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A normalized design procedure to meet sediment TMDL with vegetative filter strips.[1]

Abstract

This paper presents a vegetative filter strip (VFS) design procedure to meet sediment TMDL using the graphical modeling system VFSMOD-W. The core program, the vegetative filter strip model VFSMOD, simulates overland flow and sediment dynamics within the VFS based on vegetation, soil type, and topography. The inputs to run the model (rainfall hyetograph, and source area's runoff hydrograph and sediment load) are automatically generated by the system based on a user given design storm (in terms of return period) and application area characteristics (crop system and soil type). These 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 this tool, a design example for representative conditions in the Piedmont region of North Carolina is presented (clay and sandy-clay top soils). Simulations were conducted representing a ratio of source area to filter length from 3:1 to 258:1. Rainfall totals for return periods T=1,2,5 and 10 yrs (54-103 mm), were used to generate 6-hour storm hyetographs and runoff hydrographs from source areas with a mean slope of 2%. The optimal filter design can be obtained when setting an objective TMDL (75% sediment reduction) over the program's graphical output. Analysis of VFS performance including graphs showing sediment delivery ratios is presented to demonstrate the utility of this approach.

Keywords: vegetative filter strips, modeling, TMDL, sediment, hydrology design, computer program, water quality.

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Introduction

A design procedure to meet sediment TMDL by using vegetative filter strips (VFS), a common BMP, is presented. In principle, the objective of the design effort is to answer the question: what would be the optimal constructive parameters for a VFS on a given area to meet certain regulatory standards? (i.e. sediment 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. Computer models with a sound physical base can help in this effort when properly managed. One such modeling system (VFSMOD-W) is proposed to assist in this design task.

VFSMOD-W (Muñoz-Carpena and Parsons, 2001; Parsons and Muñoz-Carpena, 2002) is comprised of: i) a core program, VFSMOD; ii) an input preparation utility, UH; iii) and a MS-Windows graphical user interface (GUI) with built-in input help, graphical output analysis, and sensitivity analyses and uncertainty procedures (Parsons and Muñoz-Carpena, 2001; 2002).

VFSMOD (Muñoz-Carpena and Parsons, 1999; 2001) 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 (Muñoz-Carpena et al., 1993a;b). Any combination of unsteady storm and incoming hydrograph types can be used. The model is targeted at studying VFS performance on an event-by-event basis.

The model was tested with natural events data at a North Carolina Piedmont (Muñoz-Carpena et al, 1999) and a Coastal Plain (Muñoz-Carpena, 1993) experimental sites. Both sites had grass filter strips (mixture of fescue, bluegrass and bermuda grass) with ratios of field to filter lengths from 4.5:1 to 9:1. The field area had varying slope from 5-10% and the filter strip somewhat less. The soil types were Cecil clayey at the Piedmont site and Rains loamy-sand at the Coastal Plain site (Parsons et al., 1991). In general, good agreement was obtained between observed and predicted hydrology and sediment outflow values. Some sources of variability were discussed to explain some anomalous events.

Researchers at the University of Guelph (Canada) tested the model against field experimental data (Abu-Zreig et al., 2001) and analyzed VFS behavior by using the model (Abu-Zreig, 2001). They reported good agreement (R^2=0.9) between model predictions (infiltration volume and sediment trapping efficiency) and measured values.

Suwandono et al. (1999) proposed a design procedure for VFS using the VFSMOD model along with the utility UH. This procedure uses the utility UH to generate runoff hydrographs and sediment losses from upslope source areas to enable testing and evaluating the effectiveness of various VFS scenarios. 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.

This paper demonstrates the use of VFSMOD as a design tool to meet a given TMDL for sediment, expressed in terms of % reduction of sediment from a disturbed source area. Used this way, the model can assist designers, planners and regulators to determine the relative effectiveness of filter strips in a given scenario.

Design procedure

The objective is to find optimal constructive characteristics (length, slope, vegetation) of a VFS to reduce the outflow of sediment from a given disturbed area (soil, crop, area, management practices) to meet a certain TMDL (reduction in % sediment). Our target outputs for analysis will be the sediment delivery ratio (SDR) and runoff delivery ratio (RDR) computed as:

SDR = (Mass of Sediment Exiting the Filter)/(Mass of Sediment Entering the Filter)

RDR = (Runoff Exiting the Filter)/(Runoff Entering the Filter)

From a design perspective, we require the VFS to accommodate storms with return periods of at least 1 and 2 years and probably 5 and 10 years. The first step in the analysis is to generate inputs into the VFS from the soils and crops present in the source study area, for each of the design storms and soils selected for the analysis. The precipitation depths along with the area's NRCS runoff and MUSLE erosion inputs will be processed in the program's GUI through the input preparation utility (UH) to create formatted inputs for VFSMOD (hyetograph and incoming sedimentograph/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, outflow, and filter performance. For this, we must describe the actual vegetative filter strip characteristics to analyze for each runoff event. These VFS characteristics are: soil (infiltration type), filter length, and vegetation characteristics. VFSMOD-W provides a sample project that can be used as a pattern where for each soil type, the changes are made to the Green-Ampt's infiltration and soil properties. The program provides assistance to fill in this information for standard USDA soil types. Suggested Green-Ampt infiltration inputs can be found in the Help File within the program.

Filter length is selected directly in the GUI input window. The user can select one of several vegetation covers to be used in the analysis. The program provides assistance to fill in this information for standard vegetation types. The user can also select nodal slope and roughness along the filter for irregular vegetation covers.

For each combination of inputs a "project" is created within the program's GUI. This task is simplified since "cloning" and renaming of projects is possible within the program, so that only changes to the desired parameters for each combination is required. After all projects are prepared a batch simulation is started within the program interface. Upon completion the selected outputs (SDR and RDR) are extracted automatically from each simulation and tables and individual graphs for further analysis are created. A new version of the program is under development were the projects for each combination of design inputs are automatically created within the program's GUI after the user selects a range on the desired parameters. This new version also automatically produces combined analysis graphs from the output tables.

From these outputs, SDR (or RDR) versus filter length, the user can obtain the optimal filter characteristics for each return period and soil type when overlaying the pre-defined sediment TMDL expressed in terms of a desired filter effectiveness (% SDR or RDR).

Additionally, the program provides two powerful tools. Once the optimal design parameters are selected an uncertainty analysis can be conducted using the graphical tools provided. The objective of this analysis is to identify the level of confidence that the adopted design has against the uncertainties present when selecting the model inputs (Parsons and Muñoz-Carpena, 2001, 2002).

Finally a sensitivity analysis procedure is included in the GUI to identify the parameters to which the model is more sensitive for a given scenario, thus allowing the user to economize effort by focusing on better identifying just the sensitive parameters (Parsons and Muñoz-Carpena, 2001).

Application case

To illustrate the design procedure a scenario from the NC Piedmont region is selected. The length of the filter strips will be our target for analysis. The current regulations for the Neuse River Basin require a total riparian length of 50 feet (15.24 m). Within the riparian zone, there are recommendations that a portion of this should be suitable for trapping sediment. A recent ordinance passed by the Town of Cary (2000), NC, requires 100 feet (30.48 m) buffers for stream systems. Assuming that these are reasonable sizes for the buffers, we will analyze potential lengths VFS' to filter surface runoff and sediment. In this study case, the user chooses a TMDL to achieve a 75% reduction in sediment output (SDR=0.25) from the disturbed area (field crop).

We will consider two common topsoil types in the area, clay and sandy clay with 1% organic matter. A standard source area will be used for all the simulations. For the source area, the following set of inputs is used: NRCS' CN=85, slope = 0.02 (2%), source area=0.5 ha with. The MUSLE's crop and practice factors at this source area are chosen as 1 since they are not considered design factors in this example. The users could set these values to the values pertaining to their particular application. The MUSLE's soil erodibility K will depend on the soil type (texture and organic matter %) and in our case it will be 0.28 for clay and 0.33 sandy clay.

For performance analysis rainfall amounts for 6-hr storms for various return periods for the Piedmont region of NC are estimated (Schwab et al., 1996) as shown in Table 1.

Table 1. Design storms (6 hr.) for the NC Piedmont region

Return Period (yr)	Rainfall (in)	Rainfall (mm)
1	2.12	54
2	2.7	69
5	3.46	88
10	4.04	102.6

Based on these inputs, the hyetograph and VFS' incoming sediment and runoff file parameters are setup automatically by the UH program. The VFS' soil and vegetation inputs used in the study case are summarized in Table 2. A uniform slope (2%) and surface roughness (0.2) was selected for the filter.

Table 2. Soil and vegetation characteristics for the VFS designed in the application case

Soils			
Texture (USDA)	K_s (m/s)x10^{-6}	S_{av} (m)	Porosity θ_s (m^3/m^3)
Clay	0.167	0.3163	0.475
Sandy clay	0.333	0.2390	0.430

Vegetation				
Vegetation (good stand)	Density (stems/m^2)	Grass spacing s_s (cm)	Maximum height, H (cm)	Modified n n_m
Grass mixture	2150	2.2	15	0.012

A total of 64 simulations were prepared and batch run from combinations of the two soil types, the storms in Table 1, and buffer lengths of 5, 10, 15, 20, 25, 30, 50 and 100 m.

As an alternative to our design we will finally evaluate the effect of filter to buffer area ratio (F/B) on VFS performance. We will consider two different design alternatives, both meeting the aforementioned characteristics (Fig. 1). In alternative (A), the field is 300x16.7 m and the VFS is placed along the downslope field border (equal width), whereas in (B) the field is 100x50 m and the runoff is routed over a narrower VFS (3.87 m). Taking into account the filter lengths studied (5-100 m), the ranges for the F/B ratios for these two alternatives are 3-60 and 13-258 respectively.

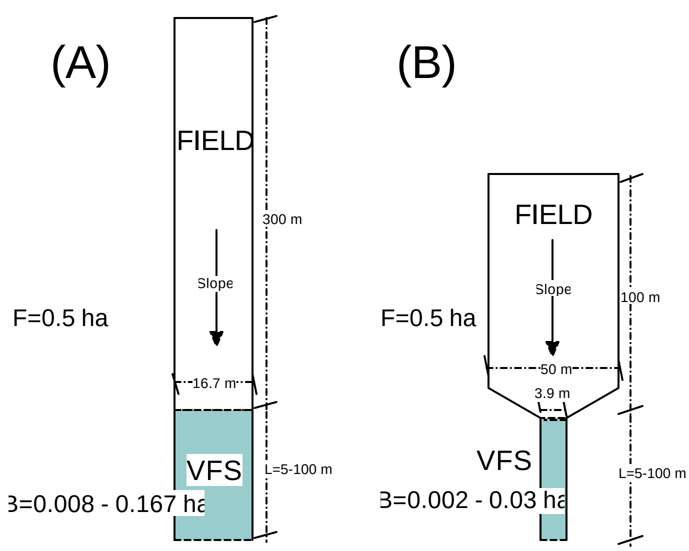

Figure 1. Design alternatives for different filter to buffer area ratios (not drawn to scale).

Results and discussion

The results from the simulations are depicted in Table 3 and Figs. 2(a-c). The figures illustrate the fact that soil type is an important element in the design process. With the conditions established in the design alternative (B), where runoff from the field is concentrated over the VFS, it was not possible to achieve the desired SDR in the clay soil (Fig. 2c) for the two largest design storms considered (T=5 and 10 yrs). In the same alternative (B), the same type of

VFS over a sandy clay soil did achieve the desired effectiveness or better after a minimum filter length of L<12 m, for all the design storms (Fig. 2d). For the design alternative A, filters with L<60 m would be effective for all the return periods studied for the clay soil (Fig. 2a), and <5 m for the sandy-clay soil (Fig. 2b) (Table 3).

Table 3. Design results for the application case (TDML 75 % sediment reduction).

Soil type (USDA)	Optimal filter length (m) to achieve the desired TDML			
	T= 1 yr.	T= 2 yr.	T= 5 yr.	T= 10 yr.
Design alternative (A)				
Clay	14	24	40	57
Sandy-clay	<5	<5	<5	<5
Design alternative (B)				
Clay	58	93	>100	>>100
Sandy-clay	1	8	9	11

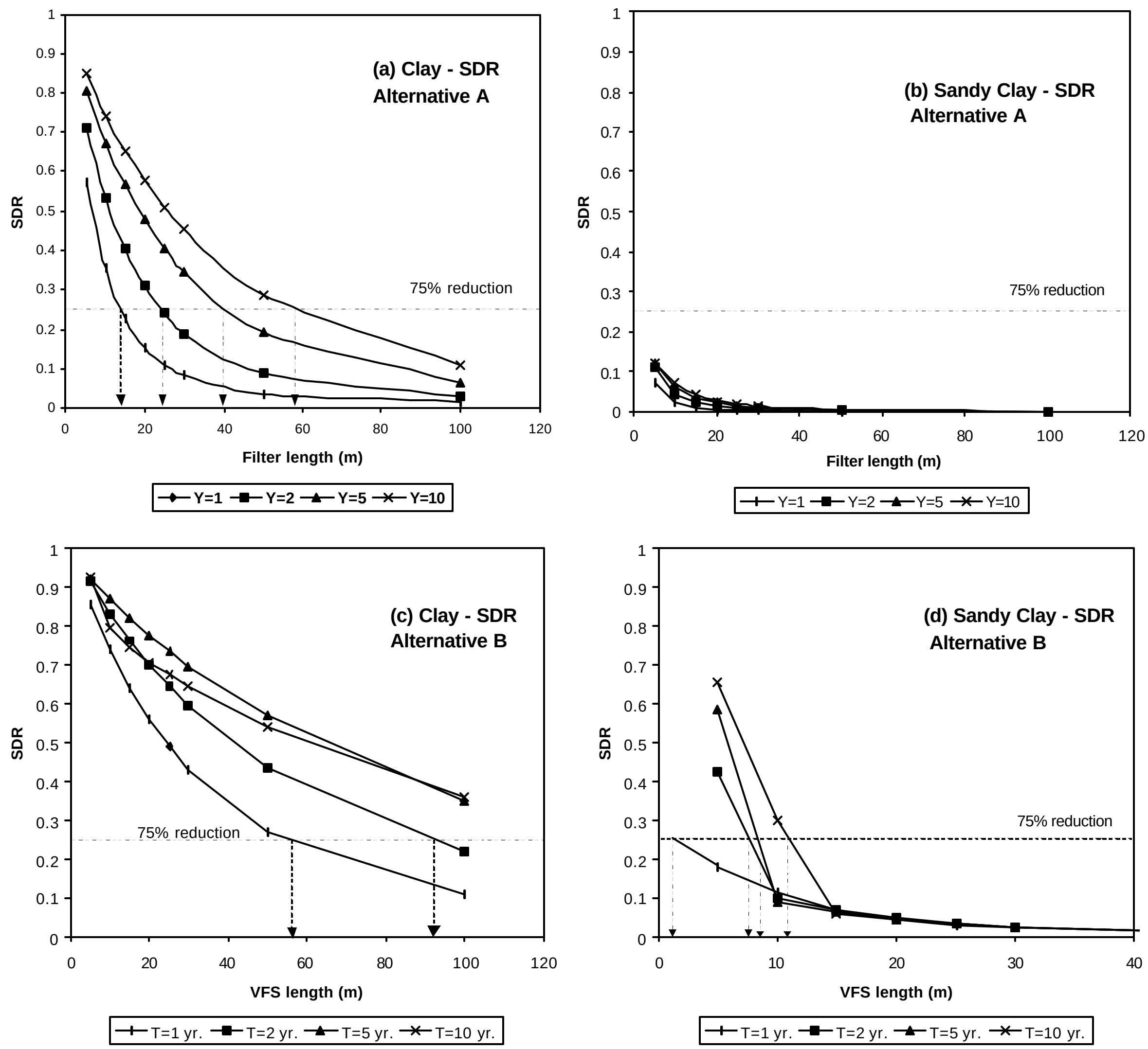

Figure 1. Design results for the application case (TDML 75 % sediment reduction).

Runoff from the VFS, in all the cases studied, was larger that the inflow from the field since infiltration was smaller that the rainfall on top the filter during the event (results not shown).

It is also worth noticing that for the conditions studied in this scenario, although intended only for illustration purposes, the aforementioned current regulations for the area would not hold for one of the two soils present in the area and design storm return periods greater than 5 years.

Conclusion

A procedure for design of vegetative filter strips using an event-based mechanistic graphical modeling system, VFSMOD-W, is shown. A desired TMDL, expressed in terms of % reduction of sediment from a disturbed source area, is used as objective function for the design method. 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). Examples are given to show the application on the method in the Piedmont region of North Carolina.

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