SEDIMENT-REMOVAL EFFICIENCY OF VEGETATIVE FILTER STRIPS

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Abstract

Field experiments on vegetative filter strips (VFS) showed average sediment-removal efficiency varied from 50 to 98% as flowpath length increased from 2.44 to 19.52 m. Almost all of the easily-removable aggregates (i.e. aggregates larger that 40 mm in diameter) can be captured within the first five meters of the filter strip. However, the remaining small-size aggregates are very difficult to remove by filtering flow through grass media, as even relatively low levels of turbulent energy in the water is sufficient to keep the finer sediments in suspension. The only effective mechanism for removal of small-size sediments is infiltration. Experiments with appreciable infiltration (low to moderate flow rates on the longer plot lengths), showed removal efficiencies of 90% or higher. The sediment-removal efficiency of the filter strip does not increase much by increasing the width of the filter strip beyond ten meters. Improved efficiency of VFS can be achieved through the installation of a drainage system to increase infiltration.

Keywords: Vegetative Filter Strips, Sediment, Removal Efficiency

Introduction

The value of vegetative filter strips (VFS) for protection and enhancement of the quality of stream ecosystems has been examined extensively in the literature (Wilson and Imhof, 1998). In appropriate settings, grass filter strips can provide slope stabilization and reduction in sediment and pollutant loads entering streams. A study by the Pollution from Land Use Activities Reference Group (PLUARG), of the International Joint Commission (IJC-PLUARG, 1987), focused attention on the effects on receiving water of non-point source (NPS) pollution. Since then NPS pollution has been an important part of studies of water quality in the Great Lakes watershed. Studies in other watershed areas such as Chesapeake Bay have given similar emphasis to NPS control as a necessary step to improved water quality. In the United States, since 1988, vegetative filter strips are an approved USDA cost-share practice under the conservation reserve program of the Food Security Act of 1985. In 1999 the province of Prince Edward Island, Canada, passed legislation requiring vegetative buffers for all watercourses in the province. In Ontario, a consortium of stakeholder groups is considering the feasibility of installing a comprehensive program of stream-buffer enhancement.

The National Conservation Buffer Initiative in the United States has demonstrated that strategically-placed buffer strips in the agricultural landscape can effectively mitigate the movement of sediment, nutrients, and pesticides within farm fields and from farm fields. When coupled with appropriate upland treatments, including crop residue management, nutrient management, integrated pest management, winter cover crops, and similar management practices and technologies, buffer strips have allowed farmers to achieve a measure of economic and environmental sustainability in their operations, enhance wildlife habitat and protect biodiversity (Federal Interagency Stream Restoration Working Group, 1999).

Background

There is an extensive literature on VFS. Some primary sources are: Wilson (1967), Neibling and Alberts (1979), Young et al. (1980), Hayes et al. (1984), Dillaha et al. (1989), Magette et al. (1989), Parsons et al. (1990), Choi (1992), Mickelson and Baker (1993), Coyne et al. (1995). Recent reporting of results include: Daniels and Gilliam (1996), Van Dijk et al. (1996), Patty et al. (1997), Lalonde (1998), Moore Jr. (1998), Barfield et al. (1998), Boyd et al. (1999), Schmitt et al. (1999), and Oelbermann and Gordon (2000). The reported experiments had vegetative filter widths ranging from less than one meter to more than thirty meters, slopes ranging from 2% to 16% and various types of grasses and pollution load. Runoff as either was generated by actual or simulated rainfall on erosion plots upstream of the VFS or was created by mixing soil, water and pollutants in a mixing tank and distributing the slurry at a controlled flow rate at the upstream of the VFS. Performance of the VFS in treatment of runoff was often evaluated based on comparing the pollutant concentrations in runoff samples at the inlet and outlet of the VFS but a better comparison is the percentage removal of pollutant mass. If installed and maintained in the condition tested in the experiments, VFS have the capacity to remove up to 50 percent or more of nutrients and pesticides, remove up to 60 percent or more of certain pathogens, and remove up to 75 percent or more of the sediments on a mass-removed basis.

VFS provide significant resistance to flow, that is, their resistance is much higher than the resistance along the upland flowpath. The higher resistance reduces flow velocity and sediment transport capacity of the overland flow within the VFS, resulting in removal of sediments and attached pollutants through deposition from overland flow. Some removal of soluble pollutants also occurs through interaction with the vegetative surfaces but infiltration, not deposition or surface reaction is the primary mechanism for removal of soluble pollutants from overland flow.

In this paper, results from the field experiments on VFS and management recommendations drawn from these results are discussed. The utility of the results in validation and modification of an existing VFS model is considered to form a design tool for VFS to achieve management objectives for reduction of non-point source pollution.

Methodology

Field experiments were conducted at the Guelph Turfgrass Institute and Environmental Research Centre, Guelph, Ontario, Canada during August and September 2000, to compare the runoff treatment performance of VFS under various flow and pollution load conditions. The vegetation cover for the filter strips was perennial rye grass (*Lolium perenne* L.). Effects of flowpath length and flow rate on performance of the filter strips in runoff treatment were studied through a comparison of test results for 2.44, 4.88, 9.67 and 19.52 m filter strips and flow rates per unit width of 0.25, 0.54, 0.80 and 1.67 L $s^{-1}m^{-1}$. The plots were 1.22 m wide, and parallel to each other with a slope of 5.1% to 7.2%. Water was supplied to two large constant head tanks located upstream of the plots. Topsoil with high clay content was brought from the Harrow Research Station, Essex County, near Windsor, Ontario. The soil was air dried, ground, and mechanically sieved through a 2-mm size mesh. Batches of soil with fixed mass (0.5, 1.0, 2.0, 4.0 and 8.0 kg) were prepared and stored in plastic bags.

For each run, soil slurry was prepared by mixing a selected mass of soil with clear water in a mixing column using high-pressure air nozzles. The constant-concentration slurry was fed at a set rate, using peristaltic pumps, into a steady-rate inflow of clear water upstream of the plots. The plots were pre-wetted with clear water for about an hour before the tests began so that a steady-state infiltration rate was reached. Flow depth within the VFS was measured near the upstream edge, at mid-length and near the outlet of the strip and the travel time (residence time) was determined as the ratio of volume of resident water in the VFS to flow rate at inlet. The duration of each run was selected to be at least three times the travel time to guarantee that the concentration of suspended sediments at the VFS exit had reached a steady-state condition. A 15-min clear-water flow was introduced between consecutive runs to wash-off residual loose sediments and pollutants remaining in the VFS from the preceding run.

Flow rates were measured at the inlet and outlet of the VFS and, in addition, for each run two runoff samples were collected at the upstream end and two at the downstream end of the filter strip. These samples were preserved and later analyzed.

One sample was tested for Total Suspended Solids (TSS) concentration, and other for aggregate size analysis. For TSS measurement, the sample was filtered through a 0.45-micron filter, oven-dried at 105° C and the captured soils weighed using a highly-accurate scale. Total sediment load entering and leaving the VFS was calculated based on observed values of TSS concentration and runoff flow rate. The sediment removal efficiency of the VFS was then calculated by comparing the sediment loads at the inlet and outlet of the VFS.

For aggregate size analysis, samples were first filtered through a 0.45-micron filter, and the residue on the filter was analyzed for aggregate size distribution using a Malvern MasterSizer (Laser-scattering-based particle-size analyzer). By comparison of aggregate-size distributions at the inlet and outlet the removal efficiency for different aggregate-size ranges was determined. This information is critical for extension of results in predicting sediment-removal efficiency of VFS from the present study to other sites and other soils.

Results

In total 58 runs were completed and 348 runoff samples were collected and analyzed for total suspended solids (TSS) as well as aggregate-size distribution. Based on observed concentrations of total suspended solids and measured flow rates, total sediment fluxes per unit width were calculated for the inlet and outlet of each filter strip. The sediment-removal efficiency of the filter strip was calculated based on the percentage reduction in sediment flux across the VFS. Fig. 1 summarizes the results for sediment-removal efficiency of the VFS (in %) for different flowpath lengths and for different input flow rates.

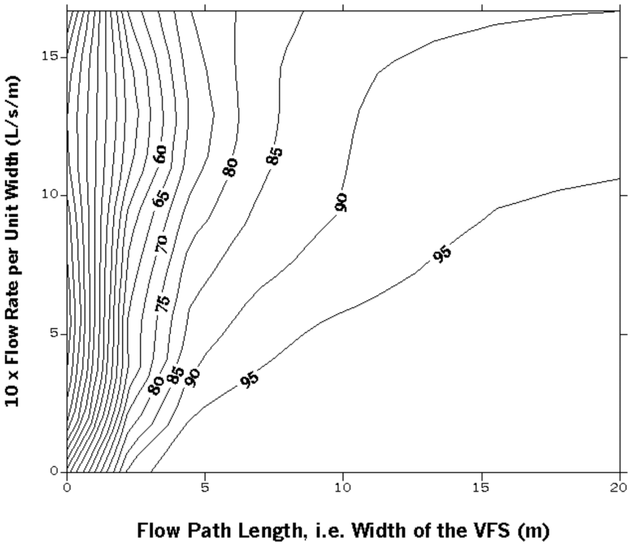

Figure 1. Average Sediment Removal Efficiency of Vegetative Filter Strips

It is evident from Fig. 1 that the first five meters of filter has a large role in removal of suspended sediments. About 50% of sediments were removed within the first 2.5 m of the filter flowpath (for all flow rates) and an additional 25% to 45% (depending on flow rate) of sediments were removed within the next 2.5 m of the filter flowpath. Almost all of the easily-removable aggregates (i.e. aggregates larger that forty microns in diameter) were captured within the first five meters of filter strip flowpath. However, the remaining small size aggregates were very difficult to remove by filtering through the grass since the relatively low turbulent energy in the water was still sufficient to keep the sediments in suspension.

The only mechanism that helped in the removal of the smaller-size sediments was infiltration. During the runs with low to moderate flow rates on the longer plot lengths, 90% or higher removal efficiencies were achieved. As is shown in Fig. 1, the sediment removal efficiency of the filter strip did not increase much for increases in strip flowpath length beyond 10 m. For example at a flow rate of 1.0 L s^{-1} m^{-1} doubling the flowpath from 10 m to 20

Table 1. Analysis of Variance for Sediment Removal Efficiency; where: DF = degrees of freedom; SS = sum of squares; MS = mean square; and F = MS / SS Error.

Source of Variation	DF	SS	MS	F	P-value
Flow Path Length	3	7768.492	2589.497	48.72832	< 0.01
Flow Rate	3	998.7219	332.9073	6.264541	0.01
Sediment Load	3	290.1713	96.72378	1.820117	> 0.10
Error	56	2975.926	53.14153		
Total	63	12033.31			

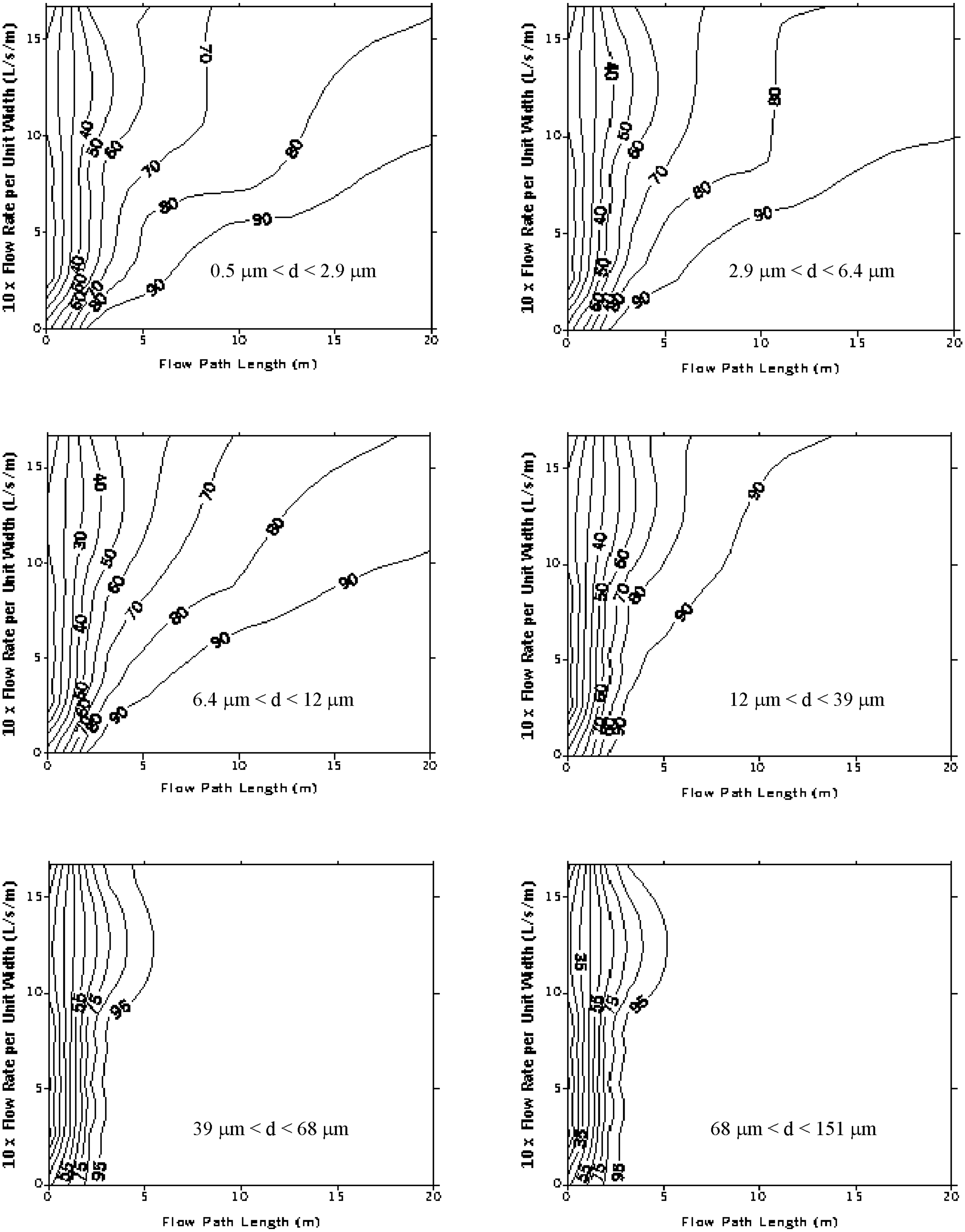

Figure 2. Sediment Removal Efficiency of VFS (in %) for different aggregate sizes.

m increases removal efficiency by less than 5%.

Sediment removal efficiency of VFS is a function of flow path length, flow rate, and sediment load quality and quantity. The analysis of variance on the sediment removal efficiency data is presented in table 1. As it is evident from table 1, the null hypothesis that sediment removal efficiency is neither a function of flow path length nor flow rate is rejected at 1% significance level. However, the null hypothesis that sediment removal efficiency is independent of sediment concentration at inflow to VFS could not be rejected even at 10% significance level.

To study the importance of sediment aggregate-size distribution on removal efficiency of VFS, the measured aggregate-size distributions for runoff samples at the inlet and outlet of the VFS were analyzed. Six aggregate size ranges were selected, i.e. (0.5-2.9), (2.9-6.4), (6.4-12), (12-39), (39-68), and (68-151) microns. The sediment removal efficiency of the VFS (in %) was calculated separately for each aggregate-size range and the results are summarized in Fig. 2. Sediment removal efficiency patterns were almost identical for the first three aggregate size ranges. Almost all (more than 95%) of the aggregates larger than 40 μm were removed within the first 2.5 m of the filter strip flowpath length. The information in Fig. 2 is critical for extension of results (i.e. predicting sediment removal efficiency of VFS) from the present study to other sites and other soils. That is, for a given site with known aggregate size distribution in the topsoil, first the percentage by weight of sediments in each aggregate size range is predicted. Then, for a given VFS and using Fig. 2, sediment removal efficiency for each aggregate size range is determined. Finally, a weighted average of sediment removal efficiencies for all aggregates size ranges is calculated.

Flow Resistance of the VFS

A major design parameter for VFS is the flow resistance, most commonly represented by the Manning's roughness coefficient n. Ree and Palmer (1949) developed the so-called 'Ur method' for estimation of Manning's n for grass-covered channels with slopes flatter than 1 in 10. The Ur method is an empirical method suggesting that Manning's n is a log-linear function of the product of the mean velocity U and hydraulic radius r (or Reynolds number, Ur/ν). Flow depth and velocity in VFS were quite small compared to conditions often found in grass-covered channels. For example, the Reynolds number in the present VFS study ranged between 10 and 100 while in the grass-covered channel study (Ree and Palmer, 1949) was between 105 and 106. Nevertheless, Fig. 3 shows that the flow-resistance coefficient (Manning's n) for the VFS study as a func-

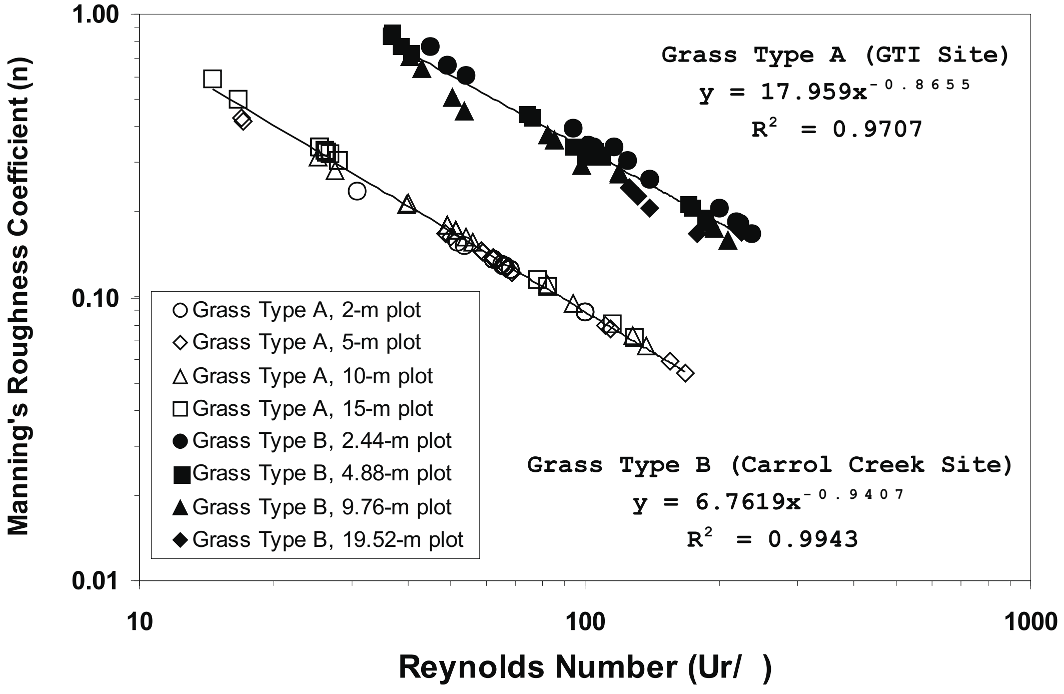

Figure 3. Flow resistance characteristics of VFS.

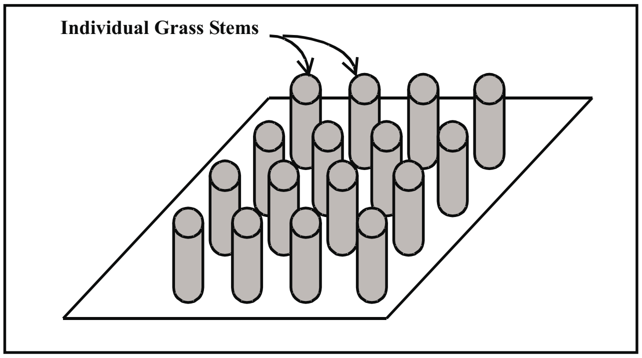

Figure 4. Simplified representation of erected turf grass media

tion of Reynolds number.

The best-fit function for Manning's roughness coefficient for VFS was log-linear with Reynolds number, that is $n = a\,Re^b$. Where a and b are constant parameters depending on the characteristics of the grass. A key hydraulic parameter in calculation of both Manning's n and Reynolds number is the hydraulic radius r. Fig. 4 shows a simplified representation of the complex hydraulics of non-submerged flow through erected turf grass.

Grass stem diameters range from 0.5 to 2.0 mm and grass density range from 40000 to 60000 stems m^{-2} which is roughly equivalent to grass spacing of 4 to 5 mm. Assuming that flow is non-submerged (i.e. depth of flow h is less than 2/3 of the height of the grass,) the hydraulic radius is defined (in 3-dimensional perspective) as the ratio of the volume occupied by water within the VFS to the total wetted surface area of vegetation stems and the bed within the VFS. The following set of equations was used in calculation of hydraulic radius:

$$V_{total} = B \cdot L \cdot h = V_{veg} + V_{water} \tag{1}$$

$$V_{veg} = \theta \cdot V_{total} = \theta \cdot B \cdot L \cdot h \tag{2}$$

$$V_{water} = (1-\theta) \cdot V_{total} = (1-\theta) \cdot B \cdot L \cdot h \tag{3}$$

$$\begin{aligned} A_{wet} &= (4 \cdot V_{veg})/D + (1-\theta) \cdot B \cdot L \\ &= 4 \cdot \theta \cdot B \cdot L \cdot (h/D) + (1-\theta) \cdot B \cdot L \end{aligned} \tag{4}$$

$$\begin{aligned} r &= V_{water}/A_{wet} \\ &= [(1-\theta) \cdot h] / [4 \cdot \theta \cdot (h/D) + (1-\theta)] \\ &= [(1-\theta) \cdot D] / [4 \cdot \theta + (1-\theta) \cdot (D/h)] \end{aligned} \tag{5}$$

The procedure used here includes θ the volumetric proportion of space occupied by vegetation, which can be measured directly by displacement volume or indirectly from stem diameter and separation spacing. Field observations indicated that θ was approximately constant (range from 0.05 to 0.07 for different flow depths). The formula for calculation of hydraulic radius shown in Eq. 5, reveals that since D/h was often a small number compared to 4θ, hydraulic radius r was approximately a constant roughly independent of flow depth h for the upper range of h. Assuming that r and S are constant parameters, Manning's n would be proportional to U^{-1}, while Reynolds number would be proportional to U. This explains the approximately inversely proportional relation between n and Re shown in Fig. 3.

Vegetative Filter Strip Models

Development of analytical procedures to model vegetative filter strips has been done at the University of Kentucky for erosion control in surface mining areas (Barfield et al., 1979, Hays et al., 1984, Tollner et al., 1982). These researchers at the University of Kentucky developed and tested a model (GRASSF) for removal of suspended solids by artificial grass media. This physically-based model takes into account a number of important field parameters that affect sediment transport and deposition through filter (sediment type and concentration, vegetation type, slope and length of the filter). Wilson et al. (1981) modified and incorporated GRASSF into SEDIMOT II, a hydrology and sedimentology watershed model. However, SEDIMOT II does not handle time-dependent infiltration, or changes in flow derived from sediment deposition during the storm event.

Williams and Nicks (1988) attempted to use CREAMS, a field scale model for Chemicals, Runoff and Erosion from Agricultural Management Systems as a tool for evaluating buffer strips. They evaluated CREAMS for a 1.6 ha wheat field in Oklahoma using buffer strip widths of 3-15 m, and slopes of 2-10%. The authors concluded that CREAMS is a "useful tool" for evaluating vegetative filter strip effectiveness in reducing sediment yield.

Munoz-Carpena et al. (1999) have recently developed the VFSMOD model. The improvements of VFSMOD model over the GRASF and SEDIMOT II models are the inclusion of: (a) state of the art description of flow through the filter; (b) changes in flow derived from sediment deposition;

(c) physically-based time-dependent infiltration; (d) handling of complex storm pattern; and (e) varying surface conditions (slope and vegetation) along the filter. The vegetative filter strip model VFSMOD (Munoz-Carpena et al., 1999) was found to be the most advanced and comprehensive model for vegetative filter strip analysis and was selected for this study.

A sensitivity analysis was performed to gain insight in the dependence of the upland NPS model (uh utility) and the VFS model (VFSMOD) outputs on certain model parameters and to assist in model calibration. Testing the upland model showed that runoff volume was very sensitive to changes in saturated hydraulic conductivity and initial soil water-content. Variations in the Manning's roughness coefficient mainly controlled the time to peak of the outgoing hydrograph and had little effect on runoff volume. The main parameters controlling erosion/ sediment yield component were: slope length, slope, soil erodibility, vegetation cover factor, and practice factor.

Testing on the sediment component of the VFS model showed that the width of the vegetative filter strip (i.e. the dimension of the strip in the direction of flow) has the greatest effect on sediment-trapping efficiency, followed by grass spacing and particle-size distribution. The effect of grass height was only visible for large events when the filter began to inundate with sediment. The main parameters controlling the hydrology outputs were saturated hydraulic conductivity of the soil and initial soil-water content; the model was insensitive to changes in the suction-at-the-wetting-front parameter. Variations in the Manning's roughness coefficient mainly controlled the time to peak of the outgoing hydrograph and had little effect on sediment output.

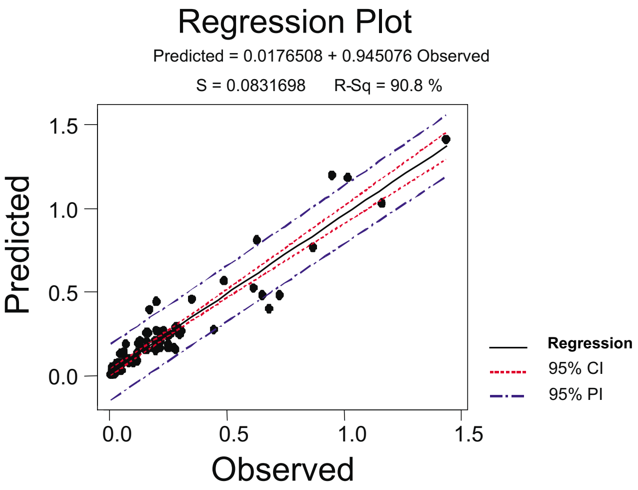

Figure 5. VFS model (VFSMOD, Munoz-Carpena et al., 1999) predicted versus observed sediment flux (g s^{-1} m^{-1}) at the VFS outlet; where: CI = confidence bands at 95% level for the regression line; and PI = prediction limits for new observations at 95% confidence level.

The vegetative filter strip model VFSMOD (Munoz-Carpena et al., 1999) was calibrated for Ontario conditions using observed field data (58 runs) collected at the Guelph Turfgrass Institute in summer 2000. Predicted values of the calibrated model versus the observed field data for sediment flux at the outlet of the filter strip is shown in Fig. 5. The statistical results from the regression analysis (with $R^2=0.90$) was encouraging, indicating a highly significant ($p<0.01$) linear relationship between the observed and predicted sediment flux.

Conclusions

Vegetative filter strips can reduce non-point source (NPS) pollution by treating overland flow before it enters streams. Field experiments on vegetative filter strips yielded average sediment removal efficiencies between 50 and 98% for 2.44, 4.88, 9.76 and 19.52-m wide filter strips. The first five meters of a filter strip is very critical and effective in removal of suspended sediments. More than 95% of the aggregates larger that forty microns in diameter can be captured within the first five meters of the filter strip. However, the remaining smaller size aggregates are very difficult to remove by filtering through grass, as even relatively low levels of turbulent energy in the water is sufficient to keep the finer sediments in suspension. The vegetative filter strip model VFSMOD (Munoz-Carpena et al., 1999) was calibrated and validated for Ontario conditions using the observed data from field experiments. Considering the complex and highly variable nature of the process involved in filtering of sediments through grass, the model has show a good potential in predicting sediment removal efficiency of VFS.

Needs for future study

This paper describes part of a larger study that, when completed, will provide management tools for site specification of vegetative filter strips based on the soil, land use, land management, and topographic characteristics of the upland area. The developed computer models will be useful to consulting engineers and other water management specialist working with farmers to reduce the discharge of pollutants from fields into adjacent streams and creeks. The VFSMOD model will be a core part of this set of computer tools. To complete the development of design tools further studies are needed to determine the effects of sediment load characteristics, uniformity of distribution of flow across the strip, flowpath length, and flow rate on sediment removal efficiency of vegetative filter strips.

Intense or prolonged rainfall events may generate such high runoff rates that the flow tends to concentrate in flowpaths between vegetative clumps. This concentration or channelization of flow significantly reduces the removal efficiency of the filter strip. Reinforcement of the natural vegetation with geosynthetic products can reduce flow concentration by spreading the flow across the full cross-section, thus improving the runoff treatment capability of the vegetative filter strip. Further study is needed of filter strips that incorporate fabric reinforcement.

In the late-winter/early-spring period when soil is often saturated (low infiltrability) and the vegetation cover is flattened (i.e. dormant season conditions), the efficiency of natural vegetative filter strips is low. Special study of performance of filter strips during snowmelt and post snowmelt conditions are needed to establish their efficiency on a fully annual basis. In soils with low infiltrability, and with sediment loads with high silt and clay content, the addition of subsurface drains to filter beds might be a practical way to enhance performance.

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Notations

A_{wet} = total wetted surface area including vegetation stems and bed, (m^2) ;
B = width of the VFS plots, (m);
C = observed sediment concentration (fraction by volume) in runoff exiting VFS, (-);
d = representative aggregate size for sediments, that is d_{50}, (m);
D = mean stem diameter for vegetation cover, (m);
g = gravitational acceleration, ($m\ s^{-2}$);
h = depth of flow, (m);
L = Flow path length (i.e. width of the VFS strip), (m);
n = Manning's roughness coefficient;
q = flow rate per unit width, ($m^2\ s^{-1}$);
r = hydraulic radius, defined as volume of water divided by total wetted area, (m);
S = slope of the channel, (-);
R_e = Reynolds number, ($U\ r\ \nu^{-1}$), (-);
U = mean apparent velocity of water, that is $q\ B^{-1}\ h^{-1}$, ($m\ s^{-1}$);
V_{total} = total volume of vegetation and water, i.e. B L h, (m^3);
V_{veg} = volume occupied by vegetation, i.e. θ B L h (m^3);
V_{water} = volume occupied by water, i.e. (1- θ) B L h (m^3);
ν= kinematic viscosity of water, ($m^2\ s^{-1}$);
θ = ratio of volume occupied by vegetation V_{veg} to total volume V_{total}, (-).

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