width, slope, vegetation) of a VFS to reduce the outflow of sediment from a given disturbed area (climate, soil, crop, size, management practices) to meet a % reduction goal for sediment runoff (as dictated by the TMDL or other environmental regulation). From a hydrological design perspective, we require the VFS to accommodate storms of selected return periods (T) for a given source area. When dealing with vegetative structures like waterways, 10−year return period storms are usually sufficient for design purposes (Schwab et al., 1996). Because vegetated waterways will usually handle greater flow velocity and rates (concentrated flow) than a VFS, a smaller return period is probably sufficient for the latter. In general, we can consider 1, 2, 5, and 10−year return period storms for VFS design. In the U.S., rainfall information needed for design storm hyetographs can be found in TP 40 (Weather Bureau, 1961), Atlas 2 (NOAA, 1973), and HYDRO−35 (NOAA−NWS, 1977). The storm duration (D) can be selected as a standard duration (i.e., 6 h) for all comparisons. An alternative procedure was presented by Bosch et al. (1999). After studying average size and duration of storms from long−term records in the Georgia Coastal Plain, they proposed to determine D as the most frequent storm duration in the highest storm intensity season of the year after discarding smaller storms (<25.4 mm), and D = 5 h was selected in the Georgia Coastal Plain study area.

As target outputs for analysis, we will select two convenient indexes, the sediment delivery ratio (SDR) and the runoff delivery ratio (RDR), which are computed as:

$$\mathrm{SDR} = \frac{\textit{mass of sediment exiting the filter}}{\textit{mass of sediment entering the filter}} \tag{1a}$$

$$\mathrm{RDR} = \frac{\textit{runoff exiting the filter}}{\textit{runoff entering the filter}} \tag{1b}$$

The first step in the analysis for evaluating VFS performance on a storm−by−storm basis is to generate inputs into the filter from the soils and land use in the source study area for each of the design storms selected for analysis. 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 (sedigraph and sediment type) produced from the given storm. These inputs along with a rainfall hyetograph are generated with the new model, UH, using readily available algorithms and equations described below.

The application of the design procedure for a particular area involves determining the size and duration of rainfall events, the range of source area conditions, and the lengths, slopes, 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 (response curves), i.e., the selected target outputs (SDR and RDR) vs. construction parameters (filter length, width, slope, vegetation), 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. The optimal filter characteristics for each return period and soil type can be obtained when overlaying the response curves with the desired filter effectiveness expressed in terms of a pre−defined sediment reduction (SDR) goal.

Design Hyetograph Generation

Synthetic rainfall hyetographs are generated in UH using equations based on the 24 h rainfall storms and adjusted to the desired frequency. For NRCS storm types II and III, the best−fit approximation for 24 h storm duration can be estimated by (Haan et al., 1994):

$$\frac{P(t)}{P_{24}} = a + \frac{(t-b)}{c}\left(\frac{d}{e\,|\,t-b\,|+f}\right)^{g} \quad (2)$$

where t is time from the beginning of the storm ($0 < t < 24$ h), $P(t)$ is the cumulative precipitation (mm) up to a given t, P_{24} is 24 h total rainfall (mm), and a through g are regression coefficients (table 1). In order to automate the hyetograph generation in UH, we obtained new equation 2 coefficients for the remaining NRCS storm types (I and IA) by fitting tabulated storm data from table 1 in Haan et al. (1994) with goodness−of−fit parameters of RMS deviation of 0.0088 and 0.003, and χ^2 = 3.363 and 1.539 for storm types I and IA, respectively.

For storms of any type and duration less than 24 h ($0 < D <$ 24 h), rainfall at time t, i.e., $P'(t)$, can be calculated with respect to the rainfall for the total storm (P_D) using a combination of equation 2 with the following equation generalized from that of Haan et al. (1994):

$$\frac{P'(t)}{P_D} = \frac{P\left(b+t-\frac{D}{2}\right) - P\left(b-\frac{D}{2}\right)}{P\left(b+\frac{D}{2}\right) - P\left(b-\frac{D}{2}\right)} \quad (3)$$

where $P(t)$ on the right side of the equation is calculated from equation 2, and b is the coefficient for each storm type given in table 1.

Source Area Hydrograph Procedure

The source area hydrograph generation is based on the NRCS TR−55 curve number method to determine volume of runoff in a design storm event (USDA−NRCS, 1986). This method was developed from many years of storm records for agricultural watersheds in many parts of the U.S., yielding the equation:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \text{ for } P > I_a \quad (4)$$

where
- Q = direct surface runoff depth (mm)
- P = storm rainfall (mm)
- S = maximum potential difference between rainfall and runoff (mm)
- I_a = initial abstraction (mm).

The values of S and I_a can be determined by:

$$S = \frac{25400}{\text{CN}} - 254 \quad \text{and} \quad I_a = 0.2S \quad (5)$$

where CN is the curve number for the source area.

Table 1. Coefficients obtained for equation 2 to generate synthetic hyetographs for all NRCS storm types.

Coefficient	Type I	Type IA	Types II and III[a]
a	0.4511	0.3919	0.5000
b	9.9950	7.9600	12.000
c	1.0000	1.0000	24.000
d	−0.1617	0.8430	24.040
e	−3.0163	120.390	2.0000
f	0.0130	0.3567	0.0400
g	0.5853	0.4228	0.7500

[a] Coefficients for storm types II and III from Haan et al. (1994).

Different land use conditions are used to determine CN and have been tabulated by USDA−NRCS (1986). CN is selected for antecedent moisture condition II (normal soil moisture conditions from previous rainfall events) and can vary from 0 to 100. When combinations 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:

$$t_p = \frac{D}{2} + 0.6t_c = \frac{D}{2} + t_l \quad (6)$$

where
- t_p = time to peak (h)
- D = duration of rainfall (h)
- t_c = time of concentration (h)
- t_l = time of lag (h).

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

$$t_c = L^{0.8}\,\frac{\left[\frac{1000}{\text{CN}} - 9\right]^{0.7}}{4407Y^{0.5}} \quad (7)$$

where
- L = longest flow length (m)
- CN = curve number
- Y = average watershed gradient (m/m).

The TR55 method (USDA−NRCS, 1986) is used to calculate the design peak flow (q_p, m^3/s):

$$q_p = q_u A Q F_p \quad (8)$$

where
- q_u = unit peak flow (m^3/s ha mm)
- A = watershed area (ha)
- Q = runoff volume (mm)
- 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:

$$q_u = 4.3046 \times 10^{C_o + C_1 \log(t_c) + C_2 [\log(t_c)]^2 - 6} \quad (9)$$

where C_0, C_1, and C_2 are tabulated coefficients obtained for each storm type and the value of the ratio I_a/P. To avoid the

Table 2. Polynomials used in UH to calculate the TR−55 unit peak flow coefficients.

Storm	Coeff.[a]	a	b	c	d	e
I	C_0	68.0317	−74.6930	24.9255	3.9797	2.5222
	C_1	−82.9070	105.222	−42.1670	6.7479	−0.8657
	C_2	11.1619	−26.3140	16.1126	2.9776	0.0456
IA	C_0	144.547	−136.680	41.8526	6.2829	2.3645
	C_1	−130.640	134.907	−45.7730	6.5850	−0.6384
	C_2	−55.230	47.9565	−13.5030	2.1954	−0.2644
II	C_0	−11.3120	12.1681	−6.5688	1.0577	2.5021
	C_1	16.6125	−16.3370	6.4981	−1.1784	−0.5476
	C_2	−43.0150	50.4334	−19.7400	3.2996	−0.3427
III	C_0	−11.5050	14.2182	−7.8919	1.3836	2.4007
	C_1	−64.1770	85.7116	−38.2060	6.7419	−0.8899
	C_2	65.9007	−85.8060	39.0036	6.8946	0.2078

[a] $C_k = a(I_a/P)^4 + b(I_a/P)^3 + c(I_a/P)^2 + d(I_a/P) + e$; k = 0, 1, 2; $R^2 > 0.98$.

need to look up the coefficient values in tables in UH, fourth−order polynomials were fitted for each coefficient and storm type as a function of I_a/P (table 2).

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

$$q = q_p \left(\frac{t}{t_p} e^{1-t/t_p} \right)^{3.77} \tag{10}$$

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

Source Area Sedigraph Computation

The Modified Universal Soil Loss Equation (MUSLE) is used to compute soil loss for a single storm. MUSLE is a modification of USLE (Wischmeier and Smith, 1978). This equation estimates soil loss from sheet and rill erosion. The equation for MUSLE is (Williams, 1975):

$$A_s = R_m KLSCP_{fact} \tag{11}$$

where

A_s = computed soil loss per unit area
R_m = storm−modified rainfall factor
K = soil erodibility index
LS = slope length and degree factor
C = cover and management factor
P_{fact} = 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 obtained from the hyetograph by computing the rainfall erosion index based on 30 min rainfall intensities (EI_{30}). Foster et al. (1977) suggested that R_m be calculated as a combination of the rainfall and runoff factors:

$$R_m = 0.5R_{st} + 0.35Q(q_p)^{1/3} \tag{12}$$

where R_{st} is the rainfall erosivity computed as EI_{30} (N/h), Q is the runoff depth (mm), and q_p is the peak runoff rate (mm/h). Alternatively, Williams (1975) proposed a different formulation for R_m as:

$$R_m = 9.05(Vq_p)^{0.56} \tag{13}$$

where V is the volume of runoff (m^3), and q_p is in m^3/s. Both methods (eqs. 12 and 13) are available to the user in UH.

The soil erodibility index (K) 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 length. A smaller K value indicates that the soil is less easily eroded. The length (L) and slope (S) factors are calculated following the original USLE methods (Wischmeier and Smith, 1978). C and P_{fact} are estimated based on land use and any erosion control practices, such as terracing, from NRCS tables (see Wischmeier and Smith, 1978).

After obtaining the soil loss for the storm (A_s) the incoming sedigraph into the vegetative filter strip is calculated in UH by multiplying the mean sediment concentration for the event ($C_i = A_s/V$) by the source area runoff rate for each time step (design hydrograph). The representative sediment particle characteristics of the sedigraph, i.e., effective diameter (d_{50}) and particle density, can be supplied by the user or estimated internally in UH based on the user−supplied USDA texture of the source area topsoil (Woolhiser et al., 1990).

Linking with the Vegetative Filter Strip Model

Details of the linking between UH and VFSMOD into the combined VFSMOD−W model are presented in figure 1. The three main VFSMOD submodels, two for hydrology (overland flow and infiltration) and one for sediment filtration, are linked together to produce a field−scale event−based (single storm) model. UH directly generates the rainfall hyetograph, runoff hydrograph, and sedigraph input files needed by VFSMOD so that a complete source−area/filter combination can be automatically (batch) run within VFSMOD−W. The user needs to select the source (disturbed) area parameters as well as the filter characteristic (overland flow and infiltration) (table 3). Sample inputs for a wide range of conditions are provided in the model documentation (Muñoz−Carpena and Parsons, 2003).

From a design perspective, we require the VFS to accommodate storms with several return periods. The first step in the analysis is to generate inputs into the VFS from the soils and land use in the source study area, for each of the design storms selected for the analysis. The design precipitation depths along with the area's NRCS runoff and MUSLE erosion inputs are processed through UH to create formatted inputs for VFSMOD (hyetograph and incoming sedigraph/hydrograph into the VFS). With these inputs, the VFSMOD model routes the incoming runoff and sediment, and calculates water and sediment retained at the filter (SDR and RDR). For convenience, this procedure is automated within the graphical user interface (GUI) in the later versions of the VFSMOD−W model (Muñoz−Carpena and Parsons, 2003). In addition, VFSMOD−W generates summary tables of the design results in spreadsheet format files to easily create response curves.

Application Case

To illustrate the design procedure, a scenario from the Piedmont region in North Carolina is selected. The length of the VFS is the design parameter. In this study case, a 75% reduction in sediment output (SDR = 0.25) from a typical disturbed area within the watershed is required to meet a prescribed TMDL. The current regulations for the Neuse River Basin in the region (North Carolina Administrative Code, Riparian Buffer Rule 15A NCAC 2B.0233) require all water bodies to be protected by a riparian area with a total length of 15.2 m (50 ft) containing at least 6.1 m (20 ft) of a stable, vegetated area suitable for trapping sediment. Another regulation in place in the region is a recent ordinance passed by the Town of Cary (2000), which requires 30.5 m (100 ft) buffers for stream systems.

We will consider two common topsoil types in the region: clay and sandy clay, both with 1% organic matter. A standard source area (row crop with straight row in good hydrologic condition) will be used for all the simulations (fig. 2). For the source area, the following set of inputs is used: NRCS CN = 85 and 89 for clay and sandy clay soils, slope (Y) = 0.02 (2%), source area (A) = 0.5 ha, and flow path length (L) = 100 m. The MUSLE's cover (C) and practice factors (P_{fact}) at this

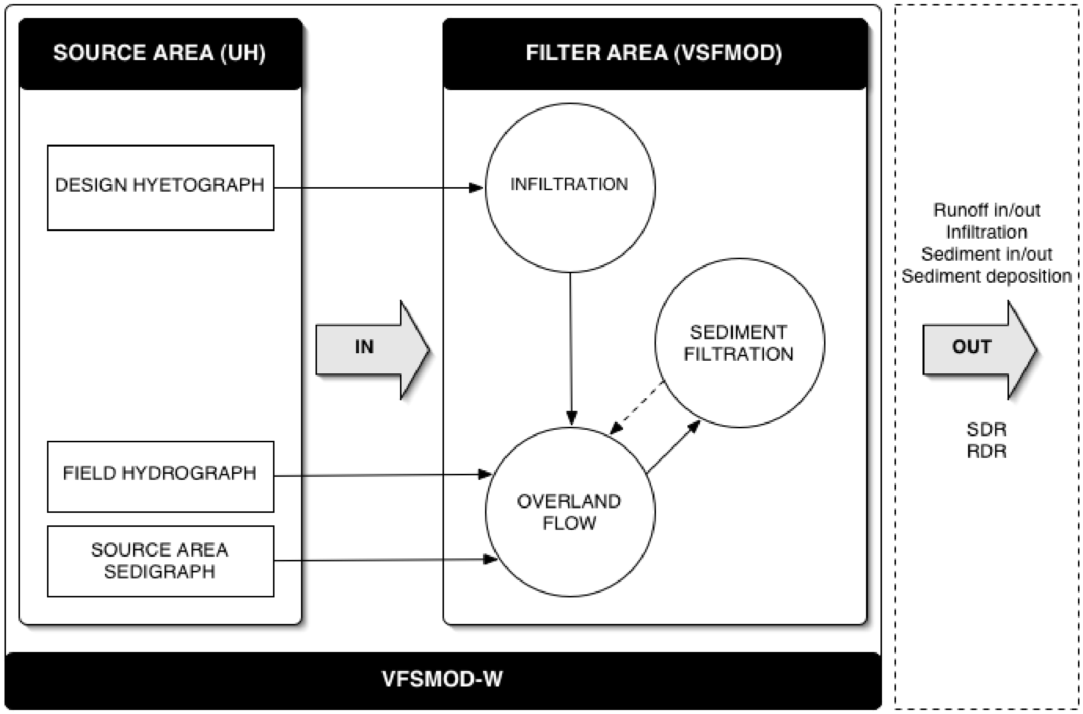

Figure 1. Schematics of the combined model (VFSMOD−W) for vegetative filter strip design.

Table 3. Input parameters for the combined model (VFSMOD−W).

Input Variable	Description
Source Area (UH)	
P	Design storm precipitation (mm).
CN	SCS curve number for source area.
A	Area of upstream portion (ha).
Storm type	Storm type (1 = I, 2 = II, 3 = III, 4 = IA).
D	Storm duration (h).
L	Length of the source area along the slope (m).
Y	Slope of the source area (%).
Soil type	USDA texture for source area top soil.
K	USLE soil erodibility index.
C	USLE cover and management factor.
Pfact	USLE conservation practice factor.
Filter Area (VFSMOD)	
FWIDTH	Width of the strip (m).
VL	Length of the plane (m).
NPROP	Number of segments with different surface properties (slope or roughness).
SX(I)	X distance from the beginning of the filter, in which the segment of uniform surface properties ends (m).
RNA(I)	Manning's roughness for each segment (s $m^{-1/3}$).
SOA(I)	Slope at each segment (unit fraction, i.e., no units).
VKS	Saturated hydraulic conductivity, K_s (m/s).
SAV	Green−Ampt's average suction at wetting front (m).
OS	Saturated soil−water content, θ_i (m^3/m^3).
OI	Initial soil−water content, θ_s (m^3/m^3).
SM	Maximum surface storage (m).
SS	Spacing of the filter media elements (cm).
VN	Filter media (grass) modified Manning's n_m (0.012 for cylindrical media) (s $cm^{-1/3}$).
H	Filter media height (cm).
VN2	Bare surface Manning's *n* for sediment inundated area and overland flow (s $m^{-1/3}$).

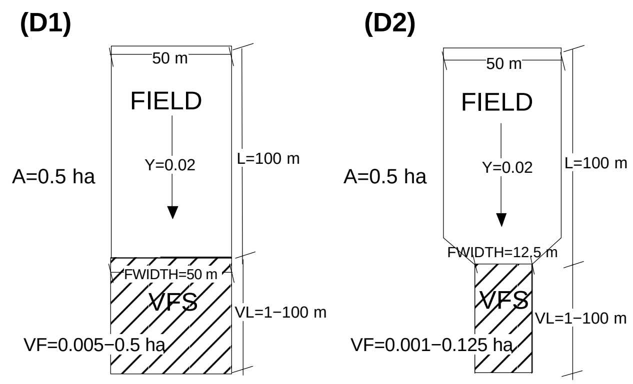

Figure 2. Design alternatives for different filter to buffer area ratios (not to scale, labels described in table 3).

source area are chosen as 1 since they are not considered design factors in this application. The user can set these factors to the values pertaining to a particular application, which can be used to take into account any source area BMPs. The MUSLE's soil erodibility factor (K) depends on the soil type (texture and organic matter %); in our case, it will be 0.28 for clay and 0.33 for sandy clay. The storm−modified rainfall factor (R_m) is calculated in this application with Williams' method (eq. 13).

For performance analysis, four North Carolina Piedmont 6 h design storms (type II) with return periods (T) of 1, 2, 5, and 10 years are selected (Bonnin et al., 2003), as shown in table 4.

Based on these inputs, the hyetograph and the VFS's incoming sediment and runoff file parameters are setup automatically by the UH program. The VFS's soil and vegetation inputs used in the design are summarized in table 5. A uniform slope (SOA(I) = 0.02) and Manning's surface roughness (RNA(I) = 0.2) was selected for the filter, and bare soil Manning's roughness was set to VN2 = 0.04.

Table 4. Design storms (6 h) and UH field runoff and erosion values for the NC Piedmont soils (symbols defined in eqs. 4 to 13).

Return Period (years)	P (mm)	Clay Soil (d_{50} = 0.23 μm)				Sandy Clay Soil (d_{50} = 0.66 μm)			
		Q (mm)	q_p (m^3/s)	R_m (N/h)	A_s (kg/m^2)	Q (mm)	q_p (m^3/s)	R_m (N/h)	A_s (kg/m^2)
1	54.0	29.0	0.062	61.8	0.81	22.7	0.047	46.2	0.71
2	69.0	42.1	0.088	92.3	1.22	34.6	0.071	73.9	1.13
5	88.0	59.5	0.124	136.0	1.79	50.8	0.102	111.3	1.70
10	102.6	73.2	0.153	171.5	2.26	63.8	0.127	143.3	2.19

We also evaluate the relationship of field to buffer area ratio (A/VF) to VFS performance. For this analysis, we consider two design alternatives, both with the same source area (fig. 2). In the first alternative (D1), the VFS is placed along the downslope field border (equal width, FWIDTH = 50 m), whereas in D2 the runoff is routed over a narrower VFS (FWIDTH = 12.5 m) with a conveyance system (berms). Taking into account the filter lengths studied (1 to 100 m), the ranges of the A/VF ratios are 4 times larger for alternative D1 than for D2 for the same filter length (100:1 to 1:1 and 400:1 to 4:1 for D1 and D2, respectively) (fig. 2).

For the design analysis, 400 simulations were run from combinations of the two soil types, the two design alternatives, the four design storms in table 4, and buffer lengths of VL = 1 to 100 m in steps of 2 m for the first 20 m and 5 m thereafter.

Results and Discussion

The results from the simulations are depicted in table 6 and figures 3a to 3d. The figures illustrate the importance of soil type in the VFS design. For design alternative D1 and all the return periods studied, filters with VL > 10.2 m (>33 ft) resulted in >75% sediment reduction (SDR < 0.25) for the clay soil (table 6, fig. 3a), while VL > 2.0 m (>7 ft) is sufficient for the sandy clay soil (table 6, fig. 3b). However, with the more demanding conditions established in design alternative D2, where runoff from the field is concentrated over the VFS, significantly longer filters with lengths VL > 44.2 m (>145 ft) would be required to meet the desired TMDL for the clay soil and VL > 3.6 m (12 ft) for the sandy clay soil.

The different design results obtained for the clay and sandy clay soils are not only a factor of runoff production or infiltration characteristics for each soil type, but of the properties of the sediment generated from each source area. The UH source area outputs for the design application (table 4) show that while the more permeable sandy clay soil moderately reduced runoff (13% to 22%) and soil losses (3% to 13%) with respect to the clay soil, the characteristic sediment particle size (d_{50}) changed considerably between the two sites (0.23 and 0.66 μm for clay and sandy clay soils, respectively). Clay particle transport and filtering in a VFS is mostly in the form of suspended sediment load, while most of the sandy clay particles are transported as bed load. Bed load transport is effectively retained in the initial (entry) part of the filter and upslope field tail after the sudden drop in velocity and transport capacity caused by the dense vegetation. Suspended load requires longer filter lengths for deposition (Hayes et al., 1979, 1984; Tollner et al., 1976, 1977). The relatively less importance of infiltration characteristics in the application was magnified by the fact that runoff from the VFS, in all the cases studied, was not reduced and generally was larger than the inflow from the field (runoff delivery ratio, RDR > 1) since infiltration was smaller than (or equal to) the rainfall on the filter during the events (fig. 3). In addition, further concentration of flow in narrower strips (smaller FWIDTH) could result in filter failure for a given storm, where the filter will be filled up with sediment and thereafter route all sediment through to the outlet without any further (and future) deposition possible, possibly resulting in surface runoff concentration and channeling. Additional simulations for narrower VFS (not shown) showed that this problem is experienced in the conditions of the application case with FWIDTH < 5m.

It is also worth noting that for the conditions in this design case, although intended only for illustration purposes, the Neuse River regulation for the grass portion of the riparian area (6.1 m) will fail to meet the desired TMDL in the clay soil for the larger storms (5 and 10 years) in design alternative D1 and for any of the storms in D2. The Neuse River's total riparian regulation of 30.5 m (assuming all grass) on clay soil will suffice to meet the TMDL for all storms in D1, but it will fail for all storms in D2. The more stringent requirement of the Town of Cary (30.5 m buffer) on clay soil will accommodate the TMDL for all combinations except for the larger storms (5 and 10 years) in the D2 alternative (table 6, figs. 3a and 3c). All current regulations will suffice for both locations with the sandy clay soil (table 6, figs. 3b and 3d). In the context of these results, any relaxation of the buffer requirement to a lesser length or along less of the source area boundary will result in failure to meet the design goals. On the other hand, if a reduction of the area dedicated to filter is desired using a design similar to D2 several alternatives could be considered. For example, in addition to modifying FWIDTH, the designer could study the effect of adding conservation practices in the source area (modifying P_{fact} and C factors). This points out a potential strength of VSFMOD−W, since VFS and conservation practices can be designed at the same time.

This application case clearly illustrates the importance of using an objective design procedure based on the specific location characteristics when implementing VFS as an effective off−site BMP.

Table 5. Soil and vegetation characteristics for the VFS designed in the application case (symbols defined in table 3).

Soils						
Texture (USDA)	Field CN	VKS ($\times 10^{-6}$ m/s)	SAV (m)	OI (m^3/m^3)	Porosity ≈ OS (m^3/m^3)	SM (m)
Clay	89	0.167	0.3163	0.125	0.475	0.0
Sandy clay	85	0.333	0.2390	0.125	0.430	0.0

Vegetation				
Vegetation (good stand)	Density (stems/m^2)	Grass Spacing, SS (cm)	Maximum Height, H (cm)	Modified n, VN
Grass mixture	2150	2.2	15	0.012

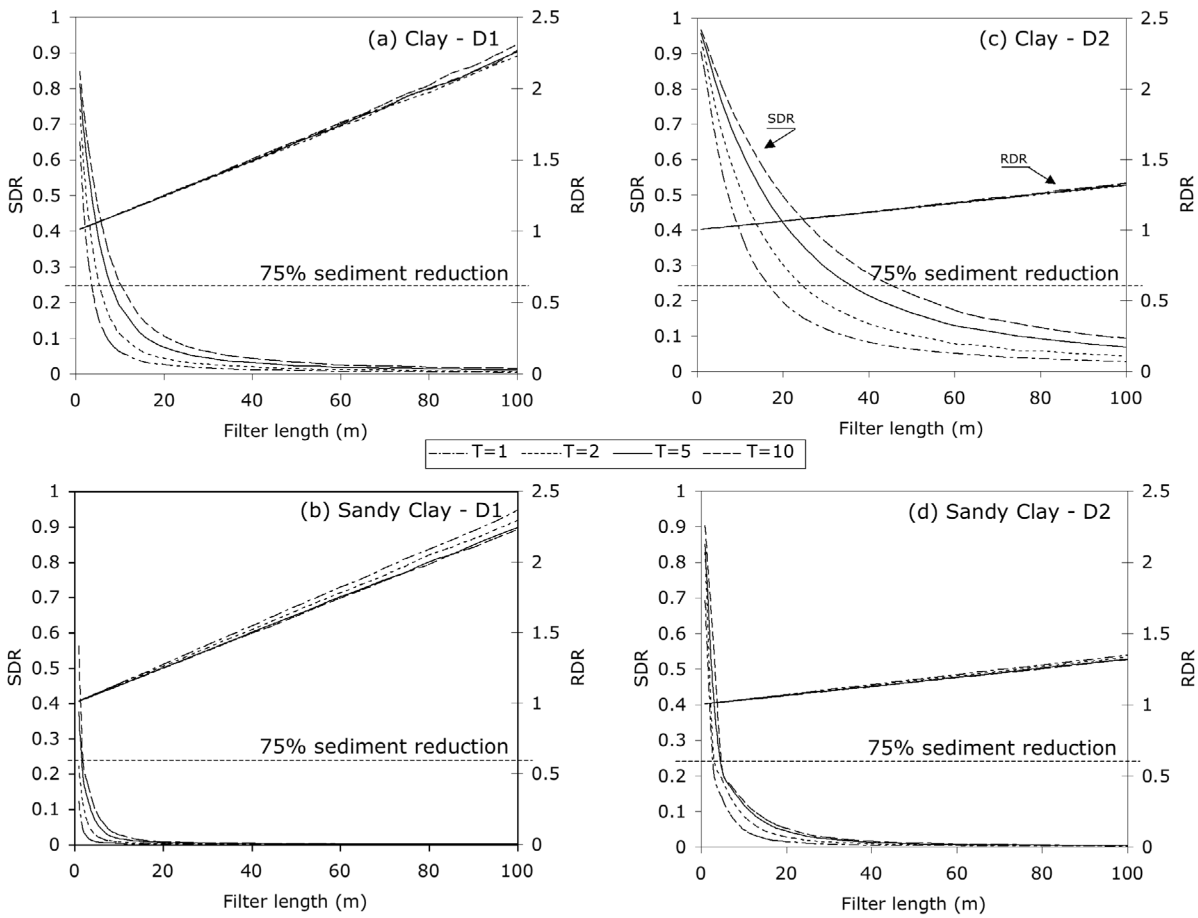

Figure 3. Response curves obtained in the design application case.

Table 6. Design results for the application case (75% sediment reduction).[a]

Soil Type (USDA)	Minimum filter length (m) to achieve the desired TMDL			
	T = 1 year	T = 2 years	T = 5 years	T = 10 years
Design Alternative D1				
Clay	3.6	5.4	8.0*	10.2*
Sandy clay	<1.0	<1.0	2.0	2.0
Design Alternative D2				
Clay	16.2**	23.9**	35.0***	44.2***
Sandy clay	3.1	3.4	3.5	3.6

[a] Filters longer than the regulated minimum filter lengths are denoted by: (*) Neuse River grass area (6.1 m), (**) Neuse River total riparian buffer (15.2 m), and (***) for both Town of Cary (30.5 m) and Neuse River areas.

Limitations of the VFSMOD-W Model

The limitations of VFSMOD−W are derived from its components. Although the NRCS curve number and MUSLE approaches adopted for the UH source (field) area component are widely accepted and used because of their simplicity and availability of inputs for many areas of the world, they are purely empirical, and some factors (land use) are subjective. The MUSLE method is valuable for management purposes (comparison of alternatives) since it separates land use (C and P_{fact}) from site−specific factors (R_m, K, and LS), but its predictive capability is limited without calibration due to its subjectivity. This method yields average soil loss per unit area for each event and does not account for ephemeral gullies or deposition within the source area; thus, it frequently overestimates sediment yields. Finally, MUSLE was developed for croplands, rangelands, and forests at the plot (small) scale.

For the filter area, VFSMOD handling of overland flow as sheet flow could pose problems when a filter is not properly maintained and concentrated flow occurs within the filter. The dominant overland flow in the filter must also meet the kinematic wave assumptions (i.e., no backwater effects and smooth slopes, typically less than 10%). In addition, since parameters to describe hydrology and sediment transport in VFS are highly variable, field variability is an inherent source of error. A range of variation in the saturated hydraulic conductivity values is usually needed to fit the model to observed data. Although this variation can be explained by changes in surface conditions due to seasonal and biological factors, these changes can be difficult to quantify in field situations. The latest version of VFSMOD−W's GUI incorporates numerical and graphical uncertainty and analysis of sensitivity procedures to quantify uncertainty in the model application for a given scenario (Parsons and Muñoz−Carpena, 2001, 2002). The filter sediment trapping algorithms assume the formation of a regular (triangular and trapezoidal) sediment wedge deposition in the front of the filter. Although predictions from this approach have been found satisfactory with this and other models, this might not be acceptable in some cases, especially when non−uniform or concentrated flow are present. The sediment−filtering component only considers net trapping or deposition within the filter, i.e., no erosion and transport in the filter is allowed. While this will not present a problem in a well−maintained filter with uniform, shallow (grass not submerged) overland flow, maintenance (mowing and removal of grass, no traffic, and practices to maintain uniform vegetation like reseeding, re−leveling, and replanting at the end of the filter design life when the filter fills up or after a major event) is critical to guarantee the design value of the filter. Dillaha et al. (1989), when conducting an on−farm filter survey in Virginia, found that many of the filters were no longer effective due to flow concentration (channeling) and sediment deposition with time. To account for this from a design perspective, a factor of safety should be considered when selecting the appropriate filter characteristics for each application.

Summary and Conclusions

A procedure for design of vegetative filter strips using a field−scale, event−based, mechanistic and graphical modeling system, VFSMOD−W, is presented. The objective of the procedure is to obtain the minimum filter length to achieve a desired runoff sediment reduction from a disturbed source area during a design storm of a given return period. A new model, UH, was developed and linked to the vegetative filter strip model VFSMOD to facilitate the design task within VFSMOD−W. UH 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. With this combined modeling tool, the procedure is both flexible and comprehensive, since a wide range of design parameters can be utilized in the procedure (design storm of a given return period, different soil types, vegetation, slope lengths, field crop and management, and filter to buffer area ratios). This design method has been automated within the graphical user interface (GUI) in the later versions of the VFSMOD−W model (Muñoz−Carpena and Parsons, 2003).

A potential strength of the resulting model is that conservation practices in the disturbed area and filter characteristics can be studied together to achieve the most economical design. The limitations of VFSMOD−W can be traced to its components. Because of the empirical nature of some of them, calibration of the different model components is recommended to achieve plausible results. The design procedure is applicable only to well constructed and maintained filters where uniform, shallow (grass not submerged) overland flow is present.

The capability and versatility of VFSMOD−W was illustrated with a design case for conditions similar to those of the North Carolina Piedmont region where the goal was to obtain a runoff sediment reduction of 75% (SDR = 0.25). A range of conditions was included in the analysis from combinations of two soil types present in the area, two design alternatives (one concentrating the field outflow into a smaller filter and the other with a filter of the same width as the field), four return period design storms (T = 1 to 10 years), and buffer lengths of VL = 1 to 100 m in steps of 2 to 5 m. For the range of design storms considered, the optimal filter lengths obtained were 1 to 4 m for the sandy clay soil and 8 to 44 m for the clay soil. These results indicate that in this case longer filters than those required by current regulations in the area (6 to 30 m) are needed to achieve the desired sediment reduction goal. The application shows how a fixed regulation or set of guidelines might not be effective when implementing VFS.

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