Water Qual. Res. J. Can. 2010 · Volume 45, No. 1, 59–68

GDVFS: A New Toolkit for Analysis and Design of Vegetative Filter Strips Using VFSMOD

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The Guelph design tool for vegetative filter strips, GDVFS, is a toolkit for the analysis and design of vegetative filter strips (VFSs). The upland hydrology model UH and the vegetative filter strip model VFSMOD (the two main components of GDVFS) were adopted from an existing interface (VFSMOD-W), and new nutrient and bacteria transport add-ons for UH and VFSMOD were incorporated into GDVFS. Other utilities and tools were also included in GDVFS to provide a capable toolkit for the analysis and design of VFSs. The published evaluation of computational procedures used in GDVFS indicates that these procedures perform very well in the estimation of VFS sediment and phosphorus removal efficiencies. According to these results, comparison of the predicted and observed values for sediment and phosphorus removal efficiencies indicates 10 and 20% error, respectively. This paper provides descriptions on the capabilities and methodology followed in the GDVFS toolkit.

Key words: **vegetative filter strip, design tool, nonpoint source pollution control, stormwater management**

Introduction

Runoff generated in a hillslope catchment, which carries sediment-bound and dissolved pollutants, enters the watershed stream network through flow paths perpendicular to the stream segments. A strip of dense vegetation called a vegetative filter strip (VFS) constructed at the downstream edge of the field within the buffer zone of a stream segment can effectively reduce the pollution of the stream by i) trapping the sediment and therefore sediment-bound pollutants carried in the surface runoff through particle settlement mechanism within the vegetated strip, and ii) facilitating the infiltration of the surface flow containing dissolved pollutants.

To design and evaluate VFSs, generally based upon mass removal of sediment, Munoz-Carpena et al. (1999) developed the vegetative filter strip model VFSMOD. To improve the capabilities of VFSMOD, the Guelph design tool for VFSs, GDVFS, was developed by the authors to provide a new interface linked with nutrient and bacteria yield and transport models.

GDVFS was developed in two phases. The first phase mainly focused on adding phosphorus transport components based on the results obtained from field experiments, and the second phase focused on incorporating bacteria transport components.

Background on the Development of GDVFS

Early works on development of the vegetative filter strip model were initiated at the University of Kentucky. Barfield et al. (1979), Tollner et al. (1976, 1977), and Hayes et al. (1984) developed the GRASSF model for filtration of suspended solids by grass filter strips. Wilson et al. (1981) modified and incorporated GRASSF into SEDIMOT II, a hydrology and sediment transport model for mined areas. Munoz-Carpena et al. (1999) incorporated a field-scale upland hydrology model (the UH model) along with VFSMOD, a modified version of GRASSF, in a user interface called VFSMOD-W (IFAS 2010). The capabilities of the graphical user interface and the online support services of VFSMOD-W contributed to the popularity of this public-domain toolkit.

The hydrology and the sediment transport components of VFSMOD-W were retained in GDVFS without any change, and new phosphorus and bacteria yield and transport components as well as tools to facilitate the data preparation and visualization of the model outputs were included in the current version of GDVFS. The performance of the phosphorus and bacteria transport components were evaluated using the data obtained from several field experiments conducted on VFSs.

General Description of GDVFS Computation Procedures

Hydrology and Sediment Transport Model

To estimate runoff and sediment flow at the downstream end of a field, which is the most effective location to construct VFSs, the UH model was adopted from the VFSMOD-W interface. Upland is the field upstream of the VFS, and the inflow to the VFS is the runoff carrying sediment generated within the upland area. The UH model employs methodologies that have been the subject of much research and have been extensively evaluated during the last four decades.

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The UH model estimates the runoff hydrograph using the SCS method developed by the U.S. Soil Conservation Service based on a set of modelling parameters, including soil texture, land cover, total rainfall depth, storm pattern and duration, and geometry of the upland field.

The sedimentation process considered in the UH model consists of soil erosion and sediment transport and deposition. The Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) is used to estimate the long-term average annual rate of sheet and rill erosion based on rainfall pattern, soil erodibility, field topography, land cover, and support management practices. To estimate sediment yield at the outlet of the upland field (downstream end of a field) for a single rainfall event, the modified version of the USLE, MUSLE (Williams and Berndt 1977), is used in the UH model. In this approach, the sediment yield estimates are based on the total runoff volume, peak runoff rate, and the soil, landuse, topographic, and support management parameters of the USLE.

To add phosphorus and bacteria yield and transport components to the UH model, additional procedures were incorporated in GDVFS to determine the amount of phosphorus and bacteria attached to the eroded soil at the point of detachment and at the field outlet, as well as the portion that is nonattached to the particles and transported by runoff.

Upland phosphorus yield and transport component (UH_P). Phosphorus enters a VFS in particulate (attached to the surface of the eroded sediment particles) and soluble (in solution) form. The sediment eroded from upland agricultural fields has more sediment-bound phosphorus per unit weight at the field outlet compared with the topsoil in the upland source area since the large particles, which constitute the major portion of the weight of the eroded soil, would settle prior to reaching the field outlet. This is due to the selective processes of erosion and transportation of the fine soil particles. To estimate the sediment-bound phosphorus losses from the upland agricultural fields, an algorithm similar to the one used in the CREAMS model (Knisel 1980) has been adopted in the upland phosphorus yield and transport component of GDVFS (UH_P). In this approach, the specific surface area of the eroded sediment particles at the field outlet is estimated and the amount of phosphorus attached to the sediment particles is computed using the concept of enrichment ratio. The amount of phosphorus transported by the eroded sediment is estimated using the following equation:

$$SED\mathrm{P} = SOIL\mathrm{P} \times SED \times PER \tag{1}$$

where *SED*P is the amount of particulate P transported with surface runoff (kg of P per ha); *SOIL*P is the P content in the upland field (kg of P per kg of soil) in the top 10 mm of soil surface layer; *SED* is the amount of soil loss from upland area (kg/ha); and *PER* is the phosphorus enrichment ratio.

PER is defined as the ratio of the specific surface area of the sediment at the field outlet to the specific surface area of the eroded soil at the point of detachment that can be estimated knowing the aggregate size distribution of the eroded soil at the point of detachment and the particle size distribution of the sediment at the field outlet.

An approach proposed by Foster et al. (1985) was adopted to estimate the aggregate size distribution of the eroded soil at the point of detachment (clay, silt, sand, small aggregates, and large aggregates). In this approach, the aggregate size distribution of the eroded upland soil is estimated from the fraction of primary soil particles (clay, silt, and sand) by using the following empirical equations:

$$ORcl = 0.26PRcl \tag{2}$$

$$ORsa = PRsa(1 - PRcl)^5 \tag{3}$$

$$ORsg = 1.8PRcl \text{ (when } PRcl < 0.25) \tag{4}$$

$$ORsg = -0.6(PRcl - 0.25) + 0.45 \text{ (when } 0.25 \le PRcl \le 0.50) \tag{5}$$

$$ORsg = 0.6PRcl \text{ (when } PRcl > 0.50) \tag{6}$$

$$ORsi = PRsi - ORsg \tag{7}$$

$$ORlg = 1 - (ORcl + ORsi + ORsa + ORsg) \tag{8}$$

In equations 2 to 8, the *PR* prefix represents the fraction of primary particle classes in the upland soil (clay, silt, and sand), and the *OR* prefix represents the fraction of each particle class in the eroded soil at the point of detachment (clay, silt, sand, small aggregate, and large aggregate). This approach has been experimentally evaluated by Meyer et al. (1992).

A computational procedure was also added to GDVFS to estimate the particle size distribution of the sediment at the field outlet based on the aggregate size distribution of the eroded soil at the point of detachment. The following routing function, developed and evaluated by Williams (1980), was used in GDVFS:

$$\omega_{oi} = \frac{\omega_i e^{-\beta\sqrt{d_i}}}{(\frac{q_p}{Q_P})^{0.56}} \tag{9}$$

where ω_{oi} is the portion of particle size d_i contained in the sediment; ω_i is the portion of particle size d_i contained in the soil; q_p is the peak runoff rate at the outlet of the source area; Q_p is the peak rate of rainfall excess; and β is a routing coefficient defined as:

$$\beta = \frac{-\ln(\frac{q_p}{Q_P})^{0.56}}{4.47} \tag{10}$$

To estimate soluble phosphorus entering the VFS, GDVFS uses a methodology suggested by Sharpley et al. (1981). In this approach, the average dissolved phosphorus concentration in the storm runoff (mg/L) is estimated by the following equation:

$$P_d = \frac{K\, P_0\, EDI\, \rho_b\, t^{\alpha}\, W^{\beta}}{V} \qquad (11)$$

where P_d is the amount of phosphorus desorbed into runoff from soil in time t (mg of P per L); P_0 is the initial amount of available phosphorus present in the soil (mg of P per g of soil) estimated using a P extraction technique; EDI is the effective depth of interaction between the soil and the surface runoff (cm) and is defined as the thickness of the surface layer of soil (usually 1 cm) which interacts with rainfall and runoff; ρ_b is the bulk density of the soil (g/cm^3); t is the desorption reaction duration (min); W is the water-soil ratio (cm^3/g); V is the runoff volume during the storm event (cm^3); and K, α, and β are constants for a given soil.

Evaluation of UH_P. Performance of the upland phosphorus yield and transport module (UH_P) for particulate P was evaluated using the experimental data reported by Rudra et al. (1985). These data, which were collected during the 1971 to 1975 period, were used for validation of the UH and UH_P models. These experimental data were collected from four plots (plots 3, 4, 7, and 8) that measured 44.2 × 6.4 m with a relatively uniform slope of 8.2, 8.4, 8.8, and 8.9%, respectively, along the length. These plots were situated in the southwest corner of the University of Guelph campus in Ontario (approximate latitude/longitude of 43.527, -80.225). Event-based data (rainfall, total runoff amount, sediment yield, and particulate P) and land surface environment data including soil, landuse, and manure application for a nonsnow period of five years (1971 to 1975), were used for this study. The soil on the plots was Guelph loam (well drained loamy soil with hydrologic soil group B), and the land use for all plots during the 1971 to 1975 period was continuous corn. The land management practices on plots 3 and 7 included stover left on the surface, no tillage, and no manure application. For plots 4 and 8, the management practices included stover removed, fall plowed, and manure application. The initial concentration of phosphorus in the top 1-cm layer of the soil on these plots was 1.85 ppm (Bray-extraction method). The liquid poultry manure application rate along with P content and application schedule on each plot during the testing period is given in Table 1.

TABLE 1. Liquid poultry manure application and schedule on each plot used in evaluation of GDVFS upland phosphorus yield and transport module (UH_P)

Year	*Date of application*	*Average application per plot (L)*	*Manure phosphorus content (%)*
1971	Jan. 8 – 11	520	0.21
1971	Jan. 23	530	0.20
1971	Jan. 25	510	0.19
1971	Feb. 18	670	0.15
1972	Jan. 10	560	0.19

The UH and UH_P models were calibrated by comparing computed event runoff (mm), soil loss (t/ha), and particulate P yield (kg/ha) with the observed experimental data for plots 3 and 4. The calibration was performed by adjusting the sensitive parameters to obtain a minimum sum of square error between the computed and observed runoff and particulate P loads for selected events. The comparison focused on nonsnow months from May through October. The calibrated models were validated using the data from plots 7 and 8 for the same events used in the calibration. The calibration and validation results are presented in Tables 2 and 3, respectively. These results are similar to the results obtained by Rudra et al. (1985) by application of the field-scale model CREAMS on the plots. This is due to the piggyback nature of the particulate P on sediment, and sediment on runoff. Any error introduced in the estimation of runoff results in the magnification of errors in the estimation of sediment load and particulate P loads. The UH model standard error of prediction was 3.8 t/ha (41%) for sediment and 2.8 t/ha (46%) for phosphorus, similar to the CREAMS results reported by Rudra et. al. (1985).

Upland bacteria transport component. Similar to phosphorus, bacteria entering the VFS was divided into particulate-bound (attached to the surface of the sediment particles) and free-floating bacteria. A procedure was added to GDVFS to estimate bacteria applied in the upland area with the assumption that the manure application was uniform over the upland area and the bacteria from the manure was uniformly distributed over the entire upland surface. With these assumptions, the total number of bacteria over the entire area, in colony forming units (CFU), is equal to the rate at which the manure is applied over the area (kg/ha) multiplied by the concentration of bacteria in CFU per kilogram. This computation, along with the computation of bacteria die-off, is done on a daily basis. From the total amount of bacteria applied, the upland bacteria transport component of GDVFS divides the bacteria into two fractions: bacteria in water (free-floating/soluble) and bacteria on the sediment (particulate). To quantify these fractions, the following empirical equations for the retention coefficient or partitioning coefficient developed by Burge and Enkiri (1978), Reddy et al. (1981), and Ling et al. (2002) were used:

TABLE 2. Comparison of observed and computed runoff depth, soil loss, and particulate P content for major rainfall events used for calibration of GDVFS upland phosphorus yield and transport module (UH_P)

Plot number	Event date (month dd, yy)	Observed			Simulated		
		Runoff (mm)	Soil loss (t/ha)	Particulate P (kg/ha)	Runoff (mm)	Soil loss (t/ha)	Particulate P (kg/ha)
Plot 3	June 13, 71	13.3	6.64	1.35	13.4	6.11	5.33
	July 26, 71	9.1	2.76	0.34	9.6	3.71	3.47
	August 26, 71	7.5	0.26	0.59	7.8	2.89	2.80
	May 16, 74	13.5	2.67	5.49	13.7	5.48	4.68
	June 19, 75	2.0	0.19	0.45	2.1	0.54	0.69
	August 23, 75	11.9	0.58	1.68	12.3	4.46	4.28
Plot 4	June 13, 71	14.2	21.20	7.85	13.4	9.52	7.80
	July 26, 71	17.8	16.59	4.60	17.3	12.14	9.62
	August 26, 71	7.4	2.84	1.03	7.8	4.51	4.10
	May 16, 74	20.3	14.12	42.48	20.3	14.15	10.58
	June 19, 75	6.7	6.94	7.17	6.6	4.17	4.04
	August 23, 75	20.5	23.77	15.13	20.2	13.39	11.03

TABLE 3. Comparison of observed and computed runoff depth, soil loss and particulate P content for major rainfall events used for validation of GDVFS upland phosphorus yield and transport module (UH_P)

Plot number	Event date (month dd, yy	Observed			Simulated		
		Runoff (mm)	Soil loss (t/ha)	Particulate P (kg/ha)	Runoff (mm)	Soil loss (t/ha)	Particulate P (kg/ha)
Plot 7	June 13, 71	16.2	9.70	3.14	13.4	6.84	5.87
	July 26, 71	7.0	2.25	0.67	9.6	4.16	3.83
	August 26, 71	7.4	0.75	0.59	7.8	3.25	3.10
	May 16, 74	15.5	5.26	8.96	13.7	6.16	5.17
	June 19, 75	1.3	0.15	0.39	2.1	0.61	0.77
	August 23, 75	6.6	1.53	2.24	12.3	5.02	4.74
Plot 8	June 13, 71	12.2	33.16	6.05	13.4	10.45	8.45
	July 26, 71	5.1	4.58	2.02	17.3	13.33	10.42
	August 26, 71	2.5	1.63	0.43	7.8	4.97	4.46
	May 16, 74	19.9	13.83	30.15	20.3	15.56	11.48
	June 19, 75	6.4	8.02	8.69	6.6	4.58	4.39
	August 23, 75	18.8	23.33	11.46	20.2	14.71	11.96

Method 1. (Burge and Enkiri 1978):

$$K_r = 1.1475(\mathrm{SA}) - 64.11\ (R^2 = 0.6438)(\text{when SA} \geq 43.5) \quad K_r = 0\ (\text{when SA} < 43.5) \tag{12}$$

Method 2. (Reddy et al. 1981):

$$K_r = 2.445(\mathrm{SA}) - 72.7;\ (R^2 = 0.97)\ (\text{when SA} \geq 29.7) \quad K_r = 0\ (\text{when SA} \leq 29.7) \tag{13}$$

Method 3. (Ling et al. 2002):

$$K_r = e^{3.9\ln(Cy) - 11.3}\ (R^2 = 0.67) \tag{14}$$

Method 4. (Ling et al. 2002):

$$PC = 50.5\ \ln(C_y) - 102.2\ (R^2 = 0.89) \tag{15}$$

where K_r is the retention coefficient (mL/g); SA is the soil surface area (m^2/g); C_y is the clay content of the soil (%); and *PC* is the partitioning coefficient with regards to soil adsorption (%).

An approach similar to the one used in the UH-P was used to determine the specific surface area of the eroded sediment particles, bacteria enrichment ratio, and the bacteria attached to the sediment.

Vegetative Filter Strip Model

To evaluate the performance of a VFS for trapping sediment and nutrients entering the VFS from the upland field, the model called VFSMOD (Munoz-Carpena et al. 1999) was adopted and incorporated in GDVFS.

VFSMOD employs the finite element approach to simulate the movement of runoff within the vegetative filter strip. A one-dimensional solution to the kinematic wave approximation of overland flow (conservation of mass and conservation of momentum) is linked to a sediment filtration model to simulate the transport and deposition of sediment based on the hydraulics of flow within the grass media. The VFS parameters consist of soil and vegetation characteristics governing the infiltration, overland flow, and sediment transport and deposition within the VFS. VFSMOD requires a runoff hydrograph for a rain event as the input to the VFS. GDVFS receives the outputs from the UH model to extract incoming sediment characteristics, storm hyetograph, and upland area storm runoff hydrograph, and generates the input dataset for the VFSMOD model.

Evaluation of VFSMOD. VFSMOD was evaluated using field experiment data collected during the period of 1998 to 2004 at the University of Guelph in Ontario. Field experiments were conducted in the summer of 1998 in the Carol Creek watershed near Elora, Ontario, during the summer of 2000 at the Guelph Turf Grass Institute and Environmental Research Centre, Guelph, Ontario, and during the summers of 2003 and 2004 at the Elora Research Farm of the University of Guelph. Six types of vegetation cover tested include:

Type A. An equal mixture of perennial ryegrass (*Lolium perenne L.*), Kentucky bluegrass (*Poa pratensis L.*) and reed canarygrass (*Phalaris arundinacea L.*);
Type B. A mixture of birdsfoot trefoil (*Lotus corniculatus L.*) and creeping red fescue (*Festuca rubra*);
Type C. Existing native vegetation, undisturbed for many years, consisting of native species (identity approximated) including wild oat (*Chasmanthium latifoliu*), quackgrass (*Elytrigia repens*), tall fescue grass (*Festuca arundinacea*), and dandelions (*Taraxacum officinale*);
Type D. Perennial ryegrass (*Lolium perenne L.*);
Type E. An equal mixture of perennial ryegrass (*Lolium perenne L.*) and red clover (*Trifolium pratense L.*); and
Type F. Kentucky bluegrass (*Poa pratensis L.*).

These experiments focused on the evaluation of the effect of vegetation, filter strip length, inflow rate, and inflow concentration (sediment, phosphorus, and bacteria) on the trapping of sediment, phosphorus, and bacteria (Lalonde 1998, Gharabaghi et al. 2000, 2001a, 2001b, 2001c, 2006, and Abu-Zreig et al. 2001, 2004).

The comparison of the model-predicted sediment removal efficiency with the observed values collected from 120 experimental results from three sets of field experiment data (1998, 1999, 2000) on VFS collected by Lalonde (1998) and Gharabaghi et al. (2000, 2001a) indicated that the predicted standard error was less than 10% (Rudra et al. 2002). The results of field experiments on 20 filters with varying length, slope, and vegetation cover showed that the slope and intercept of the linear regression lines between predicted versus observed infiltration amounts and sediment removal efficiency were not significantly different from one and zero, respectively, at the 95% probability level (Abu-Zreig et al. 2001).

VFS Phosphorus Transport Component (VFS_P). The developed UH_P module generates the required inputs from the upland area for VFSMOD as well as the VFS_P. The phosphorus removal mechanism considered in VFS_P consists of two components: 1) removal due to the settlement of sediment particles and the phosphorus attached to them within the VFS, and 2) removal due to infiltration of water carrying soluble phosphorus as well as fine suspended particles with particulate phosphorus attached to them.

Particulate phosphorus is attached to the surface of sediment particles and the total amount of particulate phosphorus is proportional with the total surface area of the sediment particles. Therefore, the phosphorus removal efficiency is the ratio of the total surface area of the sediment trapped by the VFS to the total surface area of the inflow sediment. The phosphorus enrichment ratio concept, defined as the ratio of the specific surface area of the sediment particles at the VFS outlet to the specific surface area of the sediment particles entering the VFS at the field outlet, was used to quantify the fraction of particulate phosphorus in the sediment exiting the VFS. Using the phosphorus enrichment ratio and the sediment removal efficiency (the ratio of the total amount of sediment trapped by the VFS to total amount of inflow sediment) computed in the sediment transport module, the sediment-bound phosphorus removal efficiency of the VFS is calculated as:

$$PER = \frac{(\text{specific surface area})_{out}}{(\text{specific surface area})_{in}} \tag{16}$$

$$SRE = 1 - \frac{(\text{total sediment})_{out}}{(\text{total sediment})_{in}} \tag{17}$$

$$PRE = 1 - \frac{(\text{total surface area})_{out}}{(\text{total surface area})_{in}} \tag{18}$$

$$PRE = 1 - \frac{(\text{specific surface area})_{out}}{(\text{specific surface area})_{in}} \times \frac{(\text{total sediment})_{out}}{(\text{total sediment})_{in}} \tag{19}$$

Substituting equation 13 and 14 into 16:

$$PRE = 1 - PER \times (1 - SRE) \tag{20}$$

where PRE is the phosphorus removal efficiency; PER is the phosphorus enrichment ratio for the VFS; and SRE is the sediment removal efficiency of the VFS.

Using the data from three sets of field experiments on the VFS collected by Lalonde (1998) and Gharabaghi et al. (2000, 2001a), the following relationship was developed between the VFS *PER* and the d_{50} of the sediments entering the VFS (r^2 = 0.72):

$$PER = 0.05\, d_{50} + 0.85 \tag{21}$$

where *PER* is the VFS phosphorus enrichment ratio, and d_{50} is the median sediment particle size entering the VFS (mm). The empirical equation derived for the VFS phosphorus enrichment ratio (equation 21) includes the removal due to infiltration of the suspended fine particles.

For each set of experimental data, GDVFS was calibrated to satisfy the water balance within the VFS (total runoff entering the VFS, total runoff leaving the VFS, infiltration within the VFS) followed by the sediment and phosphorus removal efficiencies. The model prediction standard error for the phosphorus removal efficiency was less than 15% (Fig. 1). To include phosphorus removal due to the infiltration of water carrying soluble phosphorus, the water balance within the VFS was carefully satisfied and the removal efficiency was estimated based on the comparison between the total amount of soluble phosphorus entering and leaving the VFS.

VFS bacteria transport component (VFS_B). The VFS_B of GDVFS is somewhat similar to the VFS phosphorus transport module described earlier. The additional processes included in VFS_B are the adsorption of bacteria to the vegetation surface and the change in bacteria concentration due to resuspension. The specific surface area approach used to calculate the particle-attached bacteria lost in the VFS was adopted from Rudra et al. (2002). Similar to VFS_P, and based on the concept of the particulate phosphorus enrichment ratio discussed earlier and the sediment removal efficiency calculated in the sediment transport module, the sediment-bound bacteria removal efficiency in the VFS was calculated using the following equation:

$$BRE = 1 - BER \times (1 - SRE) \tag{22}$$

where *BRE* is the bacteria removal efficiency; *BER* is the bacteria enrichment ratio for the VFS; and *SRE* is the sediment removal efficiency of the VFS. The amount of particle-attached bacteria adsorbed to vegetation is computed using an adsorption capacity of the VFS approach outlined by Newham et al. (2005).

Similar to the VFS phosphorus transport component, water balance within the VFS was carefully satisfied to include the bacteria removal due to infiltration of water carrying bacteria nonattached to the particles. The bacterial removal efficiency was estimated based on the comparison between the total amount of bacteria nonattached to the particles entering and leaving the VFS. To quantify the amount of particle-attached (i.e., particle size > 50μm) resuspended bacteria, the approach suggested by Tian et al. (2002) was adopted. According to this approach the bacteria resuspension rate for the settled particle-attached bacteria was computed by the following equation:

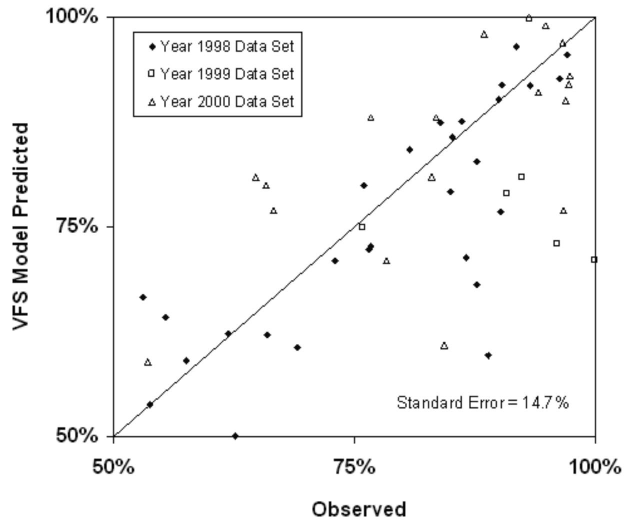

Fig. 1. Comparison of observed and simulated phosphorus removal efficiencies of the VFS.

$$R = 1 - e^{\left(\frac{V_0 - V}{S}\right)} \tag{23}$$

where *R* is the daily resuspension rate; *V* is the outflow volume; V_0 is the threshold volume; and *S* is the parameter controlling the resuspension.

The developed approach for bacteria (*Escherichia coli*) removal by VFS was evaluated using the field experimental data collected by Clarke (2007) and Moharir (2007). These experiments focused on the effect of vegetation (Kentucky bluegrass, perennial ryegrass, and mixed sod), filter strip lengths (5, 10, and 15 m), and inflow rates (0.5, 1.0, and 1.5 L/s) on bacteria removal. This data set was randomly partitioned into two groups; one set was used for calibration of the developed algorithm and the second for the validation. The observed and modelled results show a bacterial removal efficiency of 69% for the suspended bacteria and 98% for the particle-attached bacteria transported through the VFS (Moharir 2007).

Overview of the GDVFS Interface

GDVFS is a graphical user interface for the two main components, the UH and VFSMOD models, and the corresponding phosphorus and bacteria transport submodels. The modelling concept used in the GDVFS components is categorized as event-based since the entire simulation is performed based on a single rain event. Input parameters are introduced to GDVFS in the form of a "project," and each project folder has a standard subfolder structure in which the project data files are stored. GDVFS is capable of generating and storing scenarios for major computation modules for future access. Some basic tools are also provided in GDVFS, which help the user to evaluate the outputs or directly access and modify the input files within the GDVFS environment.

Application of GDVFS in Simulation Mode

GDVFS can be used in simulation mode to evaluate the performance of an existing VFS. To simulate the hydrological processes, GDVFS requires rainfall depth, storm duration, and a standard rainfall pattern, characteristic of an event-based model, as input parameters. The modelling concept used in GDVFS to estimate erosion and sediment yield is essentially proposed for a field-size upland area, although the same concept is widely used by other sediment transport models regardless of the size of the upland area.

In simulation mode (Fig. 2), sediment, phosphorus, and bacteria movement within the upland field and the VFS are simulated using input parameters provided by the user. In this mode, the user provides all the input data for a given scenario. The online help included in the GDVFS data entry forms assists users to specify the simulation parameters. The structure of the simulation mode helps users to prepare the input data and run the program in a proper sequence. A set of default parameters has been included in some data entry forms, which can be used to setup the input dataset using predefined parameters. The default parameters can be modified and stored by the user for further use to generate or modify other scenarios.

The list of the input parameters for the UH model is given below:

- Total area of upland field (ha)
- Flow path length (m)
- Average flow path slope (%)
- Soil texture
- NRCS (Natural Resources Conservation Service) curve number
- USLE crop factor
- USLE practice support factor
- Total rainfall depth (mm)
- Storm duration (hours)
- Synthetic rainfall pattern (SCS)

The results of the UH model along with the user-defined VFSMOD parameters are used to simulate the VFS. The VFSMOD input parameters are as follows:

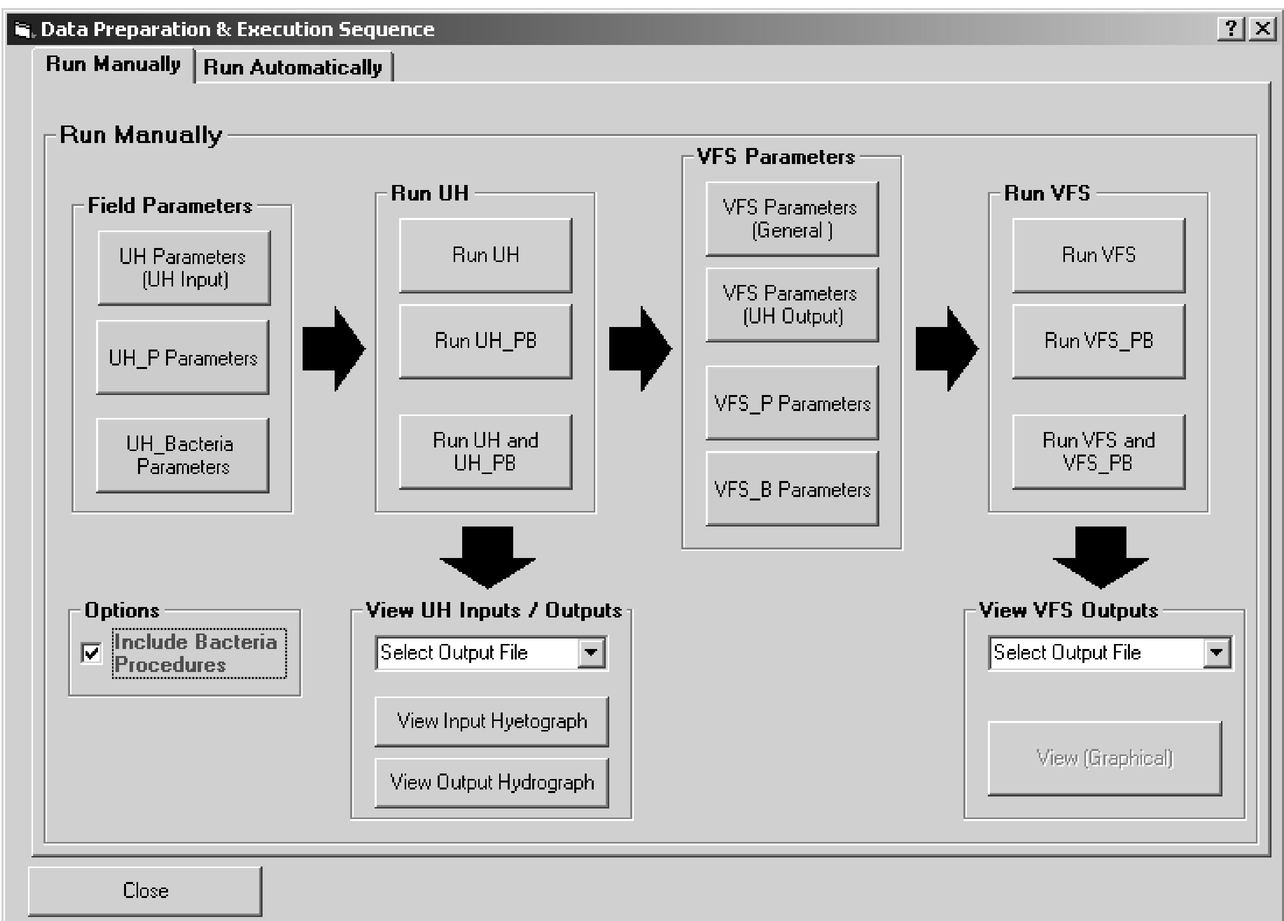

Fig. 2. GDVFS simulation steps.

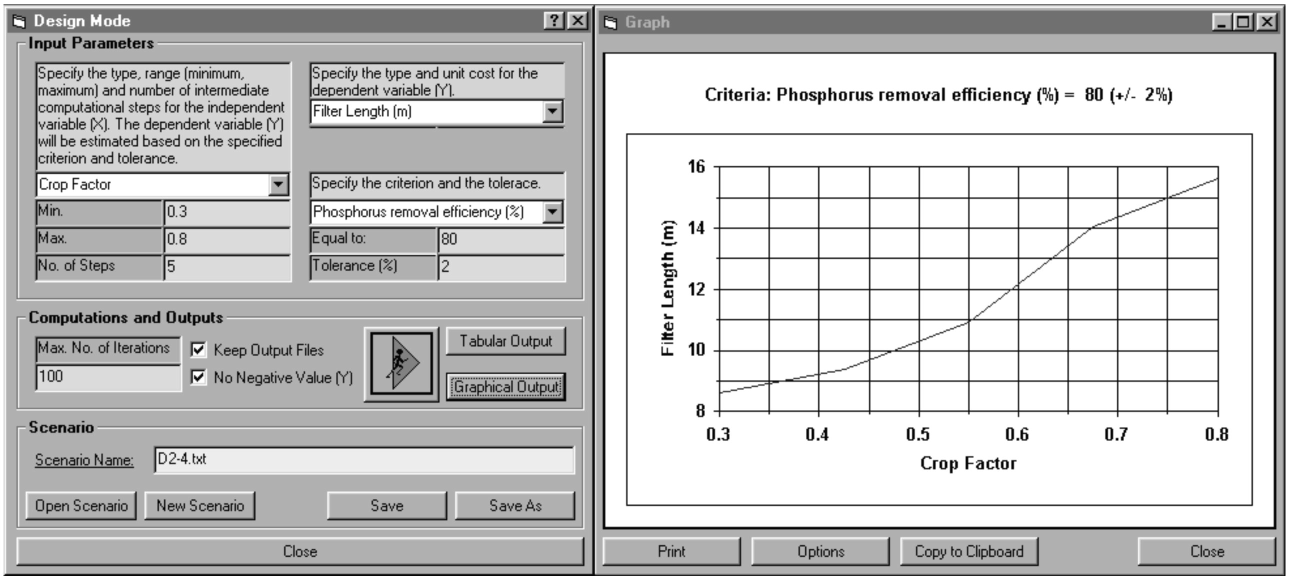

Fig. 3. Data preparation for the application of GDVFS in design mode.

- Vegetation parameters
  - Spacing of the filter media elements (cm)
  - Filter media (grass) Manning's *n*
  - Filter media height (cm)
  - Bare surface Manning's *n*
- Overland flow parameters
  - Width of the filter strip (m)
  - Filter length in flow direction (m)
- Infiltration soil parameters
  - Saturated hydraulic conductivity, *Ks* (mm/h)
  - Green-Ampt's average suction at wetting front (mm)
  - Saturated soil-water content, θs (m^3/m^3)
  - Initial soil-water content, θi (m^3/m^3)
  - Maximum surface storage (mm)
- Incoming sediment characteristics
  - Portion of incoming sediment with diameter >37 µm
  - Incoming flow sediment concentration (g/L)
  - Porosity of deposited sediment (ratio)
  - Sediment particle size, diameter d_{50} (µm)
  - Sediment particle density (g/cm^3)

Application of GDVFS in Design Mode

When used in design mode (Fig. 3) for a set of known parameters, GDVFS executes the computational modules iteratively to size the filter strip to satisfy a user-defined criterion. An independent variable specific to the site is selected by the user from geometrical and topographic characteristics of the upland area, total rainfall, rainfall duration, the USLE crop management factor, the USLE soil erodibility factor, the USLE practice support factor, and the quantity of applied fertilizer and/or manure. The criterion is selected from sediment concentration, phosphorus concentration, total sediment, total phosphorus, sediment removal efficiency, phosphorus removal efficiency, and bacteria removal efficiency.

In the example shown in Fig. 4, the total rainfall was set as an independent variable, filter geometry (length) was set as an unknown dependent variable, and sediment removal efficiency equal to 80% was set as criterion. GDVFS executes the vegetative filter strip model iteratively to satisfy the specified criterion for each computation step within the independent variable

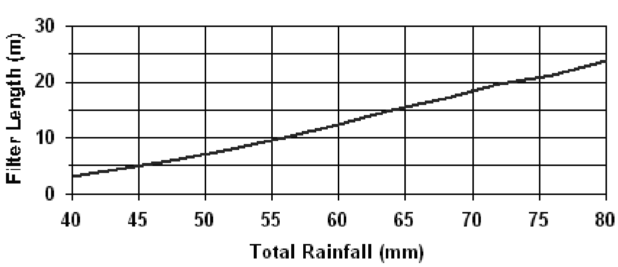

Fig. 4. Change in length of the VFS with rainfall depth obtained by the application of the GDVFS in design mode. Criteria: Sediment Removal Efficiency (%) = 80 (+/- 1%).

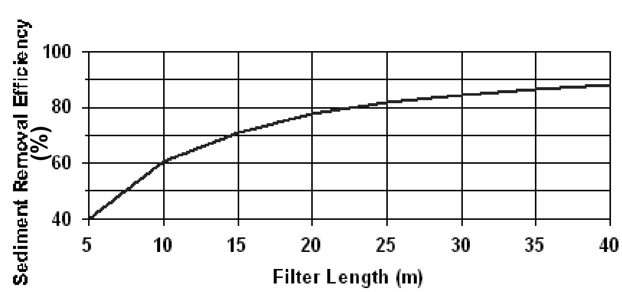

Fig. 5. Relationship between the length of the VFS and the sediment removal efficiency obtained by application of the GDVFS in design mode.

domain specified by the user (in this example total rainfall was changed from 40 to 80 mm).

Figure 5 shows an example of another application of GDVFS in design mode, which can be used to determine the VFS outflow characteristics (sediment concentration, phosphorus concentration, total sediment, total phosphorus, sediment removal efficiency, and phosphorus removal efficiency) with the variation of the VFS geometry (filter length).

Summary

The UH component of GDVFS simulates the quantity and quality of runoff from the upland area entering the VFS. The VFSMOD component simulates the transport of runoff and sediments through the VFS. The upland phosphorus and bacteria transport components of GDVFS are used to estimate the amount of phosphorus and bacteria initially available within the upland field, and to break down the sediment yield from the upland field into particle size classes. The soluble and particulate phosphorus and bacteria entering the VFS are removed mostly through the infiltration and sediment deposition mechanisms in the VFS. The output of VFSMOD is used to estimate the removal efficiency of the VFS for sediment, phosphorus, and bacteria. The VFSMOD component also estimates the amount of infiltration along the length of the VFS, the dominant mechanism responsible for trapping suspended bacteria and soluble phosphorus.

The developed GDVFS toolkit can be used for site specific design of VFSs to control nonpoint source pollution and to evaluate the performance of existing filter strips based on the characteristics of the upland area contributing to the VFS.

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Received: 24 March 2009; accepted: 25 September 2009.