VFSMOD-W

Vegetative Filter Strips Hydrology and Sediment Transport Modelling System

MODEL DOCUMENTATION & USER'S MANUAL

version 2.x (draft 3.x)

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VFSMOD was initially developed in the Department of Biological and Agricultural Engineering by Dr. Rafael Muñoz-Carpena under the direction of Dr. John E. Parsons. The model and associated documentation is supplied as-is with no warranty - explicit or implied. The model is provided to as an educational and research tool. This version is the fourth moving the model from a research tool to one available for general users. As with any model, the results are totally dependent on the user's ability to wisely select input parameters that represent the "field" and to interpret the results. We will make every effort to provide assistance and encouragement as our other commitments allow. We do ask that you reference our work if you find it helpful in your pursuits.

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Part I: VFSMOD-W: Model Documentation

1. Introduction

Runoff carrying sediment from nonpoint sources has long been recognized as a major pollutant of surface water. Sediment-bound pollutants, such as phosphorous and some pesticides, are also a major pollution concern. Several management practices have been suggested to control runoff quantity and quality from disturbed areas. One such management practice is vegetative filter strips (VFS), which can be defined as (Dillaha et al., 1989) areas of vegetation designed to remove sediment and other pollutants from surface water runoff by filtration, deposition, infiltration, adsorption, absorption, decomposition, and volatilization. These bands of planted or indigenous vegetation separate a water body from a land area that could act as a nonpoint pollution source. 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 translates into sediment deposition in the filter due to a decrease in transport capacity (Wilson, 1967). Barfield et al. (1979) and Dillaha et al. (1986) reported that grass filter strips have high sediment trapping efficiencies as long as the flow is shallow and uniform and the filter is not submerged.

Researchers (Dillaha et al., 1989; Parsons et al., 1991) have found that the filter length (L_f) controls sediment trapping up to an effective maximum length value, thereafter, additional length does not improve filter performance. This maximum effective length depends on the source area, topography, and the hydraulic characteristics of the strip.

Several modeling efforts have been undertaken to simulate VFS efficiency in removing pollutants from surface waters. Researchers at the University of Kentucky (Barfield et al. 1978, 1979; Hayes 1979; Hayes et al., 1982, 1984; Tollner et al., 1976, 1977) developed and tested a model (GRASSF) for filtration of suspended solids by artificial grass media. The model is based on the hydraulics of flow, and transport and deposition profiles of sediment in laboratory conditions. This physically based model takes into account a number of important field parameters that affect sediment transport and deposition through the filter (sediment type and concentration, vegetation type, slope and length of the filter). Flow is described by the continuity equation and steady state infiltration, i.e. flow decreases linearly from upstream to downstream in the filter.

Wilson et al. (1981) modified and incorporated GRASSF into SEDIMOT II, a hydrology and sedimentology watershed model. A simple algorithm to calculate the outflow hydrograph was incorporated into the model and up to three different slope changes throughout the filter could be considered. The model does not handle time

dependent infiltration, an accurate description of flow through the filter, and changes in flow derived from sediment deposition during the storm event.

This work presents a design-oriented computer modeling system (VFSMOD-W). The MS-Windows32 graphical user interface (GUI) integrates the numerical model VFSMOD, a utility to generate inputs for the model based on readily available NRCS site characteristics (UH), and uncertainty, analysis of sensitivity and design menu-driven components.

VFSMOD, the core of the design system, is a model to study hydrology and sediment transport through vegetative filter strips. The model combines the strength of: a) a numerical submodel to describe overland flow and infiltration, b) the University of Kentucky's algorithm developed specifically for the filtration of suspended solids by grass. This model formulation effectively handles complex sets of inputs similar to those found in natural events. The improvements of this combined model over the GRASSF or 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 soil water infiltration; d) handling of complex storm pattern and intensity; and e) varying surface conditions (slope and vegetation) along the filter.

VFSMOD, UH and additional components are described in this Part I from a theoretical and modelling structure perspective. The user manual for the command line versions of VFSMOD and UH is given in Part II along with annotated applications, detailed description of input and output files, and recommended input values. Part III describes the integrated package (VFSMOD-W) as a whole under the MS-Windows environment. Part IV contains appendixes with detailed description on model variables and a collection of tables with recommended inputs for a variety of soil, climate and plant conditions. Each Part builds on the previous ones. Although the reader is encouraged to read through the sections in sequence to gain in depth knowledge of the system, section II contains the essentials to run the MS-Windows design-oriented application.

2. VFSMOD: Model Components, Processes and Solution Techniques

VFSMOD is a field scale, mechanistic, storm-based model designed to route the incoming hydrograph and sedimentograph from an adjacent field through a vegetative filter strip (VFS) and to calculate the outflow, infiltration and sediment trapping efficiency.

The model handles time dependent hyetographs, space distributed filter parameters (vegetation roughness or density, slope, infiltration characteristics) and different particle size of the incoming sediment. Any combination of unsteady storm and incoming hydrograph types can be used.

VFSMOD consists of a series of modules simulating the behavior of water and sediment in the surface of the VFS. The current modules available are (Figure 1):

RAINFALL

Green-Ampt Infiltration → Kinematic Overland Flow ← FIELD INFLOW

Sediment filtration

VFS OUTFLOW
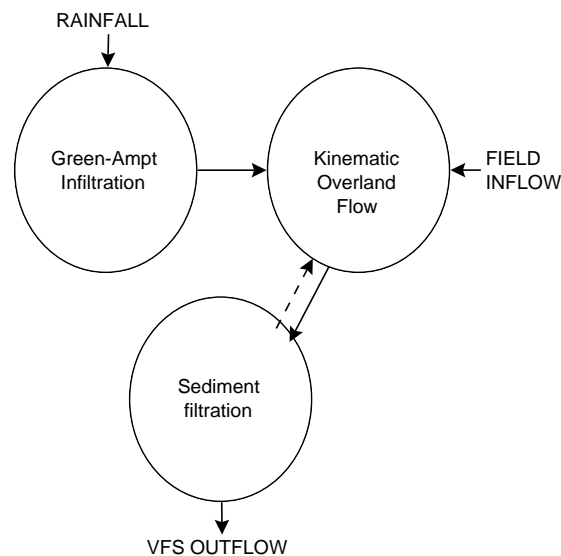
Figure 1. Schematic representation of the VFSMOD

i) Green-Ampt infiltration module: a module for calculating the water balance in the soil surface; ii) kinematic wave overland flow module: a 1-D module for calculating flow depth and rates on the infiltrating soil surface; iii) sediment filtration module: a module for simulating transport and deposition of the incoming sediment along the VFS.

VFSMOD is essentially a 1-D model for the description of water transport and sediment deposition along the VFS. The model can also be used to describe transport at the field scale (or field edge) if flow and transport is mainly in the form of sheet flow (Hortonian) and the 1-D path represents average conditions (field effective values) across the VFS.

The VFSMOD model uses a variable time step, chosen to limit mass balance errors

induced by solving the overland water flow equation. The time step for the simulation is selected by the kinematic wave model to satisfy convergence and computational criteria of the finite element method based on model inputs (Muñoz-Carpena et al., 1993a,b).

The model inputs are specified on a storm basis. State variables are integrated after each event to yield storm outputs.

2.1 Hydrology

This program solves the kinetic wave approximation of the Saint- Vennant's (1881) equations for overland flow (KW) for the 1-D case as presented by Lighthill and Whitham (1955) such as:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i_e(t) \quad \textit{(Continuity equation)} \tag{1}$$

$$S_o = S_f \quad \textit{(Momentum equation)}$$

Then a uniform flow equation equation can be used as a link between the q and h, such as Manning's:

$$q = q(h) = \frac{\sqrt{S_o}}{n} h^{\frac{5}{3}} \tag{2}$$

Where h is depth of overland flow [L], q is the flow per unit width of the plane [L^2T^{-1}], S_o is the slope of the plane, S_f is the hydraulic or friction slope, and n is Manning's roughness coefficient [$LT^{-1/3}$]. The initial and boundary conditions can be summarized as:

$$h = 0; 0 \leq x \leq L; t = 0 \tag{3}$$
$$h = h_o; x = 0; t > 0$$

where h_o can be 0, a constant or a time dependent function, such as the incoming hydrograph from the adjacent field. This could also be a linkage to other water quality models describing the runoff source area.

The rainfall excess *ie* is calculated from the hyetograph and a modification to the Green-Ampt infiltration method at every time step (Muñoz-Carpena et al., 1993). The overland flow model was coupled, for each time step, with an infiltration submodel based on a modification of the Green-Ampt equation for unsteady rainfall (Chu, 1978; Mein and Larson 1971, 1973; Skaggs and Khaheel, 1982; Muñoz-Carpena et al., 1993b):

$$f_p = K_s + \frac{K_s M S_{av}}{F_p} \qquad (4)$$

$$K_s(t - t_p + t_o) = F - M S_{av} ln\left(1 + \frac{F}{M S_{av}}\right) \qquad (5)$$

where f_p is the instantaneous infiltration rate, or infiltration capacity, for ponded conditions [m/s], K_s is the saturated vertical hydraulic conductivity [m/s], $M = \theta_s - \theta_i$ is the initial soil-water deficit [m³/m³], S_{av} is the average suction across the wetting front [m], F_p is the cumulative infiltration after ponding [m], F is the cumulative infiltration for the event [m], t is the actual time [s], t_p the time to ponding, and t_o is the shift of the time scale to correct for not having ponded conditions at the start of the event.
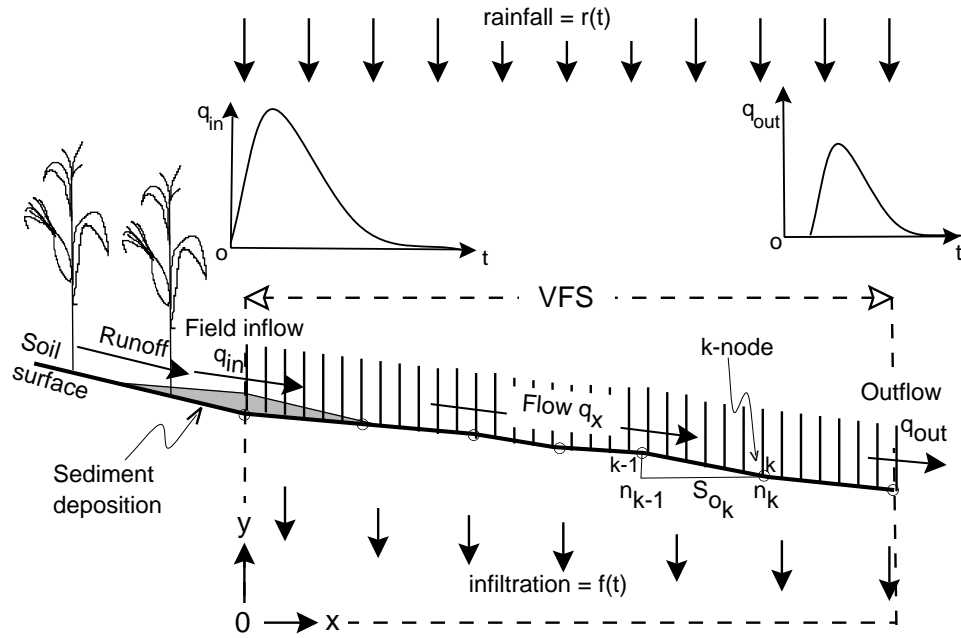
Figure 2. Domain discretization for the finite element overland flow submodel.

Rainfall excess, i_e in equation 1, is calculated for a given rainfall distribution for each node and time step by the infiltration model. The hydrograph representing runoff from the adjacent field is input as a time dependent boundary condition at the first node of the finite element grid. The program allows for spatial variation of the parameters n and S_o over the nodes of the system (Figure 2). This feature of the program ensures a good representation of the field conditions for different rainfall events. The model can be operated to provide information on the effect of soil type (infiltration), slope, surface roughness, filter length, storm pattern and field inflow on VFS performance (i.e. reduction of the runoff peak, volume and velocity) (Muñoz-Carpena et al., 1993b). It also describes the flow rate (q), velocity (V), and depth (h) components throughout the filter for each time step.

The numerical solution is subject to kinematic shocks, or oscillations in the solution

that develop when a sudden change in conditions (slope, roughness or inflow) occurs. When linking the kinematic wave and the sediment transport models, the soil surface conditions are also changed for each time step, further increasing the potential for the kinematic shock problem. VFSMOD implements a Petrov-Galerkin formulation (non-standard) finite element to solve equations 1 and 2. This solution procedure reduces the amplitude and frequency of oscillations with respect to the standard Bubnov-Galerkin method (Muñoz-Carpena et al., 1993a), thus improving the model stability and the sediment transport predictions which depend on overland flow values.

2.2 Sediment Transport

The hydrology model is linked to a model for filtration of suspended solids by artificial grass media, developed and later tested for field conditions (Barfield et al. 1978, 1979; Hayes et al., 1979, 1984; Tollner et al., 1976, 1977, Wilson et al, 1981). It is based on the hydraulics of flow, transport and deposition profiles of sediment in laboratory conditions. The model presents the advantage of being developed specifically for the filtration of suspended solids by grass..
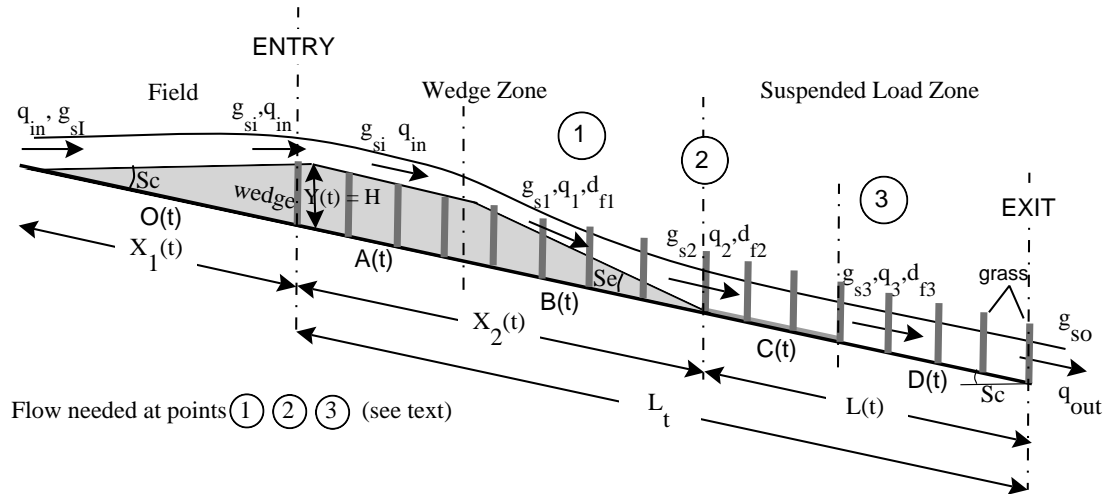
Figure 3. Filter description for the sediment transport algorithm.

The University of Kentucky algorithm considers that during a rainfall/runoff event, field runoff reaches the upstream edge of the filter with time dependent flow rate q_{in}[cm^2/s], and sediment load g_{si} [g/cm-s]. The vegetation produces a sudden increase in hydraulic resistance that slows the flow, lowers its transport capacity g_{sd} [g/cm-s], and produces deposition of the coarse material (particle diameter d_p >0.0037 cm) carried mostly as bed load transport.

The sediment trapped in this first part of the filter forms a geometrical shape that varies depending on the thickness of the deposited sediment layer at the entry of the filter, *Y(t)* [m], and the effective top of vegetation, *H* [cm]. A triangular shape at the adjacent field area and the beginning of the filter is formed when *Y(t) < H*. After *Y(t)=H,* a

trapezoidal wedge is formed (Figure 3) with three well defined zones: the upslope face of the wedge (with zero slope), $O(t)$ [cm]; the upper face of the wedge (parallel to the soil surface), $A(t)$; and the downslope face, $B(t)$, with an equilibrium deposition slope S_e for each time step (Figure 3). Together these first filter zones are termed "wedge zone", and its length changes with time as sediment is deposited.

Zone $O(t)$, external to the filter, is important in explaining field observations where a portion of the sediment is deposited in the field area adjacent to the filter. After the wedge has formed, no sediment is deposited in zone $A(t)$ and the initial load, g_{si}, moves through to the next zone, $B(t)$. In this zone, deposition occurs uniformly with distance to the deposition edge, with transport mostly as bed load. The model assumes that the sediment inflow load, g_{si}, is greater than the downstream sediment transport capacity g_{sd} at point 2 (Figure 3). The algorithm calculates the g_{sd} value for each time step and compares it with the sediment inflow load. If $g_{sd} > g_{si}$, all sediment is transported through the first part of the filter (wedge), $g_{s2} = g_{sd}$, and the sediment is filtered at the suspended sediment zone (lower part of the filter). If $g_{sd} < g_{si}$ deposition at the wedge occurs and the fraction not deposited is filtered at the lower part of the filter, $g_{s2} = g_{si} - g_{sd}$. The calculation procedure utilizes a modified Manning's open channel flow equation, continuity equation, and Einstein's sediment bed load transport function. Flow values at the filter entry and points 1 and 2 in Figure 3 (q_{in}, q_1, q_2 respectively) are needed for these calculations.

After the downside of the wedge, two zones $C(t)$ and $D(t)$ form the "suspended load zone" or "effective filter length", $L(t)$ (Figure 3). On zone $C(t)$, sediment has covered the indentations of the surface so that bed load transport and deposition occurs but the soil slope, S_c, is not significantly changed. All bed load transported sediment is captured before reaching zone $D(t)$, so only suspended sediment is transported and deposited in this zone until the flow reaches the end of the filter with sediment load g_{so}. The sediment trapping algorithm for the suspended load zone follows Tollner et al. (1976) equation based on a probabilistic approach to turbulent diffusion for non-submerged flow. Flow values at point 3 and filter exit, q_3 and q_{out} respectively (Figure 3), are needed for these calculations. Details of the implementation of the submodel are given in Muñoz-Carpena (1993).

Under extreme sediment inflow events the filter can be filled up with sediment to the top of the standing vegetation. VFSMOD accounts for this in a realistic way by allowing normal filtration up to the time step when the sediment wedge reaches the end of the filter ($X_2 \geq L_t$), and bypassing filtration from then on ($g_{so} = g_{si}$).

The original University of Kentucky sediment model uses a simple approach to calculate flow conditions at specific points of the filter and does not consider the complex effects of rainfall, infiltration, and flow delay caused by the buffer. VFSMOD provides a more accurate description of the flow conditions from the hydrology submodel whereas

changes in surface conditions (topography, roughness) due to sediment deposition during the event are obtained from the sediment filtration submodel.

2.3 Linkage between submodels

Flow conditions at the entry, exit and three inner points (1, 2, and 3) of the filter are needed for the sediment transport calculations (q_{in}, q_1, q_2, q_3 and q_{out} in Figure 3). The GRASSF and SEDIMOT II models use a simple approach to calculating those values and do not consider the complex effects of rainfall, infiltration, and flow delay caused by the filter. A more accurate description of the flow conditions are obtained from the hydrology submodel presented above. In turn, the sediment transport model supplies information on changes in surface conditions (topography, roughness) due to sediment deposition during the event that affect overland flow. This interaction between submodels is depicted in the flowchart in Figure 4.
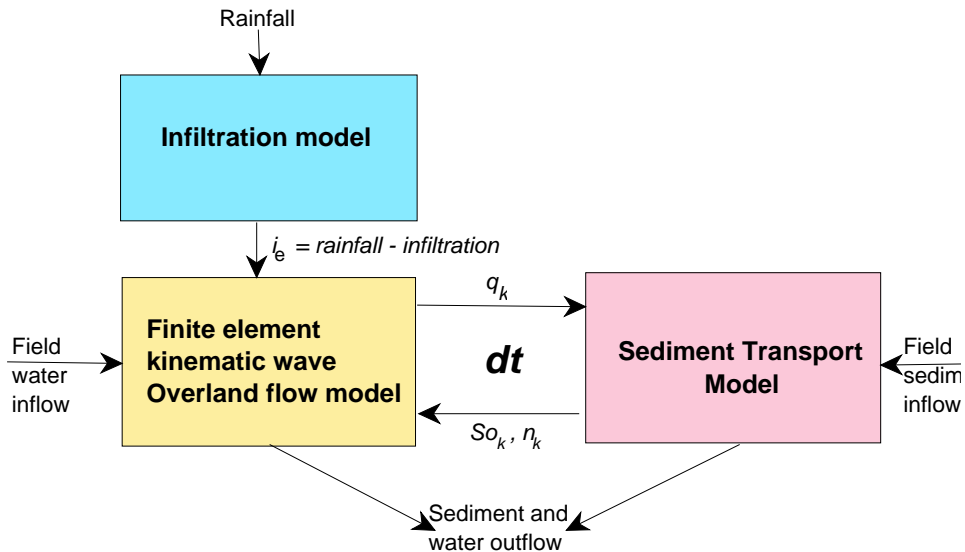
Figure 4. Flowchart showing linking between hydrology and sediment submodels.

During the simulation, feedback between the hydrology and sediment models is produced. The hydrology model supplies the flow conditions at the five locations (entry, 1, 2, 3, and exit) set in the last time step (Figure 3). The other parameters that interact through the linkage are the length, slope, and roughness in each of the sections (entry, 1, 2, 3, and exit).

After solving the sediment transport problem for a time step, new values of roughness and/or slope are selected as nodal values for the finite element grid in zones *A(t)* and *B(t)*, whereas *C(t)* and *D(t)* remain unchanged (Figure 3). Changes in surface saturated hydraulic conductivity values *(K_s)* are considered negligible. The new surface parameters are fed back into the hydrology model for the next time step. Surface changes are

accounted for in this way.

The time step for the simulation is selected by the kinematic wave model to satisfy convergence and computational criteria of the FE method based on model inputs (Muñoz-Carpena et al., 1993a,b).

At the end of the simulation, the model outputs include: information on the water balance (volume of rainfall, field inflow, filter outflow and infiltration), hydrograph, sediment balance (field inflow, filter outflow and deposition), sedimentograph, filter trapping efficiency, and sediment deposition pattern within the filter.

2.4 Solution procedure

The VFSMOD main program calls the subroutines along the solution procedure. The backbone of the model is the numerical solution to the overland flow equation and the infiltration and sediment transport models are called upon to solve the equation for each time step at the time of assembling the matrix system.

The numerical method is based on a *N+2* upwinding Petrov-Galerkin finite element method approximation for the spacial derivatives and a time weighting finite difference approximation for the time derivatives.

The non-linearity of the equation *{q=q(h)}* is taken care of by using the Picard iterative scheme inside every time step, lagging 2/3 of the power of *h* in *q*, [5/3 = 2/3(m)+1 (m+1)] for the iteration level *m*, such as:

$$[A]^{m+1} \{h\}^m = \{b(h)\} \tag{6}$$

In this program the core of the time step solution is taken care of following this steps:
(1) Form the system matrix *[A]* of constant coefficients
(2) Perform LUD decomposition over this matrix *[A]*
(3) Form the system matrix *[BM]* of constant coefficients
(4) Form r.h.s of equation (vector *{b}=[BM]{x_o}* for each time step
(5) Solve for *[A], {b}* to get a *{x}* for that time step
(6) Repeat 4 & 5 until convergence of that time step
(7) Repeat 3 & 6 until completion of desired number of time steps

The transport model supplies information to build the *{BM}* and *{b}* for each time step,

dt. The general procedure is structured into subroutines as illustrated in the next diagram.
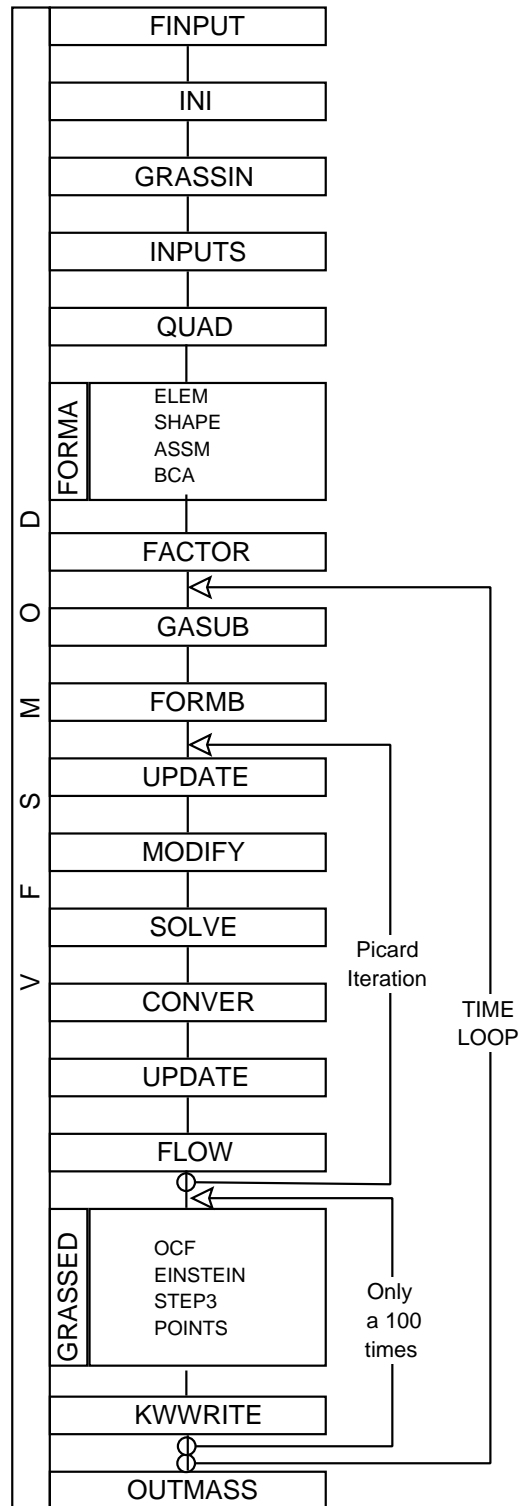
Figure 5. VFSMOD model structure

After solving the sediment transport problem for a given time step, values of *n* and S_o

are selected as nodal values for the finite element grid. The parameters are fed back into the hydrology model for the next time step, thus surface changes due to sediment deposition within the filter (sediment wedge area) are accounted for in the next time step of the hydrology simulation, as described in the previous section.

2.5 Model inputs

The program reads inputs (model parameters and model input variables) from external ASCII-files, which can be prepared from given examples using a conventional text editor. A summary of the model inputs is given in the following Table.

Class	Inputs
Green-Ampt infiltration	Rainfall hyetograph, soil saturated hydraulic conductivity, soil saturated water content, soil initial water content, soil suction at the wetting front, and surface storage.
Overland flow	Field inflow hydrograph, filter length, filter width, nodal slopes and Manning's roughness across the filter.
Sediment filtration	Modified grass Manning's roughness, Manning's roughness for bare soil, incoming sediment characteristics (median particle size, weight density, fall velocity), effective filter media spacing and height, porosity of deposited sediment, incoming sediment inflow concentration (sedimentograph), and proportion of fine sediment.
General	Number of nodes for the domain, Courant number for numerical solution, total time for the simulation.

Part II of this manual gives suggested literature values for some of these parameters when no field measurements are available. In the case of the soil hydraulic and sediment parameters, these can be chosen from soil texture using tables from the manual. The structure of these files is discussed in detail in Part II: Section 1.4 on page 44

3. UH utility - preparation of model inputs for design purposes

As an aid to set up the model inputs, the distribution package includes an utility, UH, that creates synthetic model inputs for the upslope source area based on the NRCS (SCS) design storm for a given location and soil type. The utility implements the NRCS' (SCS) curve number, unit hydrograph and Modified Universal Soil Loss Equation (MUSLE) concepts to produce ready-to-use input files for VFSMOD. These inputs are rainfall hyetograph, field inflow hydrograph and field sediment inflow and characteristics. UH and VFSMOD are intended to be run in sequence for a design case. After running UH, the remaining VFSMOD inputs needed pertain only to the vegetative filter strip characteristics (dimension, soil, vegetation, and numerical solution parameters).

The structure of UH input and output files is discussed in Part II: Section 2.3 on page 59. The following sections herein present the theory behind the methods implemented in UH.

3.1 Generation of Synthetic Rainfall Hyetographs

3.1.1 Equations for storm types II & III

For storm types II and III, the equations presented by Haan et al. (1994) are used to generate the hyetographs. The equation is:

$$\frac{p(t)}{p_{24}} = 0.5 + \frac{T}{24}\left(\frac{24.04}{2|T| + 0.04}\right)^{0.75} \tag{7}$$

where: T=t-12 with t in hours; p_{24} = the 24 hour total rainfall in cm.

For storm durations less than 24 hours, the ratio of $p(t)/p_{24}$ is used to derive the amount of rainfall at time *t* from the total rainfall for the period. The computation procedure follows that given by Haan et. al. (1994).

3.1.2 Equations for storm types I & IA

Based on tabulated data (Haan et al., 1994, pg. 48), the fitted equations using Mathematica (Wolfram, 1999) are:

- Storm type I:

$$\frac{P}{P_{24}} = \left(\begin{array}{ll} 0.4511 + (t - 9.995)\left[\dfrac{-0.1617}{-3.0163|t - 9.995| + 0.013}\right]^{0.5853} & ;-3.0163|t - 9.995| + 0.013 < 0 \\[2ex] 0.5129 & ;-3.0163|t - 9.995| + 0.013 > 0 \end{array} \right. \tag{8}$$

With an Root Mean Square Deviation (RMSD) =0.0088 and χ^2 =3.363

- Storm type IA:

$$\frac{P}{P_{24}} = 0.3919 + (t - 7.960)\left[\frac{0.0843}{120.39|t - 7.960| + 0.3567}\right]^{0.4228} \qquad (9)$$

With an RMSD= 0.0033 and χ^2 =1.539

The comparison of fitted vs. real values can be seen on Figure 6.
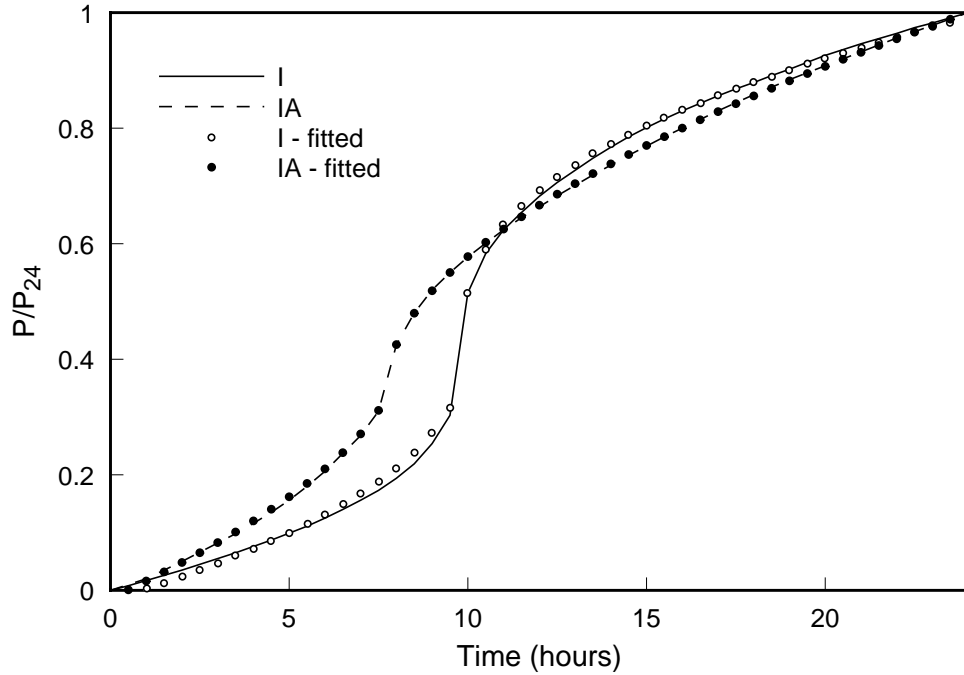
Figure 6. NRCS storm types fitted by proposed equations

To construct hyetographs for any duration, D (h), and storm type, equation (3.7) in Haan et al. (1994, pg. 49) was transformed to,

$$\frac{P}{P_D} = \frac{P(t_{mid} + t - D/2) - P(t_{mid} - D/2)}{P(t_{mid} + D/2) - P(t_{mid} - D/2)} \qquad (10)$$

where t_{mid} is 9.995 for storm type I, 7.960 for storm type IA and 12.0 for storm type II and III.

This modification from the original formula results from the fact that to construct a hyetograph for a duration < 24 h, the interval should be centered around the steepest part of the curve, i.e around t_{mid} for each one of the storm types.

An example of the hyetographs obtained for the different storm types for the event in the included sample file UH.*in* (25mm in 6 hours) can be seen in Figure 7.
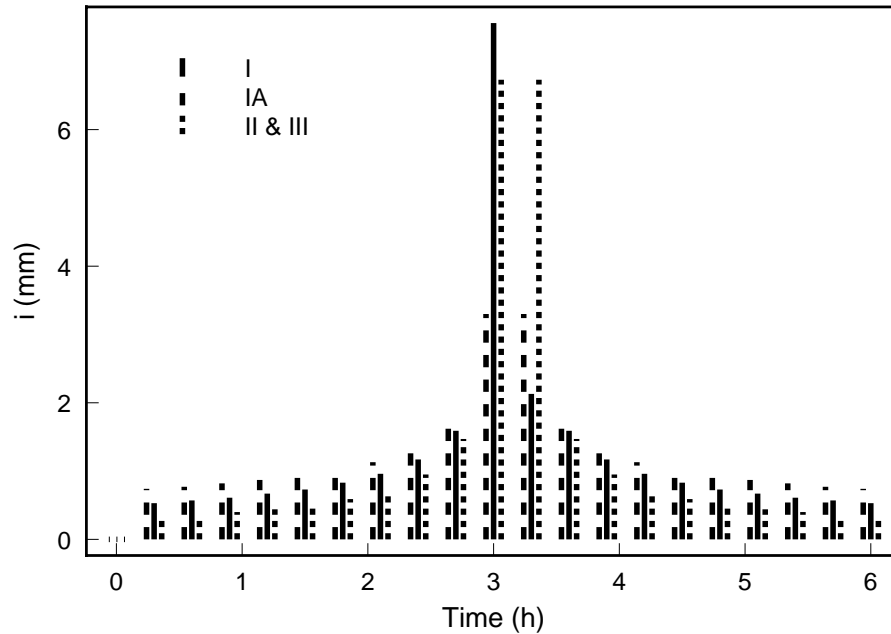
Figure 7. Rainfall hyetographs generated for different storm types.

3.2 Generation of Runoff Hydrographs

3.2.1 Computation of Total Runoff using NRCS Curver Number method (SI units)

Runoff from the source area is computed using the NRCS (SCS) Curve number method (USDA-NRCS, 1984):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{11}$$

where Q = total runoff in cm; P = total precipitation in cm and P > 0.2S; S = represents the antecedent moisture and is computed by:

$$S = \frac{25400}{CN} - 254 \tag{12}$$

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

Tables for selecting the curve number (CN) are given in Appendix 3 of this manual (see also NRCS, 1984). In the case of multiple land uses, a composite CN can be derived using a weighted average of the respective CN based on the land use areas. As in the original derivation of the method, Q is set to 0 if the precipitation is less than 0.2 of S. This

assumes that the precipitation does not replenish the available storage (ie, 0.2*S).

3.2.2 Peak flow calculation using NRCS method (SI units)

Based on the triangular hydrograph assumption the time to peak can be stimated as:

$$t_p = \frac{D}{2} + t_L = \frac{D}{2} + 0.6t_c \qquad (13)$$

Where the concentration time can be estimated by the following equations:

$$t_c = t_{t1} + t_{t2} + \ldots + t_{tn} = \frac{SL_i}{v_i} \qquad (14)$$

where t_{ti} is the transit time for each of the segments of the path between furthest point to the watershed outlet (from a hydraulics point of view), L_i and v_i are lengths and flow velocities for each segment. The velocity can be estimated from Haan et al (1994) (Table 3.20, pg. 76)

When there is little information on flow paths, an alternative equation is used in UH:

$$t_c = \frac{L^{0.8}\left(\dfrac{1000}{CN} - 9\right)^{0.7}}{4407\sqrt{Y}} \qquad (15)$$

where t_c is in hours, CN is the NRCS curve number, L in m is the maximum linear distance to the watershed outlet, Y (m/m) is the average slope (altitude difference between furthest point and outlet divided by L).

As a third option there are several simplified equations available such us Kirpich's (1940),

$$t_c = 0.0195L^{0.77}Y^{-0.385} \qquad (16)$$

where t_c is in minutes.

The design peak flow (TR55 method) (m^3/s) is calculated in UH as:

$$q_p = q_u A Q F_p \qquad (17)$$

where q_u is the unit peak flow (m^{3}s^{-1}ha^{-1}mm^{-1}), A is the watershed area (ha), Q is the runoff volume (mm) and F_p is the ponding factor that accounts for the percentage of the watershed with ponding or wetland conditions that will delay the overland flow.

.

% ponding area	F_p
0	1.00
0.2	0.97
1.0	0.87
3.0	0.75
5.0	0.72

q_u is calculated from t_c values using the following equation (SI units):

$$q_u = 4.3046 \times 10^{C_0 + C_1 \log t_c + C_2 (\log t_c)^2 - 6}$$ 　　　　(18)

where *log* is the logarithm to the base 10, t_c is in hours, C_0, C_1 and C_2 are constants obtained from the following Table based on the ratio I_a/P and the 24-hour design storm type for the area (Types I, IA, II, III) (remember, I_a=0.2 S based on NRCS curve number method).

Storm	I_a/P	C_0	C_1	C_2
I	0.10	2.30550	-0.51429	-0.11750
	0.20	2.23537	-0.50387	-0.08929
	0.25	2.18219	-0.48488	-0.06589
	0.30	2.10624	-0.45695	-0.02835
	0.35	2.00303	-0.40769	0.01983
	0.40	1.87733	-0.32274	0.05754
	0.45	1.76312	-0.15644	0.00453
	0.50	1.67889	-0.06930	0.0
IA	0.10	2.03250	-0.31583	-0.13748
	0.20	1.91978	-0.28215	-0.07020
	0.25	1.83842	-0.25543	-0.02597
	0.30	1.72657	-0.19826	0.02633
	0.50	1.63417	-0.09100	0.0
II	0.10	2.55323	-0.61512	-0.16403
	0.30	2.46532	-0.62257	-0.11657
	0.35	2.41896	-0.61594	-0.08820
	0.40	2.36409	-0.59857	-0.05621
	0.45	2.29238	-0.57005	-0.02281
	0.50	2.20282	-0.51599	-0.01259
III	0.10	2.47317	-0.51848	-0.17083
	0.30	2.39628	-0.51202	-0.13245
	0.35	2.35477	-0.49735	-0.11985
	0.4.	2.30726	-0.46541	-0.11094
	0.45	2.24876	-0.41314	-0.11508
	0.50	2.17772	-0.36803	-0.09525

To obtain the coefficients, rather than interpolating in the previos Table, a set of fourth order polynomials were obtained (see next Table).

Storm	Coef.[a]	A	B	C	D	E
I	C_0	68.0317	-74.693	24.9255	3.9797	2.5222
	C_1	-82.907	105.222	-42.167	6.7479	-0.8657
	C_2	11.1619	-26.314	16.1126	2.9776	0.0456
IA	C_0	144.547	-136.68	41.8526	6.2829	2.3645
	C_1	-130.64	134.907	-45.773	6.585	-0.6384
	C_2	-55.230	47.9565	-13.503	2.1954	-0.2644
II	C_0	-11.312	12.1681	-6.5688	1.0577	2.5021
	C_1	16.6125	-16.337	6.4981	-1.1784	-0.5476
	C_2	-43.015	50.4334	-19.740	3.2996	-0.3427
III	C_0	-11.505	14.2182	-7.8919	1.3836	2.4007
	C_1	-64.177	85.7116	-38.206	6.7419	-0.8899
	C_2	65.9007	-85.806	39.0036	6.8946	0.2078

a. $C_i = A(I_a/P)^4 + B(I_a/P)^3 + C(I_a/P)^2 + D(I_a/P) + E$; $i = 0, 1, 2$
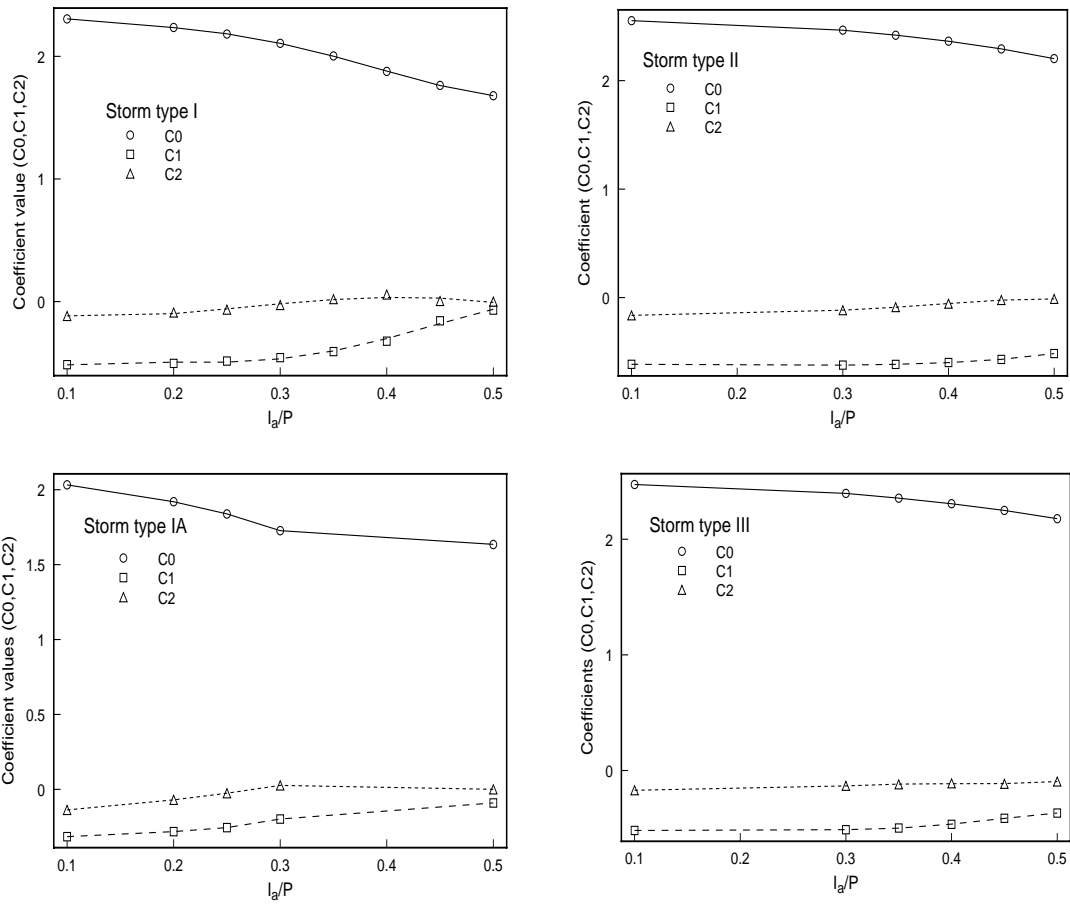
Figure 8. Coefficients predicted by proposed polynomials used in NRCS peak flow calculation

3.2.3 Time correction for hydrograph to match hyetograph

3.2.3.1 Option 1: based on NRCS abstraction method

Following the NRCS definition for abstraction and curve number we have:
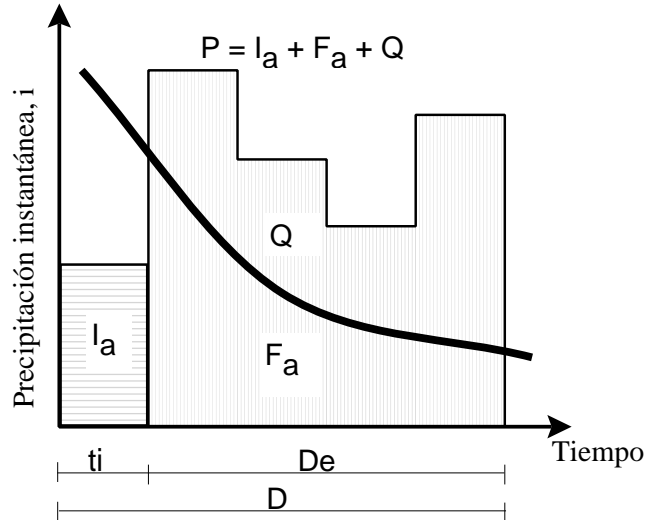
Figure 9. Precipitation partition in NRCS method.

Since we can calculate the initial abstraction as:

$$Ia=0.2 \ S, \text{ and } S=25400/CN-254 \qquad (19)$$

as shown in *.out file, we could find the time when this initial abstraction ends (*ti*) by interpolating in the constructed NRCS 10-min hyetograph (*.hyt file).

Since the starting time for runoff coincides the time rainfall excess begins, a time shifting is needed in the hydrograph to match the rainfall as,

$$toff=ti \qquad (20)$$

and all the hydrograph times will be corrected as,

$$t=t+toff \qquad (21)$$

3.2.3.2 Option 2: based on NRCS abstraction and Unit Hydrograph

Based on the unit hydrograph, by definition, the time to peak in the unit hydrograph is defined as (see Figure 10),

$$tp = t_L + De/2 = 0.6 \ t_c + De/2 \qquad (22)$$
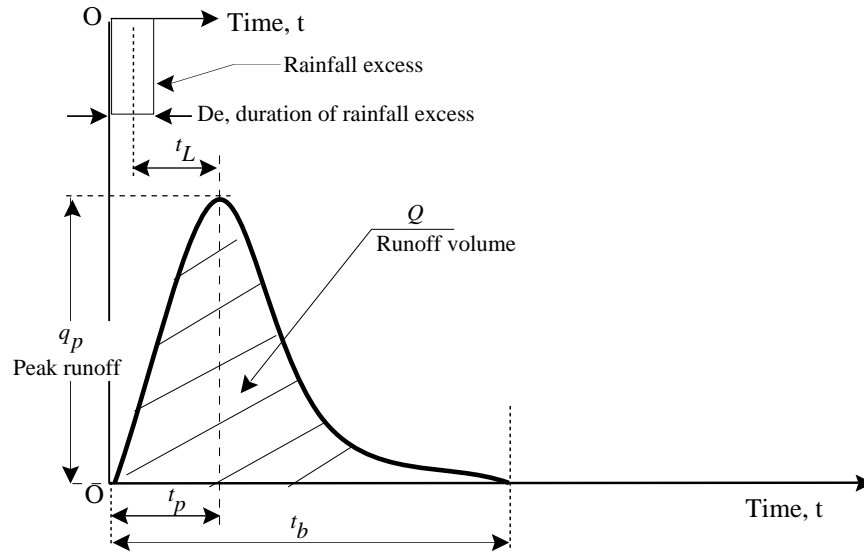
Figure 10. Hydrograph quantities used in calculation of time shifting.

We can now calculate the *duration of the rainfall excess*, *De*, as:

$$De = D - ti \qquad (23)$$

In this option 2, the corrected time to peak of the hydrograph can be obtained from the ordinate of the unit hydrograph as,

$$tp' = 0.127481*Q*A/qp \qquad (24)$$

A time shifting is needed in the hydrograph to match the rainfall as,

$$toff = tp - tp' \qquad (25)$$

and all the hydrograph times will be corrected as,

$$t = t + toff \qquad (26)$$

An example showing the calculations for both options 1 and 2 is shown bellow. Versions of UH after 0.7 implement *Option 1* since it produces runoff after the peak of the hyetograph as in observed natural events (see Figure 11).
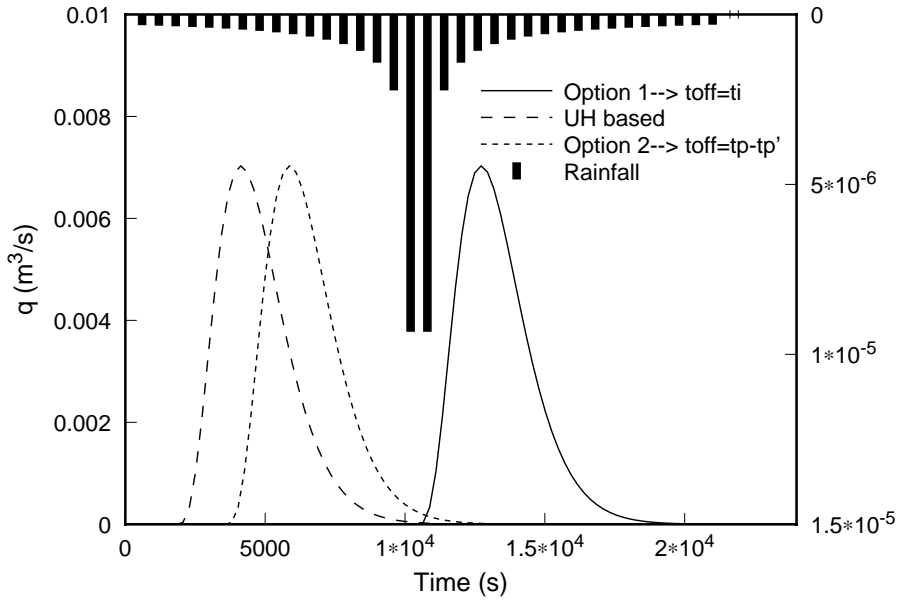
Figure 11. Time shifting of hydrographs to match the storm.

3.3 Incoming sediment load calculation

3.3.1 Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) was developed in the 1950's by Wischmeier and Smith (1978) as an empirical equation to address erosion from areas characterized by overland flow. The equation was derived from thousands of site-years of observed erosion rates around the world. The equation is given by:

$$A = RKLSCP \qquad (27)$$

A = soil loss average over the slope length;

R = combined erosivity of rainfall and runoff (see section 3.3.2);

K = soil erodibility factor, determined as the soil loss from a unit plot with dimensions 22 m (73 feet) on a 9% slope tilled up and down slope with tillage periodically to prevent surface crusting and weeds;

LS = topographic factor based on the lenght and slope and is computed as:

$$L = \left(\frac{\lambda}{22}\right)^n$$

where λ = slope length in m and n = slope length exponent, which is 0.5 for slopes > 4%, 0.4 for slopes between 3% and 4%, and 0.3 for slopes < 3%.

S = Slope factor calculated as:

$$S = 65.4s^2 + 4.56s + 0.065 \quad \text{where s=sin}(\theta); \ \theta = \text{slope angle}$$

C = cover management factor - ratio of soil loss from the particular cover - management to that of the unit plot (dimensionless)

P = conservation practice factor - ratio of soil loss from the practice to that of the unit plot (dimensionless)

The unit plots were defined as 22 m (73 feet) in length, 9% slope, tilled up and down the slope periodically to prevent surface crusting and weeds. The values L, S, C, and P are referenced to this standard plot. For example, a C=0.5 indicates that one would expect about one-half the erosion with this cover-management than from the standard plot.

Since the USLE is applicable to areas dominated by overland flow with little or no concentrated flow pathways, it lumps rill and interrill erosion.

The R factor combines rainfall and runoff erosivity. In the annual version of the equation, the units are usually expressed as EI units per unit time. The original units used by Wischmeier are (100 ft-tons/acre)(in/h) which are often referred to as the Wishmeier English EI units. R ranges from 50-550 for eastern US. In North Carolina, R ranges 330 in the Southeastern portion of the state to 175 in the Appalachians. In the Piedmont area, the annual R is approximately 250. Foster (1982) indicates that no single metric unit has been accepted although for modeling convenience he suggests Newtons/h. So to convert the Wischmeier English units to N/h, multiply R by 1.702.

The soil erodibility factor, K, is generally selected based on the top soil. The english units for K are tons/(acre EI), with typical values ranging from 0.05 - 0.60. The SI metric units for K are usually expressed as $(kg/N)*(h/m^2)$. The factor to convert english units to SI metric is to multiply by 0.1317. So, for soil losses (A=RK, the two quantities in the USLE with dimensions) expressed as kg/m^2, then the SI units for R is N/h.

K can be approximated based on data from Wischmeier et al. (1971). He developed a regression equation based on data collected from 55 midwestern soils using percentages of organic matter, primary particles (sand, silt, clay) and permeability. In GLEAMS this relationship was further simplified to:

$$K = TF(12.0 - OM) + SF + PF \qquad (28)$$

where: K = soil erodibility factor in tons/(acre EI); TF = texture factor; OM = percentage organic matter; SF = structure factor; PF = permeability factor.

TF, SF, and PF are given in the following Table for the primary soil types. K is converted to SI units, $(kg/N)*(h/m^2)$, by multiplying by 0.1317. So K in SI units (kg/

N)*(h/m^2) is given by:

$$K = 0.1317[TF(12.0 - OM) + SF + PF] \qquad (29)$$

.

TABLE 1. Factors for computing K by soil type (from GLEAMS based on data from Wischmeier et al. (1971)).

Soil Type	Sand %	Silt %	Texture Factor	Structure Factor	Permeability Factor	D50
Clay	20.	30.	0.01287	0.0650	0.075	23.0
Silty clay	10.	45.	0.01870	0.0650	0.075	24.0
Sandy Clay	50.	10.	0.01714	0.0650	0.075	66.0
Silty clay loam	15.	50.	0.02606	0.0650	0.050	25.0
Clay loam	35.	30.	0.02360	0.0650	0.050	18.0
Sandy clay loam	55.	20.	0.02778	0.0650	0.050	91.0
Silt	5.	85.	0.05845	0.0650	0.025	19.0
Silt loam	20.	60.	0.04259	0.0650	0.025	27.0
Loam	45.	35.	0.03618	0.0325	0.025	35.0
Very fine sandy loam	60.	25.	0.03877	-0.0350	0.000	35.0
Fine sandy loam	60.	25.	0.03205	0.0000	0.000	80.0
Sandy loam	60.	25.	0.02549	0.0325	0.000	98.0
Coarse sandy loam	60.	25.	0.01914	0.0325	0.000	160.0
Loamy very fine sand	84.	8.	0.03726	-0.0325	-0.025	90.0
Loamy fine sand	84.	8.	0.02301	0.0000	-0.025	120.0
Loamy sand	84.	8.	0.01624	0.0325	-0.025	135.0
Loamy coarse sand	84.	8.	0.00982	0.0325	-0.025	180.0
Very fine sand	90.	5.	0.04401	-0.0325	-0.050	140.0
Fine sand	90.	5.	0.02173	0.0000	-0.050	160.0
Sand	90.	5.	0.01481	0.0325	-0.050	170.0
Coarse sand	90.	5.	0.00827	0.0325	-0.050	200.0

3.3.2 Modifications to USLE to handle storm events

USLE was developed for extended periods, for example yearly. To attempt to use USLE for storm events, others have modified EI to represent a storm event and used this in place of R in the original equation (Williams 1975). The erosion index, EI, is a measure of total raindrop energy of a storm. One approach for computing EI is to examine 30 min rainfall intensities and compute erosion indices for these periods referred to as EI_{30}. In this approach, one sums EI over each rainfall period to obtain a rainfall-erosivity factor for the

storm.

In the CREAMS model, Cooley (1980) used

$$e \ = \ 916 + 331 \log(i) \tag{30}$$

where e is the energy in ft-ton/acre-in (1 ft-ton/acre-in = 26.38 J/m^3 or 26.38 N/m^2), i is the hourly intensity in in/h (in/h = 0.007 mm/s) and log is base 10. The E= Σ $e.r$ over the storm where r was the increment of rainfall during the rainfall period. In this situation, the product of E and the maximum 30-min rainfall intensity (I_{30}) divided by 100 is used as the erosivity factor, R, in the USLE for the particular storm. Multiplication of this by 1.702 yields consistent SI metric units of N/h.

In GLEAMS and the daily rainfall version of CREAMS, the EI$_{30}$ for a 24 hour rainfall, V_R in inches, is computed as:

$$\frac{EI_{30}}{100} \ = \ 7.87 V_R^{1.51} \tag{31}$$

The units for the daily EI$_{30}$ are ft-ton/acre-in.

For daily rainfall amounts, another approximation for EI for a storm is:

$$EI \ = \ 8.0 V_R^{1.51} \tag{32}$$

where V_R=volume of rainfall in inches. The default units for EI are (ft-tons)(in/h) and if we multiply by 1.702, then we obtain N/h.

Foster et al. (1977) suggested an improved erosivity factor for a single storm over that of substituting storm EI for R. This approach combines the effect due to runoff and rainfall into the erosivity factor. So for a single storm, Foster et al. (1977) defines R$_m$ in N/h

$$R_m \ = \ 0.5 R_{St} + 0.35 V_u \sigma_{pu}^{\frac{1}{3}} \tag{33}$$

R$_{St}$ = E I$_{30}$ where E=storm's total energy and I$_{30}$=maximum 30 min rainfall intensity in N/h; V$_u$ = volume of runoff (mm); σ_{pu} = peak rate of runoff (mm/h).

Williams (1975) suggested a further modification to R to handle areas larger than field-scale. This modification makes an attempt to account for deposition within the area which would reduce the sediment losses from the area. Foster et al. (1982) reported the modification of R as,

$$R_w \ = \ 9.05(VQ_p)^{0.56} \tag{34}$$

where R_w = storm modified R (see below for explanation of units); V = volume of runoff (m³); Q_p = peak discharge rate (m³/s).

Using R_w in place of R in the USLE is referred to as the modified USLE (or MUSLE). The units of soil loss for this version are Mg for the total watershed area and not per unit area as in the original USLE. This assumes that the soil erodibility K units are Mg.h/ha N.

3.4 Computational Structure of UH

The program UH generates the necessary inputs from the upslope source area for *vfsmod*. The inputs for UH are discussed in the User's Manual along with a sample input and data set. Figure 12 shows the computation structure of UH.

First, the input data describing the source area is read. Next, UH computes the total runoff from the source area using the SCS Curve Number method. The time of concentration, peak runoff rate and time of peak is computed by the SCS TR55 method. Next, SCS unit hydrograph theory is used to estimate the runoff hydrograph. An idealized rainfall hyetograph is generated from the SCS storm type.

MUSLE is then used to estimate the sediment loss from the source area for the storm. The sediment loss is partitioned into silt and clay based on the soil particle distribution in the top soil. The average concentration in runoff then estimated based on the total runoff and distribution of soil particles in the sediment loss.

Finally, the results are used to create input files for vfsmod. These files include data for the hyetograph, the runoff hydrograph, and sediment loss.

```
┌─────────────────────────────────────┐
│          Read Input Data for          │
│             Source Area               │
│                  ↓                    │
│          Calculate Runoff by          │
│             SCS Method                │
│                                       │
│                  ↓                    │
│                                       │
│       Calculate time of concen-       │
│       tration, Peak Flow, Time to     │
│          Peak by SCS TR55             │
│                                       │
│                  ↓                    │
│                                       │
│        Create Runoff Hydrograph       │
│        from SCS unit hydrograph       │
│                                       │
│                  ↓                    │
│                                       │
│       Develop Rainfall hyeto-         │
│         graph from SCS storm          │
│                type                   │
│                                       │
│                  ↓                    │
│                                       │
│         Calculate Storm erosion       │
│        using MUSLE & average          │
│       Sediment Concentration in       │
│                Runoff                 │
│                                       │
│                  ↓                    │
│                                       │
│     Write Input Files for VFSMOD      │
├─────────────────────────────────────┤
│        Figure 12. Computations in UH. │
└─────────────────────────────────────┘
```

Figure 12. Computations in UH.

3.5 Sensitivity Analysis of *VFSMOD*.

A sensitivity analysis was performed to gain some insight in the dependence of model outputs on certain model parameters and to assist in the model calibration (Muñoz-Carpena et al. 1999). The study showed that the main parameters controlling the hydrology outputs were soil hydraulic conductivity and initial water content whereas the model was fairly insensitive to changes in saturated water content and suction at the wetting front values. Previous research (Muñoz-Carpena et al., 1993a) showed that Manning's surface roughness controls mainly the time to peak of the outgoing hydrograph.

Testing on the sediment component of the model showed that the main parameters controlling sediment outflow are media spacing, and particle diameter. Variations in the

modified Manning's roughness had relatively little effect on the output and the effect of media height was only visible for large events when the filter began to be inundated with sediment.

3.6 Previous Testing and Applications

VFSMOD 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 sandy clay loam 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., 1999, 2001). They reported good agreement (R^2=0.9) between model predictions (infiltration volume and sediment trapping efficiency) and measured values if actual filter flow widths (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 Lowell, 2002), as well as a component to simulate fecal pathogen filtering from runoff (Zang et al., 2001).

4. Sensitivity and Uncertainty Analysis Procedures for UH and VFSMOD Built In VFSMOD-W

Haan et al. (1995) outlined the statistical procedure for evaluating hydrology and water quality models. Their procedure included: conducting sensitivity analysis, generating probability distributions for model inputs, generating probability distributions for the model outputs, and using the probability distributions of the model outputs to assess uncertainty. Using an example model, they conducted a sensitivity analysis to identify the input parameters that have the most impact on the outputs. The absolute sensitivity, S_i, of a given output, O, relative to input parameter, P_i, is defined as

$$S_i = \frac{\partial O}{\partial P_i} \qquad (35)$$

The relative sensitivity, S_{ri}, of the output parameter with respect to changes in the input parameter is computed as:

$$S_{ri} = \frac{\partial O}{\partial P_i}\frac{P_i}{O} \qquad (36)$$

Once the most sensitive inputs are identified, the model users can concentrate on determining the "best" or most appropriate values for a given desing scenario. In addition, these parameters can also be used to evaluate the uncertainty in the model outputs based on these most sensitive inputs. This approach involves selecting probability distributions for each sensitive input based on based on previous literature and field research.

After the probability distributions are identified for each of the inputs, then these distributions are sampled for typical inputs and the simulated outputs are used to determine a probability distribution for each output parameter. Two possible methods were presented for generating the general probability distributions of the output variables of interest (Haan et al. 1995 and Haan et al. 1998).

The first method was First Order Approximation (FOA) (Morgan and Henrion, 1990). In this method, the mean or expected value of the output is estimated as

$$E(O) = Model(P_b) \qquad (37)$$

and the variance is estimated as

$$Var(O) = \sum_{i=1}^{n}\left[\frac{\partial O}{\partial P_i}\right]^2 Var(P_i) + 2\sum_{i=1}^{n}\sum_{j=i+1}^{n}\left(\frac{\partial O}{\partial P_i \partial P_j}\right)Cov(P_i, P_j) \qquad (38)$$

where O is the output parameter of interest, P_b, is the base input parameter values for the

---

selected input variable, P_i is the input parameter i, n is the number of input parameters, *Var* is the variance and *Cov* is the covariance. If the input parameters are independent and uncorrelated (an assumption that is often made), then the second term is 0 (*ie*, $Cov(P_i, P_j)$ = 0). The slope of the sensitivity relationship between O and P_i is S_i. With these assumptions the variance equation becomes:

$$Var(O) = \sum_{i=1}^{n} [S_i]^2 Var(P_i) \tag{39}$$

This type of analysis produces good estimates of the mean and variance of the output parameter, O, when the coefficient of variation (Mean/Standard Deviation) of the input parameter is small and the relationship between O and P_i, over the range of potential inputs, is linear.

An alternative more general approach is the technique of Monte Carlo Simulations (MCS). An outline of this procedure is:

1) select the most sensitive input parameters,

2) develop probability distribution functions for each input parameter,

3) randomly generate input parameter datasets based on the probability distributions,

4) perform the model simulation with the randomly generated input dataset,

5) repeat steps 3 and 4 for a large number of trials,

6) generate probability distribution functions for the model outputs of interest, and

7) use the output probability distribution functions to evaluate uncertainty in the model by placing confidence levels on the outputs

Additional details on the application of this procedure can be found in Parsons and Muñoz-Carpena (2001).

5. Design Procedure

The design 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 achieve a certain reduction in % sediment (i.e. that for TMDLs). Proposed 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. To do this, the precipitation depths of selected return periods for the area, along with the area's NRCS runoff and MUSLE erosion inputs are processed through the input preparation utility (UH) to create formatted inputs for VFSMOD: hyetograph (*sample.irn*), incoming sedimentograph (*sample.isd*) and hydrograph (*sample.iro*).

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 design runoff event. Usually the most relevant VFS characteristics to consider from a design prespective are: soil type (*sample.iso*), filter length, uniformity and slope (*sample.ikw*), and vegetation characteristics (*sample.igr*). The VFSMOD sample project (*sample.prj*) provided with the package installation for all platforms that can be used as a pattern and changed for each design run. Information for standard USDA soil types Green-Ampt infiltration inputs, and vegetation covers (spacing, height) to be used in the analysis can be found in this document.

For each combination of inputs a new project must be created and the model executed. If the problem is to be prepared manually (UNIX and DOS versions) it is usually more efficient to create a naming convention for each project that reflects the simulation run characteristics. The proposed sequence is to prepare the UH (*.inp) input files (combination of source area soils types and design storms) first and then process them with UH to produce the corresponding VFSMOD inputs (*.iso, *.irn, *.isd). Afterwards, the user creates the project files (*.prj), one per simulation, as combination of the UH outputs and modification of the remaining input files (*.igr, *.ikw, *.iso) as needed. Each file must be then processed with VFSMOD and the SDR and RDR results obtained from the *.osm files. 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).

In the MS-Windows VFSMOD-W modelling system, versions 2.x and up, this task is automated. The projects for each combination of design inputs are automatically created within the program GUI after the user selects a range on the desired parameters. This new version also automatically produces combined analysis output tables (see Part III - Section 10. on page 95). 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).

An example of design results (see Muñoz-Carpena and Parsons, 2002) is included below. The graph depics the optimal filter lengths to achieve a 75% sediment reduction (SDR=0.25) in a North Carolina Piedmont site (clay soil, 0.5 Ha. source area, 2% slope, 6 hr. storm duration) with a grass mixture vegetation on the filter. Filter lengths from 14-57 m are needed to accomodate storm events associated to 1-10 year return periods. The design assumes homogeneous sheet flow across the filter in all cases.
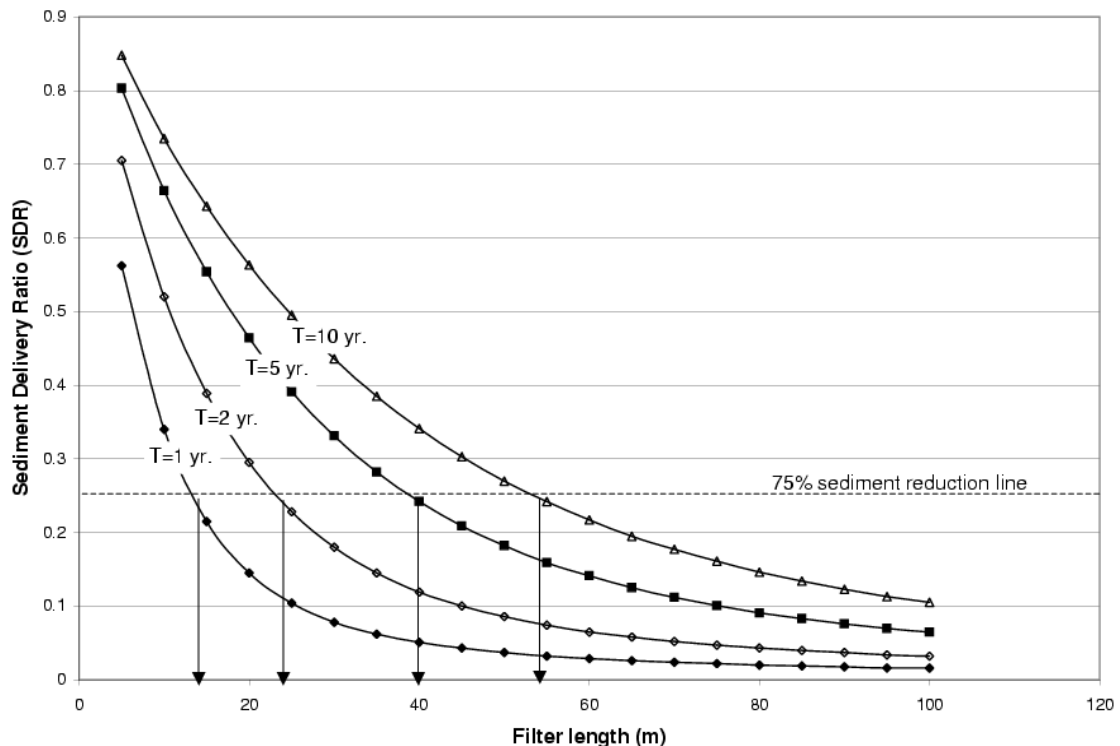
6. Potential Users and Applications of the Modelling System

VFSMOD is a research model, as such potential users are modelers and scientists involved in studies of sediment pollution from agricultural sources and its control, with the aim to gain a better understanding of the processes involved for a given scenario.

Results from this model can be used, after calibration and field testing in extrapolation or prediction studies for decision making and design (Suwandono et al., 1999, Muñoz-Carpena and Parsons, 2002; Parsons and Muñoz-Carpena, 2002). An evaluation of the model from the user's perspective following modern criteria can be found in Muñoz-Carpena and Parsons (1999).

The GUI and integrated design procedures introduced with v2.x and above, are intended to help extend the model user base to include others like engineers and environmental and natural resources experts, involved in the design, implementation, and evaluation of VFS without requiring in depth computer knowledge.

7. Known Limitations and Applicability of the Models

7.1 Known Limitations of the Model

- The handling of overland flow as sheet flow could pose problems when a filter is not properly maintained and concentrated flow occurs within the filter.

- 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 conductivity parameters 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 are difficult to quantify in field situations.

7.2 Future Research

- A revision of the sediment filtration submodel to handle particle size distribution explicitly.

- A submodel to handle sediment sorbed contaminants (such as phosphorous).

- Improvement of parameter estimation techniques, calibration procedure and reduction of the uncertainty ranges of sensitive parameters.

8. Distribution and Training

The modelling system is provided free of charge to qualified users as an educational and research tool. The model and documentation can be downloaded from the internet (http://www3.bae.ncsu.edu/vfsmod) or obtained from the authors. Limited support is available from the authors. Through the web site, the user can send feedback and questions to the authors. No formal training is available but can be arranged with the authors.

9. Acknowledgments

10. References

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Part II: *VFSMOD* and *UH*: User's Manual

1. *VFSMOD* **user's manual**

1.1 Obtaining *VFSMOD*

VFSMOD documentation, source code and binaries for a number of platforms can be obtained in digital format through internet at the following URL site:

USA: http://www3.bae.ncsu.edu/vfsmod/

The files are in ZIP/tar.gz compressed format. All necessary files to compile and run a sample application are included. Please select Windows 9x/NT/2000/XP (vfsmodpc.zip for the command line version or vfsmod-w-install.zip for the graphical user interface) or UNIX (vfsmodux.tar.gz) versions as needed. If you do not have an internet connection you can contact the authors for assistance.

1.2 Installing and running *VFSMOD*

VFSMOD (and UH) source code is distributed both in Windows 95/98/NT/2000/XP and UNIX versions along with *make* files and sample input and output files. The source code is written in standard FORTRAN77 so that compilation should be straight forward following the included *makefile* and using the proper set of files for each platform (Windows 9x/NT/2000/XP or UNIX). Binaries for a few computer platforms can also be found at the internet site.

1.2.1 Installing for a DOS/command prompt window (under Windows 9x/NT/2000/ XP):

a) From the Start Menu, Start a Command Prompt/DOS window.
b) Change to the drive and directory where you want to install.
c) Create a directory named VFSMOD
d) Expand the contents of the file vfsmodpc.zip. This should create the following directory structure

e) The executable files VFSM.EXE (and UH.EXE) can be found in the parent directory VFSMOD.

f) Run the sample case named SAMPLE, by typing "VFSM SAMPLE" at the DOS prompt. Please note that the second part of the command issued (SAMPLE) refers to a set of files located in the subdirectory INPUTS. You could run a different problem by selecting a different set of input files with the condition that they are located in the subdirectory INPUTS. In this example, if you issue the DIR command within the INPUTS directory you should see the following files:

SAMPLE.IGR SAMPLE.IKW SAMPLE.IRN SAMPLE.IRO SAMPLE.ISD SAMPLE.ISO

After you execute the command you should see a screen as follows:

```
    @    @ @@@@  @@@  @   @  @@@@  @@@
    @    @ @   @       @@ @@ @  @  @  @
   @  @  @@@    @@@  @ @ @  @  @  @   @
    @ @  @       @ @   @  @  @  @  @   @
    @    @   @@@ @   @  @@@@  @@@ 3/2002-v1.06
  -------------------------------------------------------------------------
       R.Munoz-Carpena            J.E. Parsons
    U.of Florida- USA              NCSU - USA
       carpena@ufl.edu   john_parsons@ncsu.edu
  -------------------------------------------------------------------------
  PROGRAM TO CALCULATE OVERLAND FLOW AND SEDIMENT FILTRATION THROUGH A
  VEGETATIVE FILTER STRIP, OF AN INFLOW HYDROGRAPH FROM AN ADJACENT FIELD,
  DURING A STORM EVENT. VFSMOD HANDLES THE CASE OF VARYING SURFACE COVER
  AND SLOPES AT THE NODES AND TIME DEPENDENT INFILTRATION FOR THE DOMAIN.
  -------------------------------------------------------------------------

  ... Reading inputs from inputs/sample.igr              ...
  ... Reading inputs from inputs/sample.isd              ...
  ... Reading inputs from inputs/sample.ikw              ...
  ... Reading inputs from inputs/sample.irn              ...
  ... Reading inputs from inputs/sample.iso              ...
  ... Reading inputs from inputs/sample.iro              ...
  Storm on: Unit9, g8, u183-91                     ...RUNNING...

  ...FINISHED...VFSMOD v1.06 03/2002
```

During the run a set of new files is created in the OUTPUT directory:

SAMPLE.OG1 SAMPLE.OG2 SAMPLE.OHY SAMPLE.OSM SAMPLE.OSP

The content of both input/output files is explained in detail in the following section

1.2.2 Installing together with the Windows Graphical Interface (Windows 9x/NT/ 2000/XP)

See Part III of this document describing the MS-Windows version of the system.

1.2.3 Installing on a UNIX system

a) Create a directory named VFSMOD

    mkdir VFSMOD
    mv vfsmodux.tar.gz VFSMOD
    cd VFSMOD

b) Expand the contents of the file vfsmodux.tar.gz on the new directory.

gzcat vfsmodux.tar.gz | tar xvf -

This should create the following directory structure

```
                              vfsmod
        ┌─────────┬────────────┼───────────┬──────────┐
      docs      inputs      output      src_uh     src_vfsm
```

c) An installation script *(setup)* is included in the *VFSMOD* directory. To compile and install the program simply type *setup*. The script will compile the source code and copy the executable files (*vfsm* and UH) to the *VFSMOD* directory. If your FORTRAN compiler name is not f77 you will need to edit the *makefile* found in the *src* directory. You can also clean the executable and object files by typing *setup clean*.

d) Run the sample case named *sample*, by typing ***vfsm sample*** at the UNIX prompt.

Please note that the second part of the command issued (*sample*) refers to a set of files located in the subdirectory *inputs*. You could run a different problem by selecting a different set of input files with the condition that they are located in the subdirectory *inputs*. Note that you must have all the six input files in order to run the program. In our example, if you issue the *ls* command within the *inputs* directory you should see the following files:

sample.igr sample.ikw sample.irn sample.iro sample.isd sample.iso

After you execute the command you should see a screen similar to the one given above. During the run a new set of files is created in the *output* directory:

sample.og1 sample.og2 sample.ohy sample.osm sample.osp

The content of both input/output files is explained in detail in the following section

1.3 Using the project file for input and output

Versions 1.04 and later now allow the user to create project files. These files contain the list of input and output files for the model. This enables the user to mix and match inputs from multiple simulation scenarios. Each line of the project file contains a keyword denoting the type of input and output file and the filename. A project file (sample.prj) for the sample inputs in UNIX and Windows 9x/NT/2000/XP contains the following line

:

UNIX	Windows 9x/NT/2000/XP
ikw=inputs/sample.ikw	ikw=inputs\sample.ikw
igr=inputs/sample.igr	igr=inputs\sample.igr
irn=inputs/sample.irn	irn=inputs\sample.irn
iro=inputs/sample.iro	iro=inputs\sample.iro
isd=inputs/sample.isd	isd=inputs\sample.isd
iso=inputs/sample.iso	iso=inputs\sample.iso
og1=output/sample.og1	og1=output\sample.og1
og2=output/sample.og2	og2=output\sample.og2
ohy=output/sample.ohy	ohy=output\sample.ohy
osm=output/sample.osm	osm=output\sample.osm
osp=output/sample.osp	osp=output\sample.osp

The project file in this example, sample.prj, would be saved in the *VFSMOD* directory (where the executable *vfsm* or VFSM.EXE is). To execute the model with the project file, the following would be entered:

vfsm sample.prj

In this example, the input files would be read from the *inputs* subdirectory and the output files would be created in the *output* subdirectory. In general, the project file contains all of the keywords which are:

Inputs		*Outputs*	
igr=	buffer properties for the sediment filtration submodel	*og1=*	detailed time series describing the sediment transport and deposition within the buffer
ikw=	parameters for the overland flow solution	*og2=*	detailed information on the singular points defined in the theory section of the manual
irn=	storm hyetograph	*ohy=*	detailed outputs on the inflow and outflow hydrographs
iro=	storm hydrograph from the source area	*osm=*	detailed summaries of the water and sediment balance, final geometry of the filter
isd=	sediment properties for the sediment filtration submodel	*osp=*	overall summary of filter performance with comparisons between the source area and filter
iso=	soil properties for the infiltration submodel		

1.4 VFSMOD input files

All files are in FORTRAN77 free format. The inputs are distributed among 6 files: *filename.ikw* (parameters for the overland flow solution), *filename.irn* (storm hyetograph), *filename.iro* (runoff from the adjacent field into the VFS), *filename.iso* (soil properties for the infiltration model), *filename.igr* (buffer properties for sediment filtration model), *filename.isd* (sediment properties for sediment filtration model). Note that *filename* could (and should) be replaced by any other name you would like to identify the case study with (max. 25 characters), with the only condition that all six files must be in the *inputs* subdirectory.

The name of the input file set to process is selected at the command line, and the output file set is created automatically using the name given as input. In this way, different problems can be run from the same directory without overwriting previous results.

1.4.1 filename.ikw (parameters for the overland flow solution)

1.4.1.1 Structure of the file

```
LABEL
FWIDTH
VL   N   THETAW  CR  MAXITER   NPOL   IELOUT KPG
NPROP
(SX(IPROP),RNA(IPROP),SOA(IPROP), IPROP=1,NPROP)
```

1.4.1.2 Definition

LABEL	a label (max. 50 characters) to identify the program run
FWIDTH	width of the strip (m)
VL	length of the filter strip (m)
N	number of nodes in the domain (integer) (must be an odd number for a quadratic finite element solution, but the program checks and corrects if needed).
THETAW	time-weight factor for the Crank-Nicholson solution (0.5 recommended)
CR	Courant number for the calculation of time step from 0.5 - 0.8 (recommended). See Section 6 for more details.
MAXITER	(integer) maximum number of iterations alowed in the Picard loop.
NPOL	(integer) number of nodal points over each element (polynomial degree +1)
IELOUT	(integer) flag to output elemental information (1) or not (0)
KPG	(integer) flag to choose the Petrov-Galerkin solution (1) or regular finite element (0)
NPROP	(integer) number of segments with different surface properties (slope or roughness)
SX(I)	(real) X distance from the beginning on 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)

1.4.1.3 File example

```
Unit9, g8, u183-91
3.87
8.655  57   0.5 0.8  350   3   1    1
14
0.61820.4    0.052778
1.23640.4    0.032639
1.85460.4    0.071528
2.47290.4    0.075000
3.09110.4    0.031944
3.70930.4    0.019444
4.32750.4    0.029885
4.94570.4    0.028947
5.56390.4    0.041667
6.18210.4    0.134028
6.80040.4    0.079167
7.41860.4    0.074306
8.03680.4    0.040972
8.65500.4    0.062346
```

Which corresponds to a filter on dense uniform bermuda grass with slope as follows:
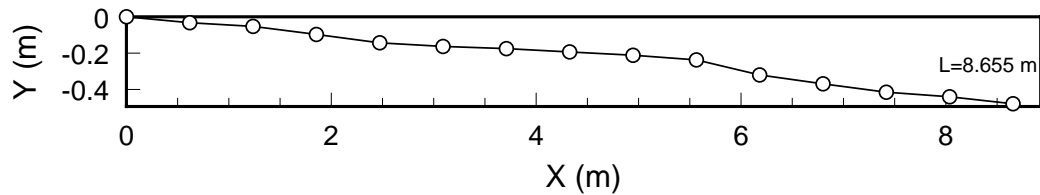
1.4.2 filename.irn (storm hyetograph)

1.4.2.1 Structure of the file

NRAIN, RPEAK
(RAIN(I,J),J=1,2)

1.4.2.2 Definition

NRAIN   (integer) number of rainfall periods including period to end simulation

RPEAK   maximum rainfall intensity for the storm (m/s)

RAIN(I,J)   time (s) and rainfall rate/intensity (m/s) over the VFS for each period. The last time step corresponds with the desired simulation time chosen by the user (typically coupled with a rainfall intensity of 0). Note also that each time corresponds to the beginning of the rainfall period, i.e. storm such as:

Period	Time interval (s)	Rainfal (m/s)
1	0.0 to 299.9	.1693E-05
2	299.9 to 599.8	.6773E-05
3	599.8 to 900.0	.1101E-04

Would be input as

```
.0000E+00   .1693E-05
.2999E+03   .6773E-05
.5998E+03   .1101E-04
.9000E+03   .1947E-04
```

1.4.2.3 *File example*

```
  12   .1947E-04
 .0000E+00   .1693E-05
 .2999E+03   .6773E-05
 .5998E+03   .1101E-04
 .9000E+03   .1947E-04
 .1200E+04   .1947E-04
 .1500E+04   .1524E-04
 .1800E+04   .5080E-05
 .2100E+04   .1693E-05
 .2400E+04   .2540E-05
 .2700E+04   .8467E-06
 .3001E+04   .0000E+00
 .3603E+04   .0000E+00
```

Note: the last pair of numbers is used to set the time when the simulation ends.

1.4.3 filename.iro (runoff from the adjacent field into the VFS)

1.4.3.1 *Structure of the file*

SWIDTH SLENGTH
NBCROFFBCROPEAK
(BCROFF(I,J),J=1,2)

1.4.3.2 Definition

SWIDTH   Source area width (m)

SLENGTH   Source area flow path length (m)

NBCROFF   (integer) number of time steps of the incoming field hydrograph

BCROPEAK   peak flow of the incoming field hydrograph (m^3/s)

BCROFF(I,J)   incoming field hydrograph: flow rate, time (s) vs. qin(m^3/s).

1.4.3.3 File example

```
4.0 34.0
68  .2192E-02
.8417E+03   .0000E+00
.8716E+03   .5724E-07
.9018E+03   .5724E-07
.9317E+03   .5724E-07
      ...         ...
```

1.4.4 filename.iso (soil properties for the infiltration model)

1.4.4.1 Structure of the file

VKS SAV OS OI   SM SCHK

1.4.4.2 Definition

VKS   saturated hydraulic conductivity, K_s (m/s)

SAV   Green-Ampt's average suction at wet 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)

SCHK   relative distance from de upper filter edge where the check for ponding conditions is made (i.e. 1= end filter, 0.5= mid point, 0= beginning)

1.4.4.3 File example

```
1.33e-5  0.37904     0.311   0.125          0.0      1.00
```

1.4.5 filename.igr (buffer properties for sediment filtration model)

1.4.5.1 Structure of the file

  SS VN   H   VN2 ICO

1.4.5.2 Definition

SS	spacing of the filter media elements (cm)
VN	filter media (grass) 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)
ICO	(integer) flag to feedback the change in slope and surface roughness at the sediment wedge for each time step (0= no feedback; 1= feedback). (See also additional info on this parameter on the "Tips to Run the Model" section.)

1.4.5.3 File example

> 2.2   0.012   15.0 .04   1

1.4.6 filename.isd (sediment properties for sediment filtration model)

1.4.6.1 Structure of the file

  NPART COARSE CI   POR
  DP SG

1.4.6.2 Definition

NPART   (integer) incoming sediment particle class according to the USDA (1975) particle classes:

NPART	Particle class	Diam. range (cm)	d_p (cm)	V_f (cm/s)	γ_s (cm^3/s)
1	Clay	<0.0002	0.0002	0.0004	2.60
2	Silt (1)	0.0002 - 0.005	0.0010	0.0094	2.65
3	Small aggregate	----	0.0030	0.0408	1.80
4	Large aggregate	----	0.0300	3.0625	1.60
5	Sand	0.0050 - 0.2	0.0200	3.7431	2.65
6	Silt (2)	0.0002 - 0.005	0.0029	0.0076	2.65
7	User selected	----	DP	model	SG

COARSE	% of particles from incoming sediment with diameter > 0.0037 cm (coarse fraction that will be routed through wedge) (unit fraction, i.e. 100% = 1.0).
CI	incoming flow sediment concentration (g/cm^3)
POR	porosity of deposited sediment (unit fraction, i.e. 43.4% = 0.434)
DP	sediment particle size, diameter, d_{50} (cm), read only if NPART=7
SG	sediment particle density, γ_s(g/cm^3), read only if NPART=7

1.4.6.3 File example

```
    4  1.0   0.034 .434
.0013   2.65
```

1.5 Model file outputs

The program writes output into ASCII-files. Each aspect of the model is written to different files. The model outputs include: information on the water balance (volume of rainfall, field inflow, filter outflow and infiltration), hydrograph, sediment balance (field inflow, filter outflow and deposition), sedimentograph, filter trapping efficiency, and sediment deposition pattern within the filter. The output files contain summaries of the main state variables in the program. Note that these files are created in the *output* directory at run time every time the model is run and that the actual file names are given by substituting *filename* by the name of the set selected at the command line. If you wish to keep the results from different simulations, it is advised that you create a new set of input files (with a different name) for each case study. The inputs and outputs included in these files are labeled in a verbose form to be self-explanatory

(a) f*ilename.ohy*

This file contains information related to the hydrology side of the problem (overland flow and infiltration). The content of this the file is controlled by the input parameter IELOUT. The first part of the file summarizes information read from the **.ikw, *.iso* and **.irn* input files along with some of the calculated parameters needed for the simulation. The second part of the file contains the inflow hydrograph (from **.iro*), rainfall excess ie calculated with the Green-Ampt model and the output hydrograph from the filter. Only 100 time-steps are printed to this file, each one is the average of the precedent NWRITE steps, where NWRITE=NDT/100.

(b) filename.og1

The file contains information related with the sediment filtration model. The first part of the file summarizes information read from the *.igr* and *.isd* input files along with some of the calculated parameters needed for the simulation. The second part of the file contains sediment transport and deposition time series for the simulation period. As before, only a 100 time-steps are printed to this file. In this case the sediment filtration step is calculated with the average flow conditions calculated as described above.

(c) filename.og2

This file contains the flow characteristics at the singular points (1-3, in and out), as defined in Part I of this manual, of the filter for the simulation period for the same 100 steps described above.

(d) filename.osm

This file contains a summary of the most relevant input parameters and output results, including a sediment and water balance, the sediment trapping efficiency of the filter for the simulation case, and the final geometry of the filter.

(e) filename.osp

Summary of the filter performance parameters and comparisons between source and filter areas.

1.6 Tips for running the model

Here are some suggestions to running the model, and answers to potential problems.

a) *The finite element model becomes unstable or blows up.*
This is due to a rapid change in boundary conditions (quick slope and/or roughness changes along the filter) or inputs (severe changes in rainfall intensity and/or inflow from the adjacent field) in your inputs. For this type of conditions the kinematic wave formulation leads to a behavior termed *kinematic shock*. The model's Petrov-Galerkin (PG) finite element formulation was developed to improve the quality of the solution for these type of special (sharp front) problems and generally overcomes the instability problem (Muñoz-Carpena et al. 1993b). The time step is calculated based on a target Courant number (CR) for the simulation (*.ikw* file) and an estimate of the less favorable conditions (maximum incoming hydrograph peak flow and rainfall intensity). In a few cases, due to the dynamic nature of the problem this is not a good estimate and the simulation will become unstable or even blow up. This can be avoided by lowering the CR at the expense of more simulation run-time. Instabilities can also be avoided by reducing/increasing the number of nodes in the domain (N).

b) *With large sediment input into the filter strip, the program blows up.*
Set ICO=0. In this case the sediment deposition is so large that the change in the nodal slope in the downstream face of the wedge creates problems to the finite element flow

solution. Petrov-Galerkin does well but it does not perform miracles on a drastically changed domain!. Setting ICO=0 ignores the changes in slope and allows the simulation to be completed. Previous comparison by the authors between runs with ICO=1 or 0 show that difference in results sre typically in the rage of 5-10%.

c) *Assigning values to KPG, NPOL.*

The order of the shape function used in the numerical solution (finite elements) can be set to linear (NPOL=2), quadratic (NPOL=3) or cubic (NPOL=4). Please note that if the order of the function is changed to any other type than quadratic (recommended) the regular finite element formulation will be run instead of the improved Petrov-Galerkin method. One could also select a regular quadratic finite element by setting KPG=1. Tests made during program development show the increase in execution time induced by selecting the PG method are small as compared with the gains in stability and accuracy obtained. Thus the setting NPOL=3 and KPG=1 are recommended.

d) *Assigning values to N*

The number of nodes of the system must be an odd number for a finite element quadratic solution, an even number if the solution is cubic and any of them if linear. The program adjusts the number of nodes automatically if the requirement is not made.

e) *If no incoming sediment characteristics are known* (d_p, g_s)

In the absence of measured inflow sediment characteristics, an estimate of the particle size could be made by knowing the soil texture of the contributing field (Woolhiser et al. 1990) (d_p in x10^{-4}cm).

Soil texture (USDA)	Expected d_p	Soil texture	Expected d_p
Clay	0 - 45	Clay-loam	5 - 30
Silty-clay	2 - 45	Sandy-loam	35-160
Silty-clay-loam	3 - 46	Loamy-sand	90 - 180
Silt-loam	3 - 50	Sandy - clay	2 - 130
Silt	8 - 30	Sandy-clay-loam	21 - 160
Loam	9 - 60	Sand	140-200+

f) *Setting the total simulation time (DR)*

The last time interval of the rainfall series (file *.irn*) is used to set the desired simulation (typically with the rainfall intensity set to 0).

g) *Reducing execution time by stopping surface changes during the simulation (ICO=0)*

Setting the flag ICO=0 in the *.igr* file will stop the model from reshaping the entrance of the filter during sediment deposition. This in turn will result in a reduction of the total execution required, since the problem will become less non-linear and fewer iterations to convergence will be needed for each time step. Initial testing of the program showed that

the sediment predictions do not change greatly, but the user is advised to assess this point for each particular application.

1.7 Sample application

A sample application case is shown by using input data collected at a NC State University experimental site (Raleigh, NC - USA). The input and output files can be found in the sample case included in the distribution package obtained from the internet sites.

1.7.1 Inputs

1.7.1.1 Hydrological inputs (files sample.ikw and sample.iso),

Description, symbol	INPUT	Value	Units
Source area flow path length, L_s	SLENGTH	34.0	m
Source area width, w_s	SWIDTH	4.0	m
Filter length, L	VL	8.655	m
Filter width, w	FWIDTH	3.87	m
Filter mean Manning's coefficient (calculated), n_1	VN_1	0.40	$s.m^{-1/3}$
Duration of the simulation	DR	3603	s
Number of nodes	N	57	--
Number of different filter segments	NPROP	14	--
Courant number, Cr	CR	0.8	--
Order of shape functions	NPOL	3 (quadratic)	--
Petrov Galerkin flag	KPG	1	--
Number of different filter segments	NPROP	14	--
Saturated hydraulic conductivity, K_s	VKS	1.33×10^{-5}	m/s
Average suction at the wet front, S_{av}	SAV	0.379	m
Water content at saturation, θ_s	OS	0.311	--
Initial water content, θ_i	OI	0.125	--
Surface storage, S_m	SM	0.0	m

The flow inputs (rainfall and incoming runoff from the field) are shown later in the output. The surface characteristics of the filter were shown as an example in section 7.1.3.

1.7.1.2 Sediment transport (files sample.igr and sample.isd)

Description, symbol	INPUT	Value	Units
Sediment inflow concentration, C_i	CI	.03400	g/cm^3
Particle size diameter (NPART=4, d_p)	DP	0.0300	cm
Particle fall velocity (NPART=4), V_f(calculated)	VF	3.0625	cm/s
Particle weight density (NPART=4), γ_s	SG	1.6000	g/cm^3

Description, symbol	INPUT	Value	Units
% of coarse particles (d_p>0.0037 cm)	COARSE	100.0	%
Porosity of deposited sediment	POR	43.4	%
Filter main slope (calculated), S_c	SC	0.0564	--
Filter media spacing, S_s	SS	2.20	cm
Filter media height, H	H	15.0	cm
Grass modified Manning coefficient, n_m	VN	0.0120	s.cm$^{-1/3}$
Manning coefficient for bare soil, n_2	VN2	0.04	s.m$^{-1/3}$
Surface changes feedback	ICO	1=YES	---

1.7.2 Outputs

1.7.2.1 Calculated simulation parameters (file sample.ohy)

Parameter	Symbol	Value	Units
Petrov-Galerkin parameters	PGPAR	0.0433, -0.0031, -0.3165, 0.1451	---
Space step	DX	0.155	s
Time step	DT	1.40	---
Number of elements in system	NELEM	28	---
Number of time steps	NDT	2568	---
Estimated maximum flow rate	QMAX	0.000735	m^2/s
Estimated maximum flow depth	HMAX	0.000735	m
Celerity of the wave	C	0.08816, 0.01389	m/s
Courant time step	DTC	1.753	s
Froude number	FR	0.143	---
Kinematic wave number	FK	1892	---

1.7.2.2 Hydrological outputs (files sample.ohy and sample.osm)

The hydrographs included in the next figure show the volume reduction (infiltration) and peak delay (increase of roughness by vegetated surface) produced by the filter over the incoming field hydrograph (input)
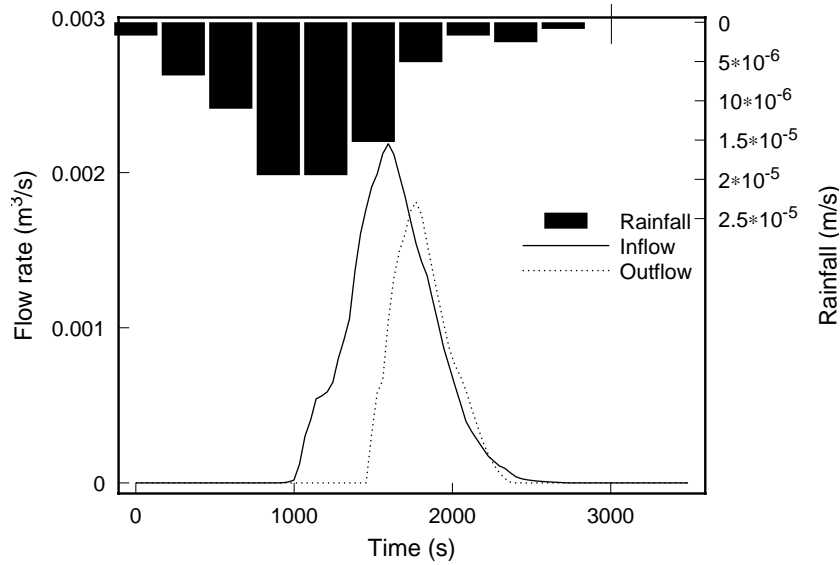
The water balance for the simulation was as follows:

Volume from rainfall	0.8423	m^3
Volume from up-field hydrograph	1.3240	m^3
Volume from outflow hydrograph	0.7674	m^3
Volume infiltrated	1.3990	m^3

1.7.2.3 Sediment transport (files sample.ig1, sample.ig2, and sample.osm)

The sedimentograph and mass balance at the filter is included in the next two figures. Both graphs show a significant load reduction due to deposition at the wedge (difference in loads between g_{si} and g_{s2}), for those parts of the event when flow was low (beginning

and tail) whereas most of the sediment in the suspended sediment zone was retained at high flow rates (when the sediment by-passes the wedge).
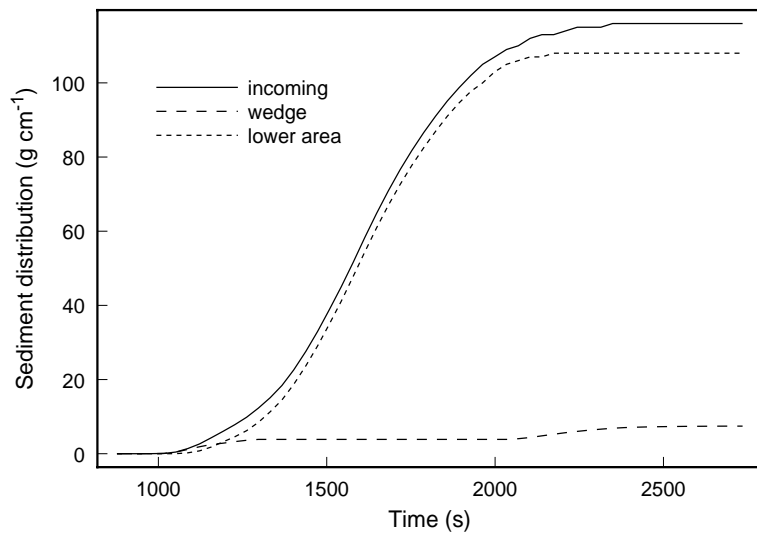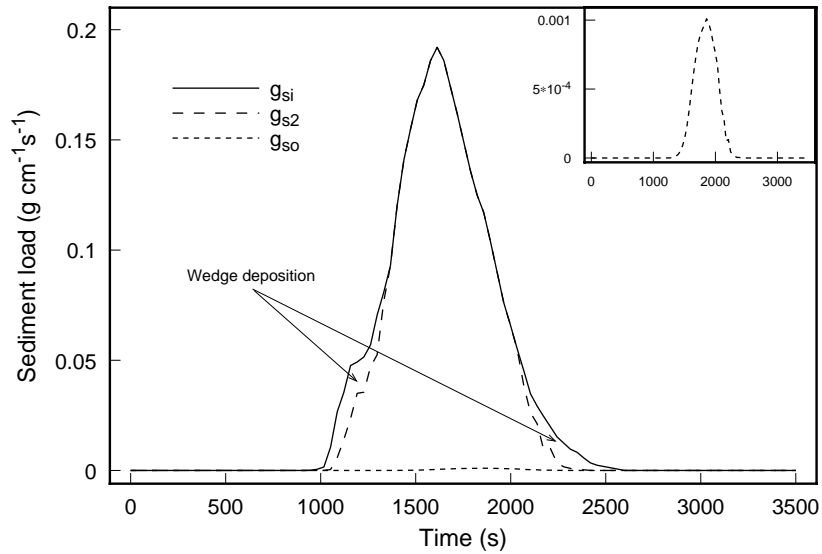
The sediment balance for the simulation was:

Total sediment inflow	116.40	g/cm	45,030	g
Total sediment outflow	0.4195	g/cm	162.3	g
Trapping efficiency (T_r)	99.6	%		

VFSMOD finally predicts the final sediment wedge geometry and deposition over the filter as:

Sediment wedge depth	Y(t)	0.85	cm
Sediment tail at field	$X_1(t)$	15.05	cm
Sediment wedge length	$X_2(t)$	4.55	cm
Effective filter length	L(t)	860.95	cm

Sediment depth in low section	DEP	0.145	cm
Rough mass balance (wedge+depth) error	---	<1	%

1.7.2.4 Filter performance indicators (file sample.osp)

Parameter	Value	Units
Source Area (input)	136.00	m2
Source Flow Length (input)	34.00	m
Source Area Width (input)	4.00	m
Filter Strip Length (input)	8.65	m
Filter Strip Width (input)	3.87	m
Mean Filter Mannings Roughness (input)	0.400	
Ratio of Filter Length to Source Flow Length	25.46	%
Total Rainfall	25.15	mm
Total Rainfall on Filter	0.842	m3
Total Runoff from Source (mm depth over Source Area)	9.74	mm
Total Runoff from Source	1.324	m3
Total Runoff out from Filter (mm depth over Source+Filter)	4.53	mm
Total Runoff out from Filter	0.767	m3
Total Infiltration in Filter	1.399	m3
Runoff Delivery Ratio (RDR)[a]	0.579	
Mass Sediment Input to Filter	45.03	kg
Concentration Sediment in Runoff from source Area	34.00	g/L
Mass Sediment Output from Filter	0.16	kg
Concentration Sediment in Runoff exiting the Filter	0.21	g/L
Mass Sediment retained in Filter	44.87	kg
Sediment Delivery Ratio (SDR)[a]	0.004	
Effective Filter Length	8.65	m
Wedge Distance	0.05	m

a. Used for design, see Part I: Section 5. on page 30

2. UH for Input Preparation: User's Manual

2.1 Installing and running UH

UH is installed by default when installing VFSMOD. See Section 1.2 on page 40 for details.

When running UH from the command line (DOS and UNIX versions) the name of the input file set to process is selected at the command line. In this way, different problems can be run from the same directory without overwriting previous results. As an example one could run (from the *VFSMOD* directory):

    uh sample2

In this example, the input file *sample2.inp* (included in the distribution package) would be read from the *INPUTS* subdirectory. After you execute the command you should see a screen as follows:

```
      ----------------------------------------------------------------
                      @    @ @    @
                      @    @ @    @
                      @    @ @@@@@@
                      @    @ @    @
                      @@@@  @    @ March 2002-v1.06
      ----------------------------------------------------------------
           R.Munoz-Carpena              J.E. Parsons
             UFL - USA                   NCSU - USA
         carpena@ufl.edu            john_parsons@ncsu.edu
      ----------------------------------------------------------------
          PROGRAM GENERATE RAINFALL AND RUNOFF INPUTS FOR
          VFSMOD.
      ----------------------------------------------------------------

      *** Opening inputs/sample2.inp
      *** Opening output/sample2.out
      *** Opening output/sample2.hyt
      *** Opening inputs/sample2.iro
      *** Opening inputs/sample2.irn
      *** Opening inputs/sample2.isd
```

During the run a set of the *VFSMOD* inputs is created in the *INPUTS* subdirectory:

    sample2.irn sample2.iro sample2.isd sample2.iso

Two more output files are created in the *OUTPUT* subdirectory that summarize the calculations performed (*sample2.out* and *sample2.hyt*). The content of these files is produced in verbose mode and is self explanatory.

Note that two more files are needed to run *VFSMOD* (filter characteristics files *.ikw and *.igr) and they are not created by UH but the user needs to set them up from field data. To continue the example given above one could copy the sample files included in the distribution package, *sample.ikw* and *sample.igr*, into *sample2.ikw* and *sample2.igr* in the *INPUTS* subdirectory. *VFSMOD* is now ready to be run by issuing the command,

vfsm sample2

2.2 Using the project file for input and output

Another way to complete the example would be to create a project sample file that includes the newly created *sample2* files and specifies *sample.igr* and *sample.ikw* as *igr* and *ikw* files (see Section 1.3 on page 42). An example of a project file (*sample.lis*) for UH is given in the following Table.

Unix	Windows 9x/NT/2000/XP
inp=inputs/sample.inp	inp=input\sample.inp
iro=inputs/sample.iro	iro=inputs\sample.iro
irn=inputs/sample.irn	irn=inputs\sample.irn
isd=inputs/sample.isd	isd=inputs\sample.isd
out=output/sample.out	out=output\sample.out
hyt=output/sample.hyt	hyt=output\sample.hyt

The project file in this example, sample.lis, would be saved in the *VFSMOD* directory (where the executable UH or UH.EXE is located). To execute the model with the project file, the following would be entered:

uh sample.lis

In this example, the input files would be read from the *inputs* subdirectory and the output files would be created in the *output* subdirectory. In general, the project file contains all of the keywords which are:

Inputs		Outputs	
inp=	inputs for the source area for UH	*irn=*	rainfall hyetograph (input for vfsmod)
		iro=	runoff hydrograph from the source area (input for vfsmod)
		isd=	sediment properties for the sediment filtration submodel
		out=	summary of the inputs and outputs from UH
		hyt=	detailed summary of of MUSLE calculations and the runoff hydrograph

All inputs for UH are in FORTRAN77 free format. The inputs are contained in *filename.inp*. Note that "filename" could (and should) be replaced by any other name you would like to identify the case study with (max. 8 characters), as in the example above. A description of this file follows.

2.3 UH input files

2.3.1 filename.inp (parameters for generating inputs for VFSMOD)

2.3.1.1 Structure of the file

P, CN, A, storm type, D, L, Y
<blank line>
soiltype
K, C, P
ieroty

2.3.1.2 Definition

P	amount of storm precipatation in mm
CN	NRCS (SCS) Curve Number for the source area (see Appendix 3)
A	Area of the upstream portion in 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 (% expressed as a fraction)
soiltype	See Table for Acceptable Soil Types
K	Soil Erodibility (If K<0, then K is computed based on texture and organic matter - See REF)
Cfact	C factor (See Table in Appendix 3)
Pfact	P factor (See Table in Appendix 3)
ieroty	Select the method to compute the storm R factor in MUSLE, not present or =1 selects Foster's Method, =2 selects Williams method, and =3 selects the CREAMS/GLEAMS method

The acceptable values for "*soiltype*" are:

Soil Types (Case Sensitive)			
Clay	Silty clay	Sandy clay	Silty clay loam
Clay loam	Sandy clay loam	Silt	Silt loam
Loam	Very fine sandy loam	Fine sandy loam	Sandy loam
Coarse sandy loam	Loamy very fine sand	Loamy fine sand	Loamy sand
Loamy coarse sand	Very fine sand	Fine sand	Sand
Coarse sand			

2.3.1.3 *File example*

file: sample2.inp

```
25 85 0.5 3 6 100 0.02

Clay
0.25 1.0 1.0
1
```

2.4 Sample application

Table 1. Parameter values for the sample run.

Parameter	Value	Parameter Description
P	25	amount of storm precipatation in mm
CN	85	NRCS (SCS) Curve Number for the source area
A	0.5	Area of the upstream portion in ha
storm type	3	storm type (1=I, 2=II, 3=III, 4=Ia)
D	6	storm duration (h)
L	100	Length of the source area along the slope (m)
Y	0.02	Slope of the source area (% expressed as a fraction)
soiltype	Clay	See Table for Acceptable Soil Types
K	0.25	Soil Erodibility (If K<0, then K is computed based on texture and organic matter - See REF)
Cfact	1.0	C factor (See Table in Appendix 3)
Pfact	1.0	P factor (See Table in Appendix 3)

ieroty	1	Select the method to compute the storm R factor in MUSLE, not present or =1 selects Foster's Method, =2 selects Williams method, and =3 selects the CREAMS/GLEAMS method

The program produces two output files that summarize the program execution. In this case, these are sample2.out and sample2.hyt. The sample2.out file contains a printout of the input data along with the runoff hydrograph and a summary. The sample2.hyt file contains the information about the rainfall hyetograph along with the outputs related to the erosion from the storm. From these results, the input files for *VFSMOD* (sample2.iro, sample2.irn, and sample2.isd) are also automatically created in the output directory.

file: sample2.out

```
File: output\sample2.out                                  UH v1.06,  3/2002


   HYDROGRAPH CALCULATION FOR WATERSHED-SCS METHOD

 Inputs
 ------
Storm Rainfall=   80.00 mm
SCS storm type= II
Storm duration=   6.0 h
SCS Curve number=  72.0
Watershed area=    5.00 ha
Maximum flow path length=  100.00 m
Average slope of flow path=    2.00 %
MUSLE type=  2 where:
  1=Foster, 2=Williams, 3=GLEAMS (See Manual)

 Outputs
 -------
Runoff volume=   22.82 mm= 1141.16 m3
Initial Abstraction=   19.76 mm
Concentration time=     0.19 h=    11.64 min
Peak flow=   0.3753 m3/s=   27.0228 mm/h
Time to peak=     0.65 h=    38.76 min

 Hydrograph based on SCS-unit hydrograph:
  time (h)      q(m3/s)    q(mm/h)

     0.00    0.0000    0.0000
     0.06    0.0019    0.1366
     0.13    0.0178    1.2783
     0.19    0.0562    4.0434
     0.26    0.1139    8.2038
     0.32    0.1813   13.0501
     0.39    0.2472   17.7981
     0.45    0.3032   21.8278
     0.52    0.3440   24.7677
     0.58    0.3678   26.4836
     0.65    0.3753   27.0228
     0.71    0.3687   26.5477
     0.78    0.3511   25.2776
     0.84    0.3256   23.4442
     0.90    0.2953   21.2627
```

```
      0.97    0.2627   18.9159
      1.03    0.2298   16.5479
      1.10    0.1981   14.2642
      1.16    0.1686   12.1361
      1.23    0.1417   10.2059
      1.29    0.1180    8.4933
      1.36    0.0972    7.0018
      1.42    0.0795    5.7230
      1.49    0.0645    4.6414
      1.55    0.0519    3.7375
      1.62    0.0415    2.9899
      1.68    0.0330    2.3775
      1.74    0.0261    1.8800
      1.81    0.0205    1.4790
      1.87    0.0161    1.1579
      1.94    0.0125    0.9024
      2.00    0.0097    0.7004
      2.07    0.0075    0.5415
      2.13    0.0058    0.4171
      2.20    0.0044    0.3201
      2.26    0.0034    0.2449
      2.33    0.0026    0.1868
      2.39    0.0020    0.1421
      2.46    0.0015    0.1078
      2.52    0.0011    0.0815
      2.58    0.0009    0.0615
      2.65    0.0006    0.0463
      2.71    0.0005    0.0348
      2.78    0.0004    0.0261
      2.84    0.0003    0.0195
      2.91    0.0002    0.0146
      2.97    0.0002    0.0108
      3.04    0.0001    0.0081
      3.10    0.0001    0.0060
      3.17    0.0001    0.0044
      3.23    0.0000    0.0033
      3.30    0.0000    0.0024

Time to ponding=   2.743 h
Duration of rainfall excess=   3.257 h
Time correction to match hyetograph=   2.743 h
```

file: sample2.hyt

```
File: output\sample2.hyt                              UH v1.06,  3/2002

 SCS 10-MIN HYETOGRAPH

 No.  Time (hr)   Rainfall(mm) Rain30 (mm)
   1     0.000       0.000       0.000
   2     0.167       1.199       0.000
   3     0.333       1.241       2.440
   4     0.500       1.287       3.728
   5     0.667       1.338       3.867
   6     0.833       1.396       4.021
   7     1.000       1.460       4.194
   8     1.167       1.533       4.388
```

```
 9     1.333        1.616     4.608
10     1.500        1.713     4.862
11     1.667        1.828     5.158
12     1.833        1.967     5.509
13     2.000        2.138     5.934
14     2.167        2.357     6.463
15     2.333        2.650     7.146
16     2.500        3.070     8.078
17     2.667        3.740     9.460
18     2.833        5.067    11.877
19     3.000       26.832    35.639
20     3.167        4.564    36.463
21     3.333        5.067    36.463
22     3.500        3.740    13.371
23     3.667        3.070    11.877
24     3.833        2.650     9.460
25     4.000        2.357     8.078
26     4.167        2.138     7.146
27     4.333        1.967     6.463
28     4.500        1.828     5.934
29     4.667        1.713     5.509
30     4.833        1.616     5.158
31     5.000        1.533     4.862
32     5.167        1.460     4.608
33     5.333        1.396     4.388
34     5.500        1.338     4.194
35     5.667        1.287     4.021
36     5.833        1.241     3.867
37     6.000        1.199     3.728


Computed Total Rain=   102.600 mm
  Actual Total Rain=   102.600 mm
  raimax30        =    36.463 mm
  I30             =    72.927 mm/h


RAINFALL ENERGY FACTOR R FOR EROSION CALCULATIONS

 a) Foster et al. (1977)
   E=    3738.632 ft-tonf/acre =    25.049 MJ/ha
   volro=    63.323 mm; qpeak=    46.011 mm/h
   Factors in Rm: Rst=   182.695; Rro=   226.905
   Rm (Foster)=   170.764 N/h

 b) Williams (1975)
   Watershed area=     0.500 ha
   V=    316.613 m3; Qp=     0.064 m3/s
   Rw (Williams)=    97.514 N/h

 c) GLEAMS/ daily CREAMS
    Rain  =102.60 mm
    R_GLM =     64.79 From Gleams - Wischmeirer
    R_GLM =    110.27 N/h,  Converted to Metric


ERODIBILITY K AND PARTICLE SIZE SELECTION

   Table for computing Ksoil (from GLEAMS and KINEROS)
    i    Soil Type        %Sand %Silt   Tex.F.    Str.F.    Per.F.    D50
```

```
 1  Clay                20.  30.  0.01287   0.0650   0.075    23.0
 2  Silty clay          10.  45.  0.01870   0.0650   0.075    24.0
 3  Sandy clay          50.  10.  0.01714   0.0650   0.075    66.0
 4  Silty clay loam     15.  50.  0.02606   0.0650   0.050    25.0
 5  Clay loam           35.  30.  0.02360   0.0650   0.050    18.0
 6  Sandy clay loam     55.  20.  0.02778   0.0650   0.050    91.0
 7  Silt                 5.  85.  0.05845   0.0650   0.025    19.0
 8  Silt loam           20.  60.  0.04259   0.0650   0.025    27.0
 9  Loam                45.  35.  0.03618   0.0325   0.025    35.0
10  Very fine sandy loam 60.  25.  0.03877  -0.0350   0.000    35.0
11  Fine sandy loam     60.  25.  0.03205   0.0000   0.000    80.0
12  Sandy loam          60.  25.  0.02549   0.0325   0.000    98.0
13  Coarse sandy loam   60.  25.  0.01914   0.0325   0.000   160.0
14  Loamy very fine sand 84.   8.  0.03726  -0.0325  -0.025    90.0
15  Loamy fine sand     84.   8.  0.02301   0.0000  -0.025   120.0
16  Loamy sand          84.   8.  0.01624   0.0325  -0.025   135.0
17  Loamy coarse sand   84.   8.  0.00982   0.0325  -0.025   180.0
18  Very fine sand      90.   5.  0.04401  -0.0325  -0.050   140.0
19  Fine sand           90.   5.  0.02173   0.0000  -0.050   160.0
20  Sand                90.   5.  0.01481   0.0325  -0.050   170.0
21  Coarse sand         90.   5.  0.00827   0.0325  -0.050   200.0

 For the selected soil type: Sandy clay
        K=      0.041 kg-h/N-m^2
      d50=       66.00 um


MISCELLANEOUS CALCS:


      L=      1.447       S=      0.182
   cfact=      1.00    pfact=      1.00


FINAL CALCS:


      A=        1.84779 kg/m^2 Using Rm (Foster)
      A=        1.05518 kg/m^2 Using Rw (Williams)
      A=        1.19323 kg/m^2 based on Gleams
   Conc=       29.18056 g/L  Using Rm (Foster)
   Conc=       16.66349 g/L  Using Rw (Williams)
   Conc=       18.84364 g/L  based on Gleams
```
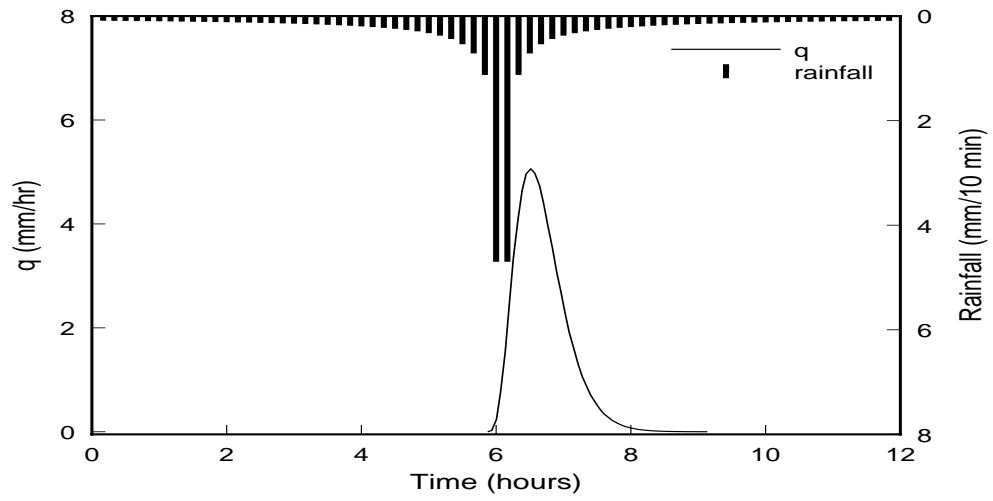
These results are depicted in the next Figure.

Part III: *VFSMOD-W*: User's Manual

1. Installation Information

The dsign oriented computer package consists of three programs to assist users in evaluating and developing design specifications for vegetative filter strips for trapping sediment and enhancing infiltration. The programs are the graphical user interface (GUI – vfsmod-w.exe version 3.00.xx or later), a program to estimate rainfall hyetographs, runoff hydrographs and storm-based erosion losses from typical source areas (UH – UH.exe, version 1.06 or later), and the vegetative filter strip model (VFSMOD – vfsm.exe, version 1.06 or later). The GUI was developed to assist users in executing the Vegetative Filter Strip Model, VFSMOD and UH. Development of the graphical user interface program (GUI) was started in March 2000. Since that time we have continued to improve the interface and add new features to the system. As such we expect there will be a number of bugs that may appear. The graphical front end, GUI for VFSMOD was developed using Visual Basic Professional Edition (version 6.0)[vb6]. The Visual Basic source code is available upon request. The programs UH and VFSMOD were developed in FORTRAN and the source code is supplied with the installation package.

This program is supplied to be installed using the Visual Studio Installer. As such, a number of controls, dll's, and other files are included and usually installed. We have made no attempt to eliminate or reduce the package, although this is a future desire. ***If you attempt to bypass setup, we have no idea what must be installed.***

The install package includes the complete Win32 distribution for vfsmod. The default installation directory is: C:\vfsmod which can be changed to any location. For example, if the installation was done for D:\vfsmod, then this directory would contain:

D:\vfsmod

Vfsmod-w.exe	Graphical user interface
Vfsmod-w.hlp	Windows Help file
Uh.exe	Utility program, UH
Vfsm.exe	Vegetative filter strip model, vfsmod
Sample2.lis	Sample project for UH
Sample.prj	Sample project for vfsmod

Readme.txtThis information
Documentation
   Vfsm.pdf   the Users Manual
Inputs\   Directory containing the inputs
   Sample.igr   Sample Overland flow inputs for VFSMOD
   Sample.ikw   Sample Buffer vegetation inputs for VFSMOD
   Sample.irn   Sample Rainfall hyetograph for VFSMOD
   Sample.iro   Sample Runoff hydrograph for VFSMOD
   Sample.isd   Sample Incoming sediment characteristics for VFSMOD

Sample.iso   Sample Infiltration soil properties for VFSMOD
Sample2.igr   Sample overland flow inputs created by UH
Sample2.inp   Sample inputs for UH
Sample2.iso   Sample infiltration soil properties created by UH
Output\   Directory containing the outputs from UH and VFSMOD
Sample2.out   Sample output from UH – used as a placeholder
SourceCode\
Uh   FORTRAN source code for UH
Vfsm   FORTRAN source code for VFSMOD

And after your first execution of vfsmod-w, then the Options file is written to this directory, vfsmod-w.cfg. The *Directory for Saving Project Files* should be:

D:\vfsmod

After this is done, vfsmod-w should be ready to analyze your vegetative filter strips.

2. Using VFSMOD

How Can the Model be Used?

This package can be used to comprehensively evaluate and develop designs for vegetative filter strips to trap sediment and enhance infiltration. A typical application of the package would follow the outline below.

(1)   Develop input datasets for UH to generate storm data for a typical upslope source area.

(2)   Run UH to develop input hydrograph and hyetograph data for VFSMOD

(3)   Develop input datasets for VFSMOD for describing the filter strip

(4)   Run VFSMOD to simulate the performance

(5)   Modify any of the inputs for UH and/or VFSMOD to better reflect target source area – filter strip.

(6)   Use the Design Option to examine a range of storm events – filter strip combinations to evaluate alternate possible designs.

After Step 5 or 6, an alternate path could examine the uncertainty associated with the proposed design. Following this path, the user can use the Sensitivity and Uncertainty Options to investigate. The steps would be:

(1)   Use the Sensitivity options to identify the most sensitive parameters for the design centered on the base input values for the target source area and filter strip.

(2)   Select the most sensitive parameters and assign these probability distributions

(3)   Use the Uncertainty section to perform Monte Carlo Simulations

(4)   Using the Analysis portion of the Uncertainty Section, examine the probability distributions for the key outputs of interest and assign confidence intervals and other estimates on the final filter strip designs (note: the program supplies basic statistics and the actual simulated data to allow the users to use other outside analysis tools to complete this analysis – users are welcome to contact us for suggestions).

3. Main Window
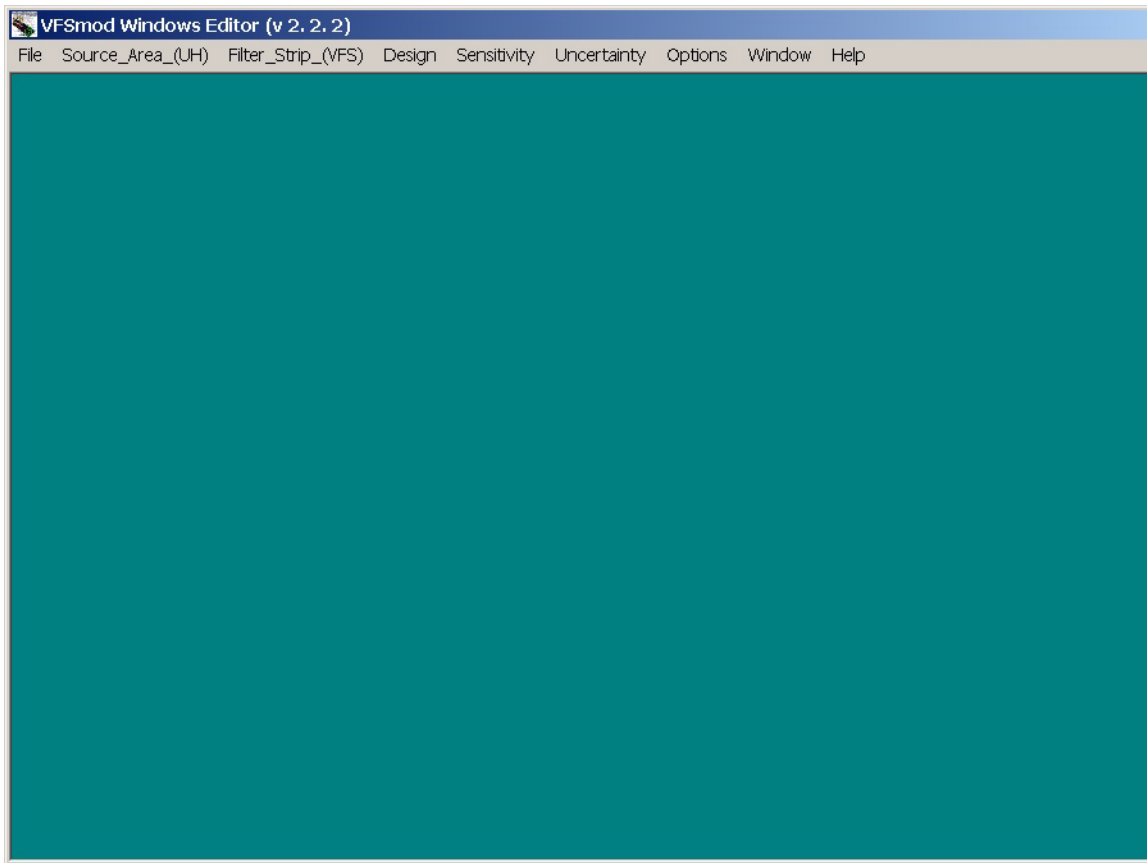
Application of VFSMOD is done via project files. The project files consist of a list of filenames identified by keywords indicating the type of input or output file. To **Open** a project file, select the **File Menu** and **Open a VFS Project File**.
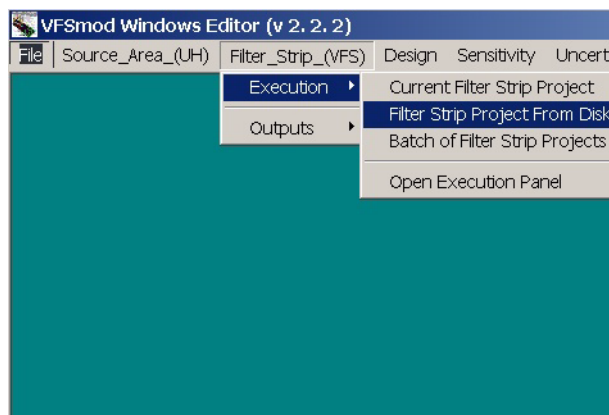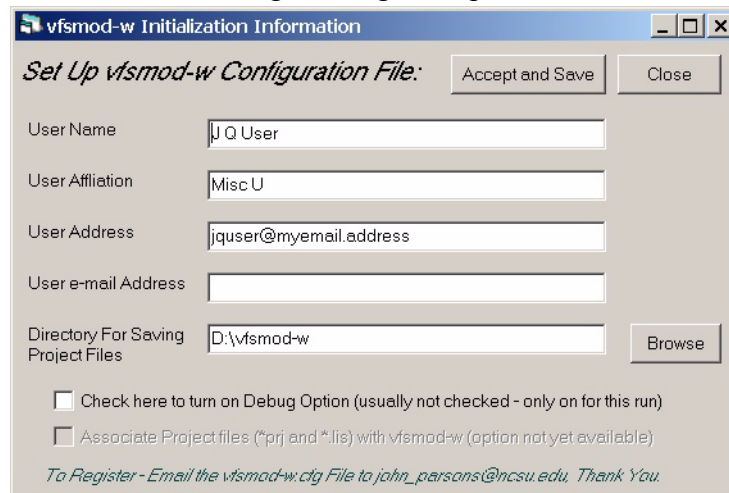

From the main window you can also execute VFSMOD. This option is available from the VFSM **menu**. This menu contains submenus for Execution and Analysis. Under the **Execution** submenu, the current project, a project from disk or multiple projects from disk can be executed. The **Analysis** submenu can be used to view output files from VFSMOD in addition to graphing and comparing some of the outputs generated by VFSMOD.

Other menu selections include Design, Sensitivity and Uncertainty. These are discussed in more details in other sections.

3.1 vfsmod-w Options File

On the main window, the Options Menu allows the user to review the program's options and user information. This information is entered the first time vfsmod-w is executed and can be checked and changed using the Options Menu.

Fill in the registration information. Be sure to select the directory where you installed vfsmod-w.exe for the *Directory for Saving Project Files*.

On the Options screen, we have included an option to associate files with extensions prj and lis with vfsmod-w.exe. This is currently not implemented. Once available this option will allow the user to click on a file with prj or lis extensions from the Explorer window and automatically load the project. You can manually accomplish this by associating these extensions with vfsmod-w.exe using the file Properties menu from Explorer.

Currently, we do not have an automatic registration for vfsmod package. The registration information is included on the Options screen. This information is stored in the file: *vfsmod-w.cfg* in the installation directory. For bug reports we may request that you e-mail us this file to assist in debugging.

4. UH Project Window

As an aid to set up the model inputs, the distribution package includes a utility, UH, that creates synthetic model inputs based on the NRCS (SCS) design storm for a given location and soil type. The utility implements the NRCS' (SCS) curve number, unit hydrograph and Modified Universal Soil Loss Equation (MUSLE) concepts to produce ready-to-use input files for VFSMOD. These inputs are rainfall hyetograph, field inflow hydrograph and field sediment inflow and characteristics.

The files used by UH are identified in the project window. There is also options to **Save** the project, **Edit** an input file and **Browse** Select a different input file. In addition, any of the input or output filenames can be changed from this window.
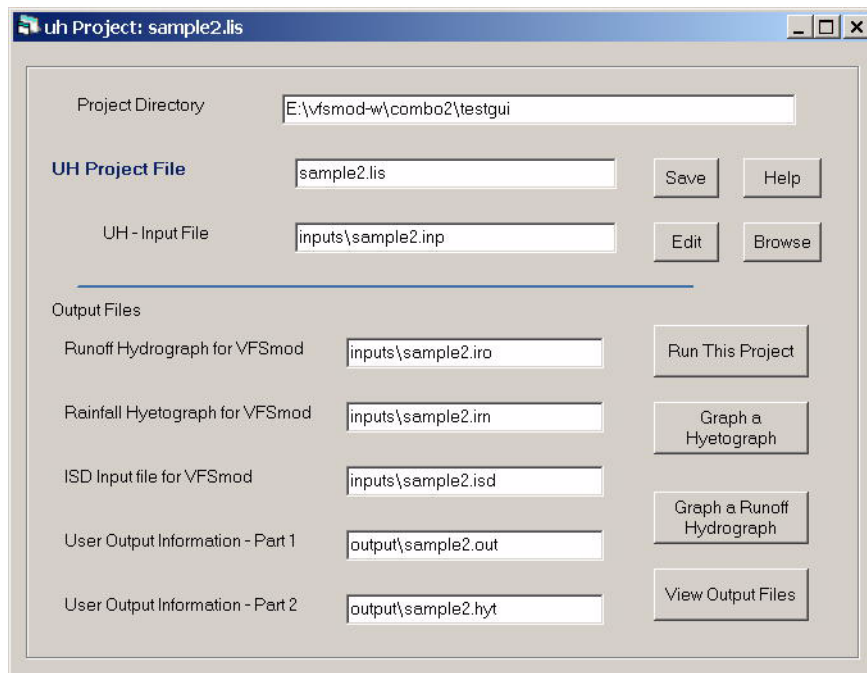
Option buttons provide shortcuts to the UH menu entry, these include the buttons:

Run This Project executes the current project

Graph Hyetograph produces bar graphs of rainfall intensity versus time, the user selects the output rainfall hyetograph file (irn)

Graph a Runoff Hydrograph oproduces a runoff hydrograph, the user selects the runoff file (iro)

View Output Files opens a text window with a user selected output file

Inputs	Outputs
inp= inputs for the source area for UH	*irn*= rainfall hyetograph (input for vfsmod) runoff hydrograph from the source *iro*= area (input for vfsmod) sediment properties for the sediment *isd*= filtration submodel summary of the inputs and outputs *out*= from UH detailed summary of of MUSLE calculations and the runoff *hyt*= hydrograph

For Tips on running/troubleshooting VFSMOD see section in Part II.

4.1 UH Input File Editing

The inputs for the UH program are entered in the text boxes.

Rainfall -This is the total rainfall for the storm in mm.

Curve Number - This is the NRCS curve number for the source area. The range is from 0 to 100. There are tables in the appendices to select See "NRCS (SCS) Curve Numbers" on page 113. for Agricultural and Urban source areas. The curve numbers given in these tables represent Antecedent Moisture Condition (AMC) II which is average moisture conditions.

Length - This is the length of the source area in m or the distance from the edge of the area (bordering the filter strip) along the upslope line to the farthest upslope point contributing runoff to the filter strip.

Area - This is the source area in hectares.

Slope - This is the slope of the source area as a fraction or the % slope divided by 100.

Storm Duration - The time of the storm in hours used to compute the hyetograph and hydrograph.

Storm Type - This is the type of rainfall event. (I, IA, II, or III). Type I is typically associated with Hawaii, coastal side of Sierra Nevada in southern California, and the interior regions of Alaska. Type IA is used to represent storms for the coastal side of the Sierra Nevada and the Cascade Mountains of Oregon, Washington, and northern California, and the coastal regions of Alaska. Type II is used to represent most of the remaining areas of the US. Type III is used for storms along the Gulf coast, southern Florida and coastal areas of the eastern US.

Soil Erodibility Factor, K - This is the USLE soil erodibility factor. (If K<0, then K is computed based on texture and organic matter) (See "Universal Soil Loss Equation (USLE)" on page 21.)

C Factor - The USLE Crop factor (See "MUSLE Crop factor C" on page 119.)

P Factor - The USLE P (Practice) factor (See "Contour factor (P) values for MUSLE equation in UH" on page 125.)

Soil Type - (for the surface soil layer (See "Definition" on page 59.)

dp – Particle Class Diameter ranges from 15 to 200 um. Tables based on soil types are used when the user specifies -1. (See "Tips for running the model" on page 50.)

Rainfall Factor - The rainfall factor for the modified storm version of USLE. Select the method to compute the storm R factor in MUSLE, not present or =1 selects Foster's Method, =2 selects Williams method, and =3 selects the CREAMS/GLEAMS method.

The User can change the name of the input file in the Input Filename window. The inputs can be saved using the **Save** button. In this case the window remains open for further editing. This is helpful to create multiple inputs. The **Close and Save** will save the inputs and close this window. The **Help** button gives this help screen.

5. VFS Project Window
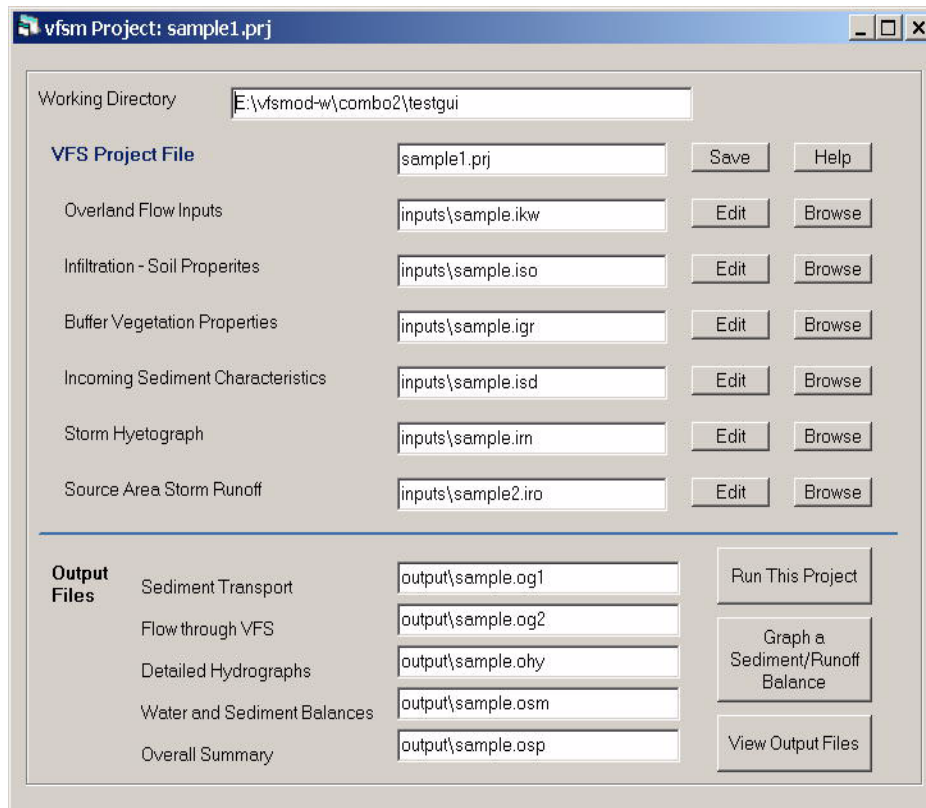
    The files used by VFSMOD are identified in the project window. There are options to **Save** the project, **Edit** any of the input files and **Browse** to Select different input files. In addition, any of the input or output filenames can be changed from this window. Other options buttons provide shortcuts to the VFSMOD menu entry, these include the buttons:

    Run This Project executes the current project
    Graph a Sediment/Runoff Balance produces bar graphs comparing sediment and runoff in and out of the filter strips, the user selects the output summary file
   **View Output Files** opens a text window with a user selected output file

    As a feature, if the user changes the project file name, then the output file names are changed to the same first level name. This feature can be overridden by changing the output file names.

| Inputs		Outputs	
igr=	buffer properties for the sediment filtration submodel	*og1*=	detailed time series describing the sediment transport and deposition within the buffer
ikw=	parameters for the overland flow solution	*og2*=	detailed information on the singular points defined in the theory section of the manual
irn=	storm hyetograph	*ohy*=	detailed outputs on the inflow and outflow hydrographs
iro=	storm hydrograph from the source area	*osm*=	detailed summaries of the water and sediment balance, final geometry of the filter
isd=	sediment properties for the sediment filtration submodel	*osp*=	overall summary of filter performance with comparisons between the source area and filter
iso=	soil properties for the infiltration submodel		

5.1 Overland Flow Inputs (ikw)

LABEL	a label (max. 50 characters) to identify the program run
FWIDTH	width of the strip (m)
VL	length of the filter strip (m)

N	number of nodes in the domain (integer) (must be an odd number for a quadratic finite element solution, but the program checks and corrects if needed).
THETAW	time-weight factor for the Crank-Nicholson solution (0.5 recommended)
CR	Courant number for the calculation of time step from 0.5 - 0.8 (recommended). (See "Tips for running the model" on page 50.)
MAXITER	(integer) maximum number of iterations alowed in the Picard loop.
NPOL	(integer) number of nodal points over each element (polynomial degree +1) [Recommended value=3] (See "Tips for running the model" on page 50.)
IELOUT	(integer) flag to output elemental information (1) or not (0)
KPG	(integer) flag to choose the Petrov-Galerkin solution (1) or regular finite element (0) [Recommended value=1] (See "Tips for running the model" on page 50.)
NPROP	(integer) number of segments with different surface properties (slope or roughness)
SX(I)	(real) X distance from the beginning on 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)
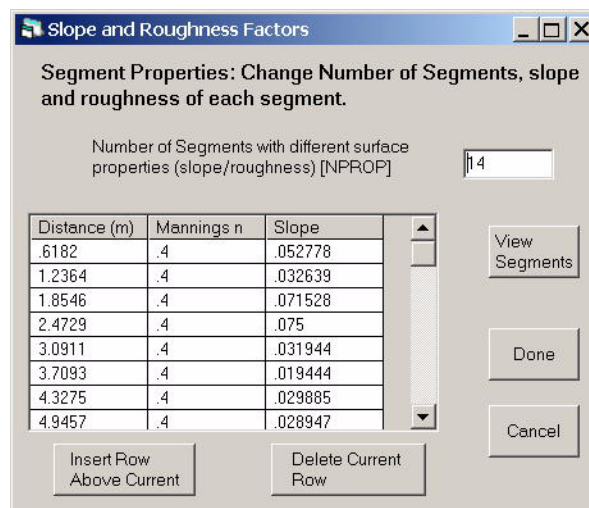
Selecting the View Segments button displays a graph of the elevation change across the filter strip. The elevation change is relative to the upslope edge of the filter strip. If the user changes VL, the length of the filter strip, then a check is made of the segment properties to ensure that the last point in SX is equal to the new buffer strip length. If it is not, then the View/Edit Segment Properties screen is opened and a warning message box is shown reminding the user to fix the segment properties data.
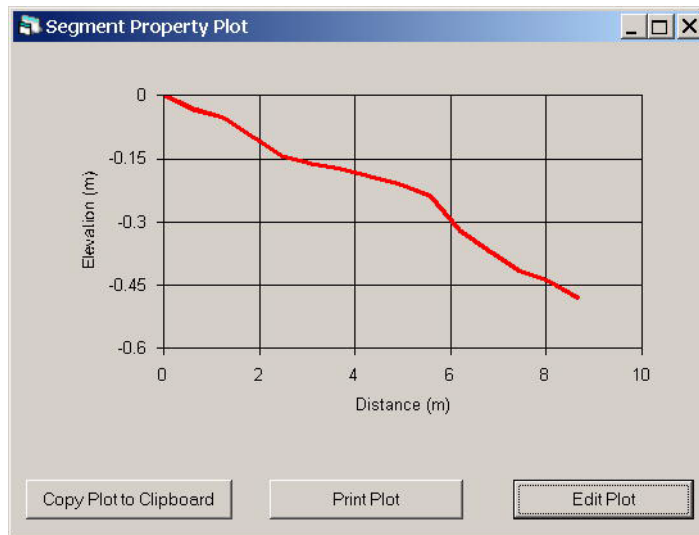
5.2 VFS Infiltration Soil Properties (iso)

VKS   saturated hydraulic conductivity, K_s (m/s) (See "Soils data (Green-Ampt parameters)" on page 110.

SAV   Green-Ampt's average suction at wet front(m) (See "Soils data (Green-Ampt parameters)" on page 110.)

OS   saturated soil-water content, θ_s (m³/m³)(See "Soils data (Green-Ampt parameters)" on page 110.)

OI   initial soil-water content, θ_i (m³/m³)

SM   maximum surface storage (m)

SCHK   relative distance from the upper filter edge where the check for ponding conditions is made (i.e. 1= end filter, 0.5= mid point, 0= beginning)

5.3 VFS Buffer Vegetation Characteristics (igr)
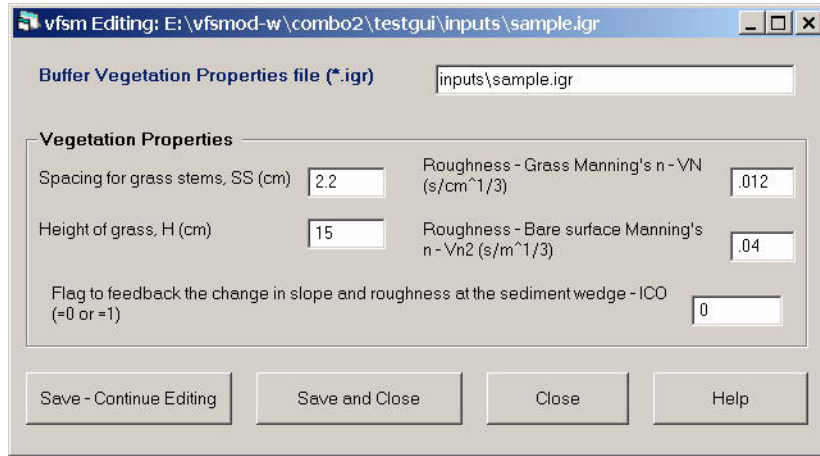
SS	spacing of the filter media elements (cm) (See "Vegetation types for VFS's" on page 111.)
VN	filter media (grass) Manning's *n* (See "Vegetation types for VFS's" on page 111.) (0.012 for cylindrical media) (s.cm$^{-1/3}$)
H	filter media height (cm) (See "Vegetation types for VFS's" on page 111.
VN2	bare surface Manning's n (See "Manning's roughness coeficient, n" on page 110.*)*
ICO	(integer) flag to feedback the change in slope and surface roughness at the sediment wedge for each time step (0= no feedback; 1= feedback) (**See "Tips for running the model" on page 50.)**

5.4 Incoming Sediment Characteristics (isd)
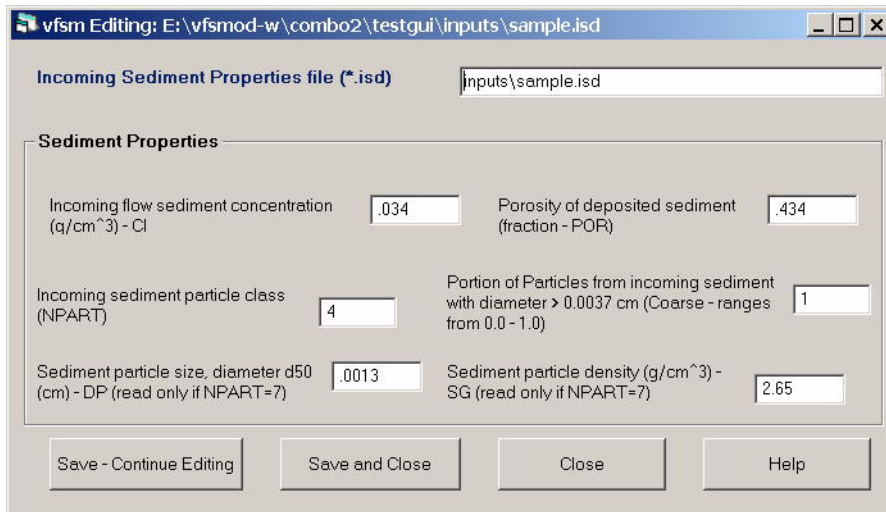
NPART	(integer) incoming sediment particle class according to the USDA (1975) particle classes:

NPART	Particle class	Diam. range (cm)	d_p (cm)	V_f (cm/s)	$_s$ (cm^3/s)
1	Clay	<0.0002	0.0002	0.0004	2.60
2	Silt (1)	0.0002 - 0.005	0.0010	0.0094	2.65
3	Small aggregate	----	0.0030	0.0408	1.80
4	Large aggregate	----	0.0300	3.0625	1.60
5	Sand	0.0050 - 0.2	0.0200	3.7431	2.65
6	Silt (2)	0.0002 - 0.005	0.0029	0.0076	2.65
7	User selected	----	DP	model	SG

COARSE	% of particles from incoming sediment with diameter > 0.0037 cm (coarse fraction that will be routed through wedge) (unit fraction, i.e. 100% = 1.0).
CI	incoming flow sediment concentration (g/cm^3)
POR	porosity of deposited sediment (unit fraction, i.e. 43.4% = 0.434)
DP	sediment particle size, diameter, d_{50} (cm), read only if NPART=7
SG	sediment particle density, $_s$(g/cm^3), read only if NPART=7

5.5 Storm Hyetograph (irn)

The hyetograph input files can be manually entered or generated using the UH program. See the UH program documentation for further information.
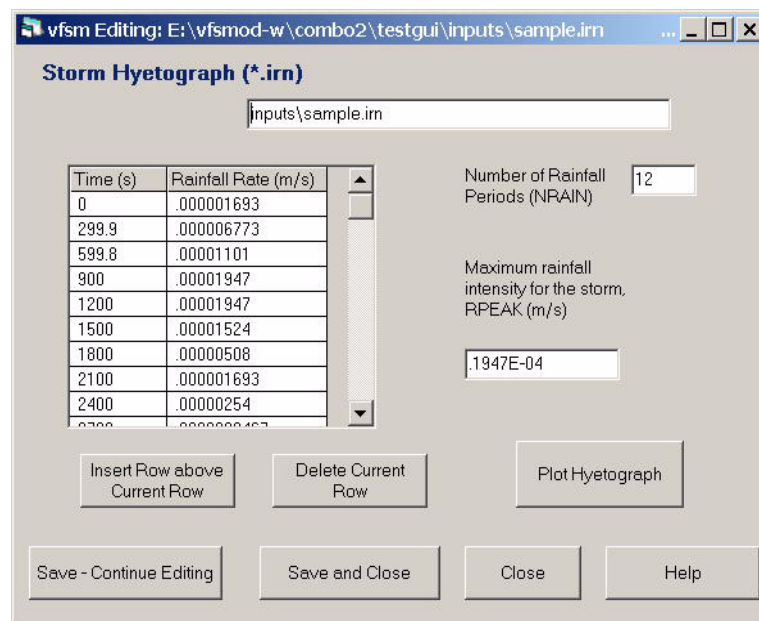
NRAIN	(integer) number of rainfall periods including period to end simulation

| RPEAK	maximum rainfall intensity for the storm (m/s)
RAIN(I,J)	time (s) and rainfall rate o intensity (m/s) over the VFS for each period. The last time step corresponds with the desired simulation time chosen by the user (typically coupled with a rainfall intensity of 0). Note also that each time corresponds to the beginning of the rainfall period.

The hyetograph can be viewed by selecting the Plot Hyetograph button.
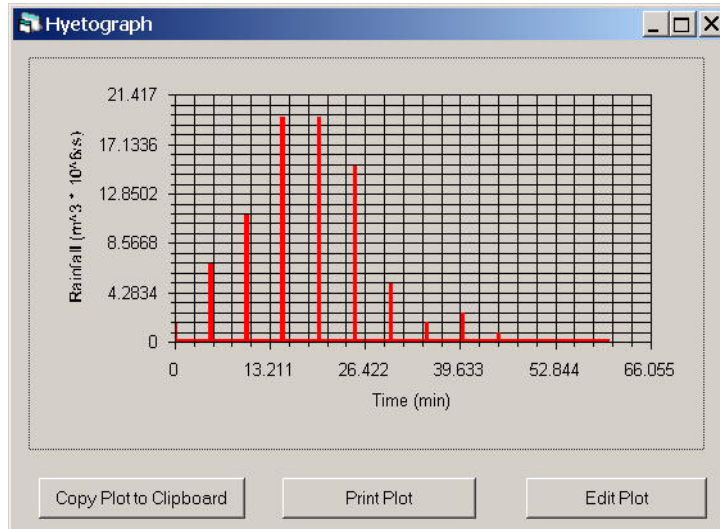
5.6 VFS Source Area Storm Runoff (iro)

The runoff hydrographs from the source area can be manually entered or generated using the UH program. See the UH program documentation for further information.
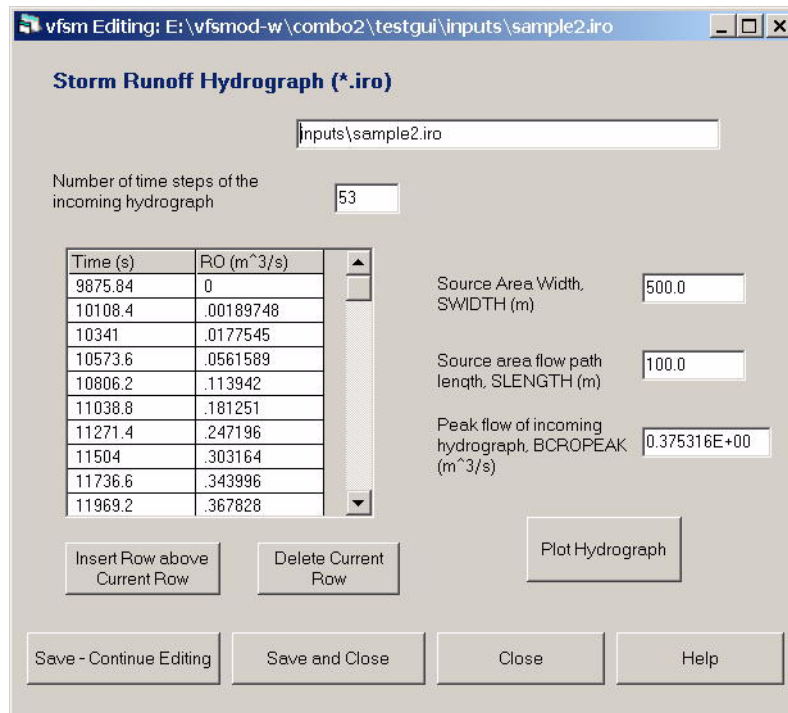
SWIDTH	Source area width (m)
SLENGTH	Source area flow path length (m)
NBCROFF	(integer) number of time steps of the incoming field hydrograph
BCROPEAK	Peak flow of the incoming field hydrograph (m^3/s)
BCROFF(I,J)	incoming field hydrograph: flow rate, time (s) vs. qin(m^3/s).

The hydrograph can be viewed using the Plot Hydrograph button.
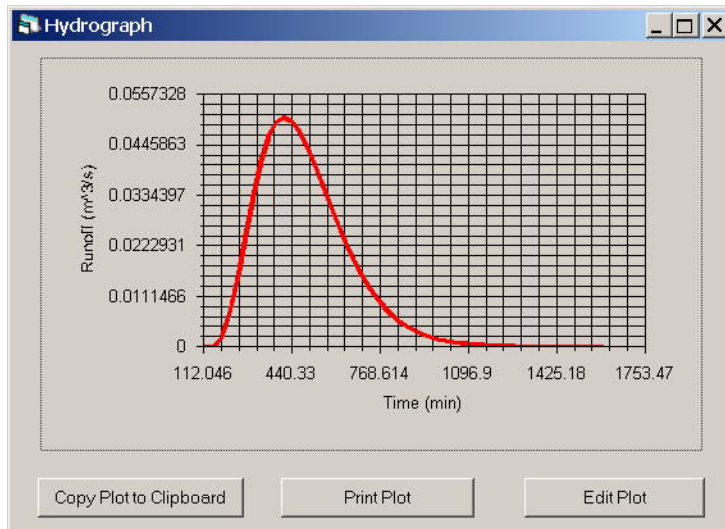
6. Processing and Analysis of VFSMOD Results

A description of the VFSMOD output files can be found in Part II of this Documentation. In this version, limited analysis of the output files is available. These options are available from the VFSMOD menu's Outputs option.
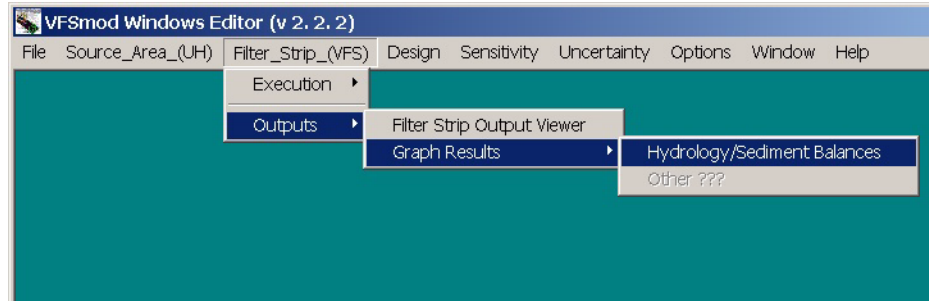
Currently, the output files can be viewed by selecting the VFS Output Viewer menu and the user can create plots of the Hydrology and Sediment Balances for the simulation. The user selects a results file for each of these options.
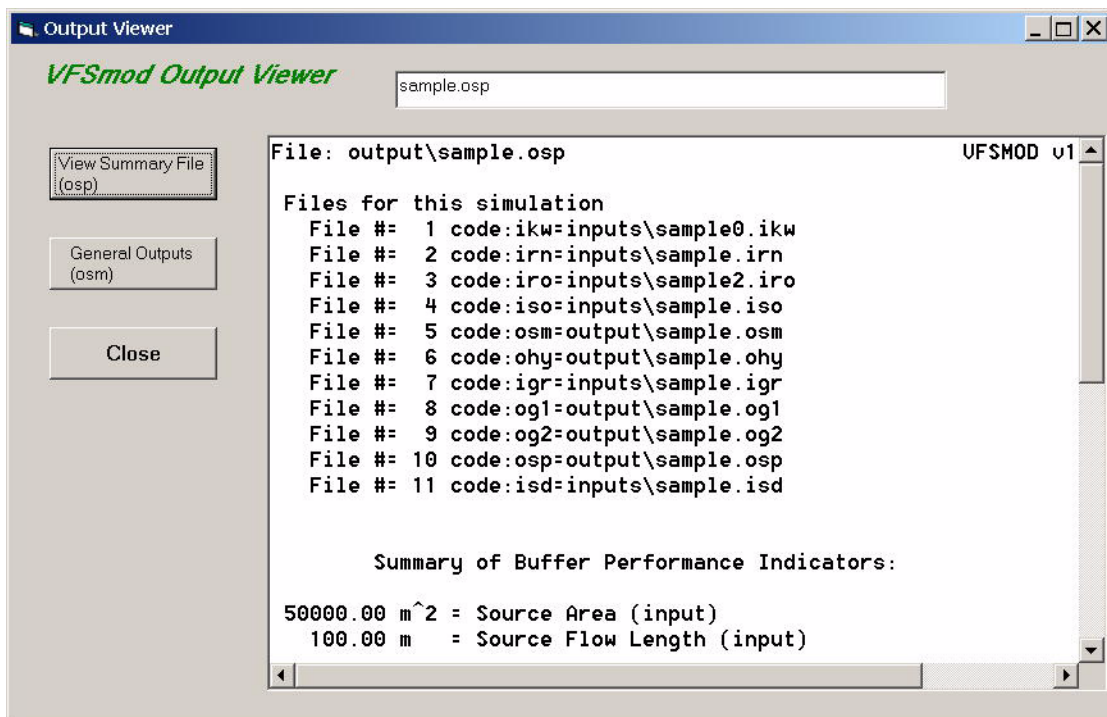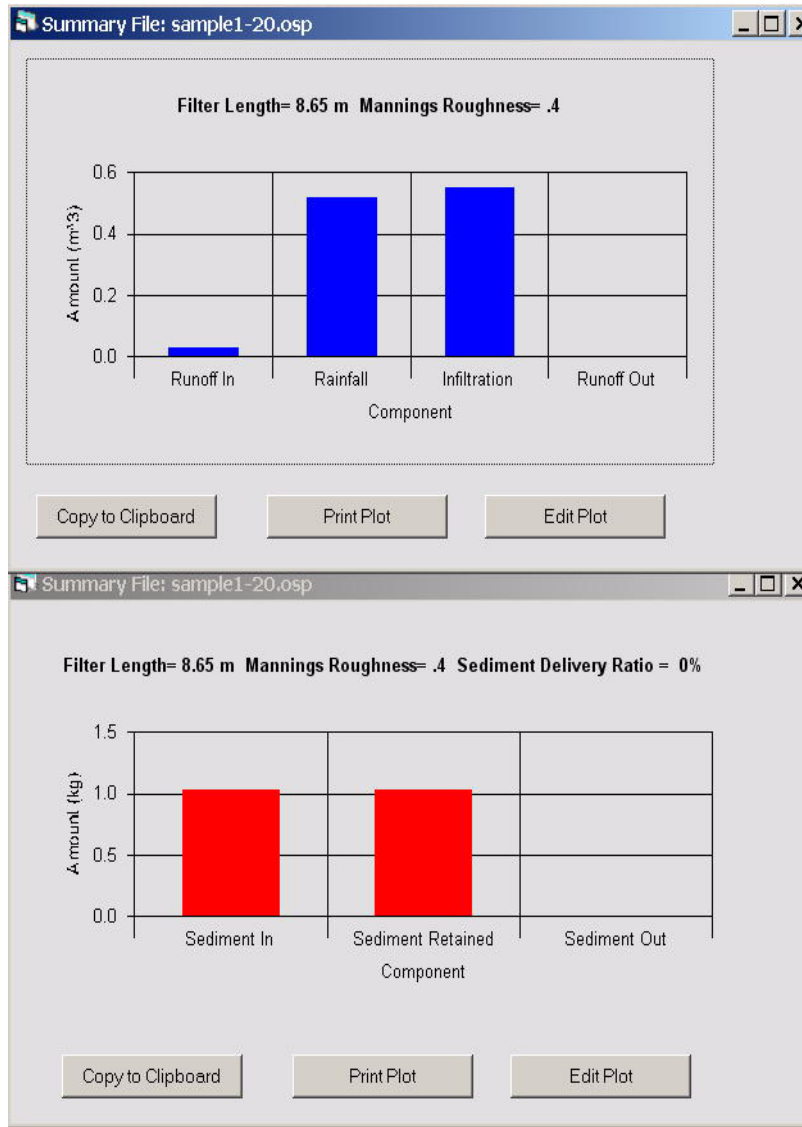
All of the output files are in ASCII format and can be imported into other applications for further processing.

We are planning to implement other analysis options in future versions.

7. Using the Plot Windows

The user can make graphs of various input and output parameters. Each of the Plot windows offer option buttons to **Copy the Plot to the Clipboard**, **Edit the Plot**, or **Print the Plot**. A plot of a runoff hydrograph is used as example to illustrate the various options.
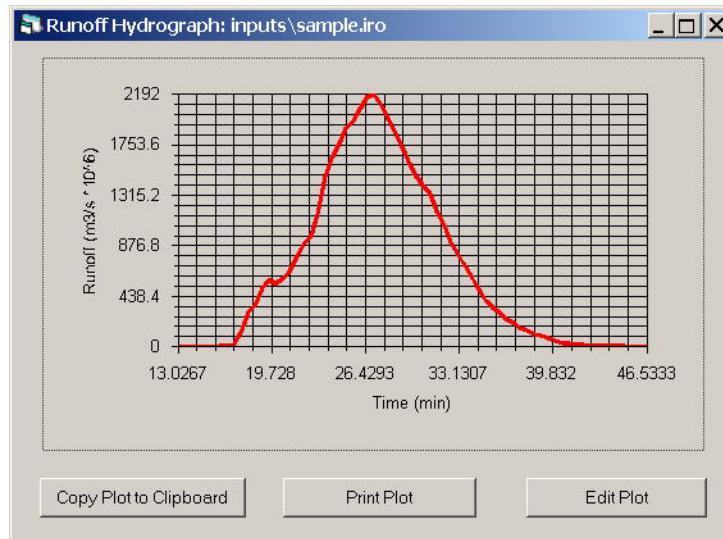
Selecting the **Edit Plot** button, the plot can be customized. The Axis titles can be changed along with setting the minimum and maximum values of the range along with how many labels. A Title for the Plot can also be added. The effect of these changes can be viewed by selecting the **Preview Button**.

Once Plot editing is complete, the **Plot can be Copied to the Clipboard**. The Plot can then be inserted into another application such as a word processor. For example, the plot can be inserted in Word by Selecting Edit – Paste Special –Picture or Device Independent Bitmap. If you desire only the data used to create the plot, then use Paste. In Powerpoint, use Paste Special and Device Independent Bitmap. The plot is copied to the Clipboard as a Windows Metafile (wmf) for optimum resolution.

The plot can also be printed by selecting the **Print Plot** button. The plot can be previewed along with selecting the printer, paper size and orientation.
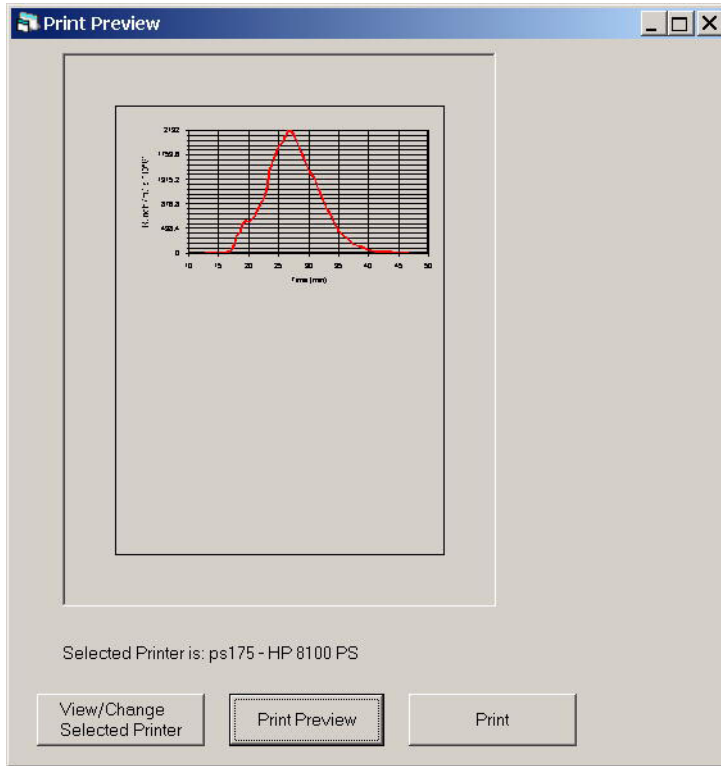
8. Sensitivity Analysis Screens

Sensitivity analysis can be done on a number of the input parameters for both the UH model and VFSMOD. Set the ones you would like to analyze and leave the others unchecked.

For the UH model, sensitivity analysis can be done for Curve Number (CN), Soil Erodibility Factor (K), Crop Factor (C), and the Practice Factor (P). The user selects the parameters to consider using the Check boxes and enters the minimum, maximum and an increment for the parameter. The base value shown is the value in the base project files. These values are used in some of the analysis screens. In addition to setting the values, the user can load a different base project and once the inputs are set, do the simulations. If the user would like to also do the analysis for the VFSMOD parameters, they can switch to the VFSMOD screen.
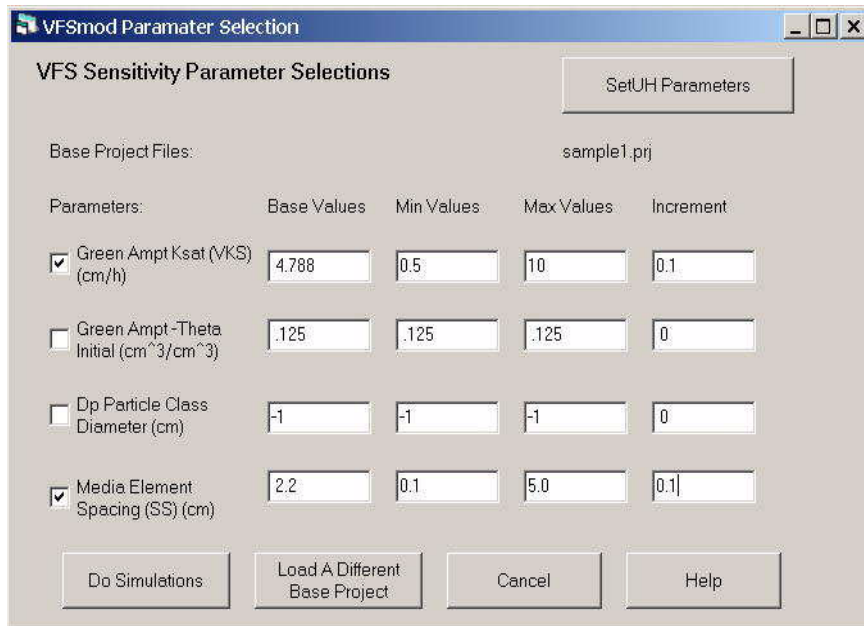
Similar to the UH screen, only selected parameters are available for sensitivity analysis. Currently, the parameters are the saturated vertical conductivity and initial water content for the Green Ampt infiltration submodel for the filter strip and the Dp (Particle Class diameter) and SS (Media Element Spacing) parameters. Selection of each parameter is done with the Check boxes and setting minimum and maximum values along with an increment for the sensitivity analysis.

Once the simulations are complete, the user can do some analysis using the VFSMOD. Selected storm outputs are saved in files for each parameter selected. For example, if Curve Numbers are selected, then the suggested name for the output of the sensitivity parameters is: UHCNsens.sen.
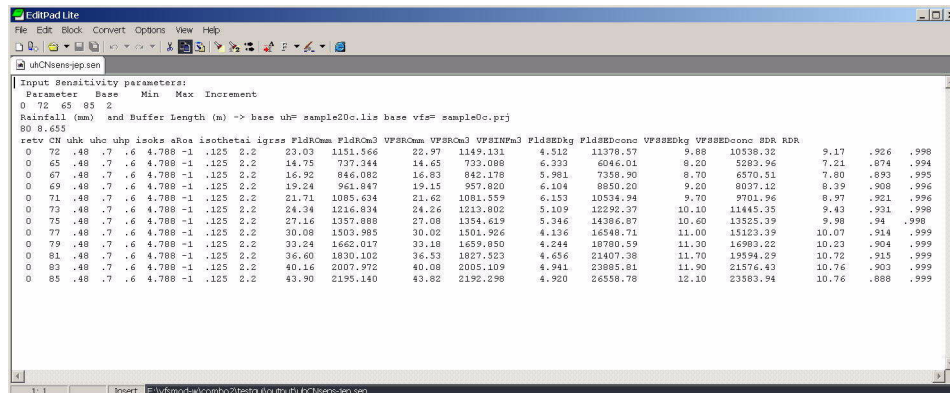
The format of this file is space separated that is easily imported into another analysis package such as spreadsheet. To import in a spreadsheet one selects space-separated data (treat multiple spaces as one). The first five lines denote general information on the

parameter and the base project file. This information includes the parameter range, total rainfall for the event and the filter strip length along with the base project filenames. The tabular information presents the event level outputs and starts on the 7th line. Each line contains the results for one of the simulations. The columns are: retv – the return value for that simulation (0 indicates that simulation had no errors), CN – the curve number input, UHk – soil erodibility K input, UHc – crop factor input, UHp – practice factor input, isoks – the Green-Ampt saturated K input, aRoa - , isothetai – Green Ampt initial soil water content, and igrss – stem spacing input. Next the summary outputs for the storm are given. These include FldROmm and FldROm3 – the runoff from the source area (field) in mm and m3, VFSROmm and VFSROm3 – the runoff from the vegetative filter strip area in mm and m3, VFSinfm3 – the amount of infiltration in the vegetative filter strip in m3, FldSEDkg and FldSEDconc – the sediment from the source area (field) in kg and kg/L, VFSSEDkg and VFSSEDconc – the sediment lost from the vegetative filter strip in kg and kg/L, and SDR – the sediment delivery ratio (Mass Sediment from VFS/Mass Sediment from Field) and RDR – the runoff delivery ratio (Runoff from VFS/Runoff from Field). A separate file is written for each parameter.

The user selects the Analysis option from the Sensitivity menu and selects the file to analyze.
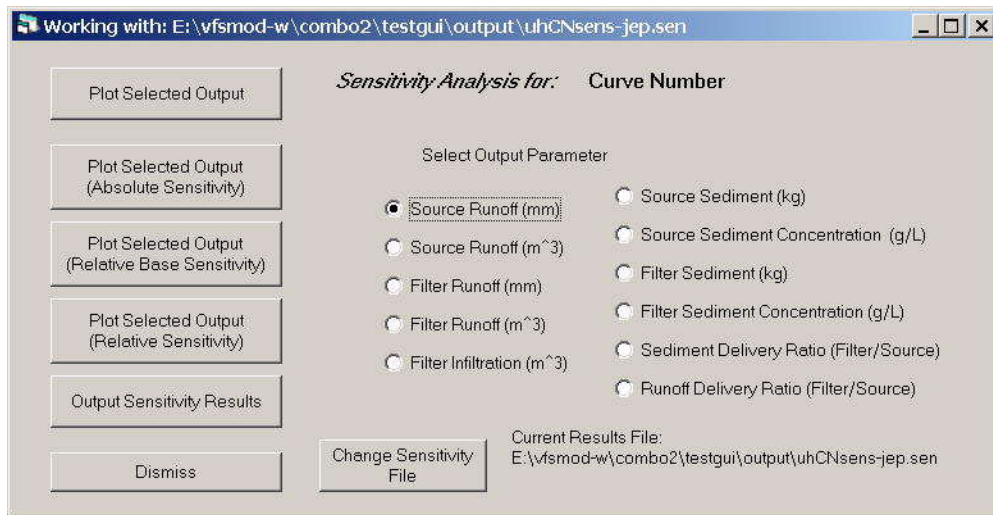
From this screen, selected storm outputs are available for analyses. Various plots of the outputs versus the inputs along with some statistics are available. For example, the Curve Number was varied from 76 to 95 and produced Source Runoff from 85 mm to 138 mm. Selecting **Plot Selected Output** produces:
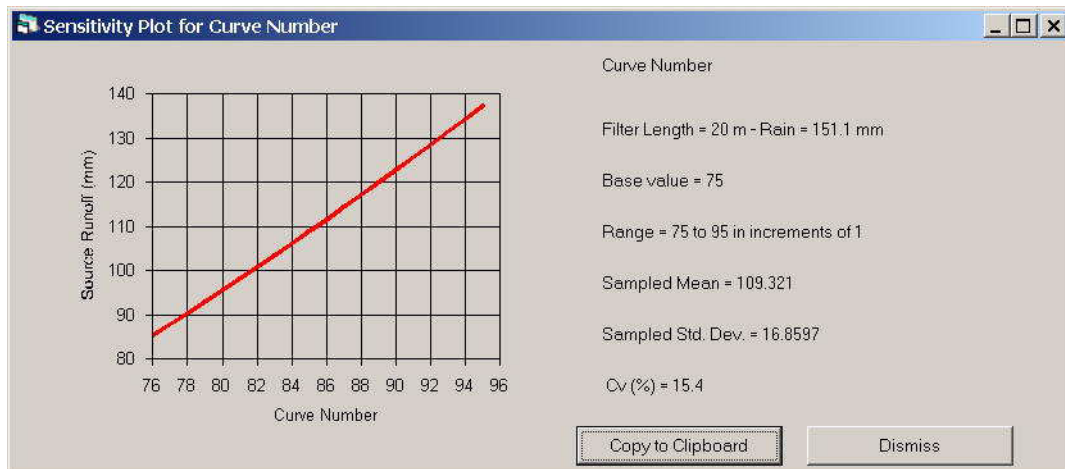
Other plotting and summary options include:

Plot Selected Output (Absolute Sensitivity) This produces a plot of slope of the output versus the input (example Slope of Source Runoff versus CN)

Plot Selected Output (Relative Base Sensitivity) This produces a plot of (Output – BaseOutput)/(Input – BaseInput) * (BaseInput/BaseOutput) versus the Input

Plot Selected Output (Relative Sensitivity) This produces a plot of slope of the output versus the input times Input/Output versus the Input

Output Sensitivity Results This produces an output file with all of the statistics.

Here are examples for each of these.

Plot Selected Output (Absolute Sensitivity)
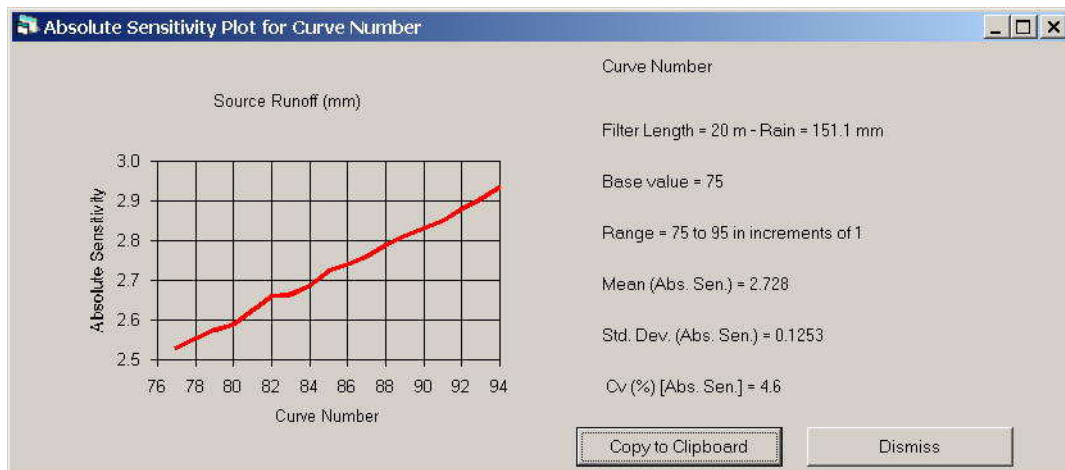
Plot Selected Output (Relative Base Sensitivity)
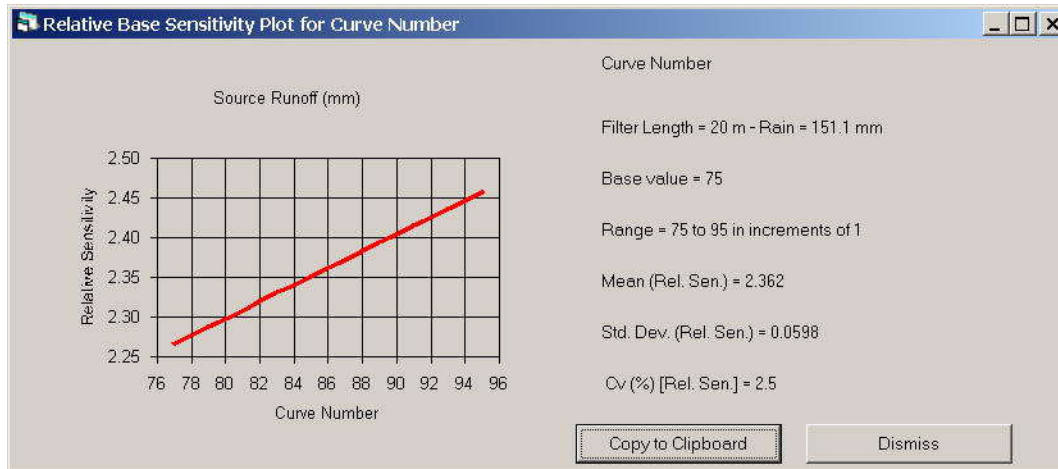
Plot Selected Output (Relative Sensitivity)
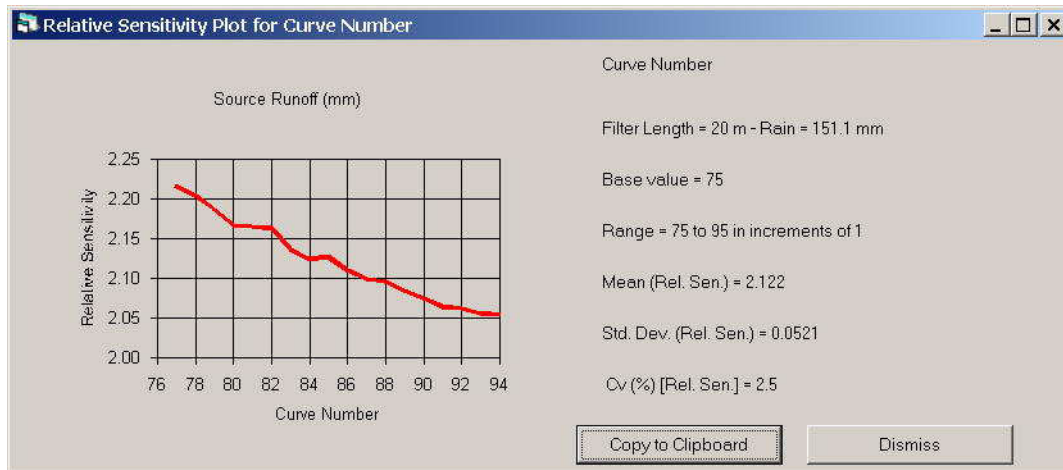
Output Sensitivity Results

This output file contains all of the analyses for each of the above graphs and the statistics. This is useful for further analyses using other application packages such as spreadsheets.

9. Uncertainty Analysis Screens

Uncertainty analysis can be done on a number of the input parameters for both the UH model and VFSMOD. These are done using base values from a specific UH and VFSMOD project. Select the input parameters you would like to analyze and leave the others unchecked. For each of the selected input parameters, select a probability distribution and specify the parameters to define the distribution.

For the UH uncertainty analysis, Curve Number (CN), Soil Erodibility Factor (K), Crop Factor (C), and the Practice Factor (P) can be selected. The user selects the parameters to consider using the Check boxes and selects the probability distribution. Currently, the normal, log-normal, triangular, and uniform are available. After selecting the distribution, the Set Parameters button opens the window to enter the parameters defining the distribution. For the normal and log-normal distribution, the mean and standard deviation are entered. The peak and maximum and minimum values specify the triangular distribution. The minimum and maximum values determine the range for sampling the uniform distribution. If the user would like to also do the uncertainty analysis for the VFSMOD parameters, they can switch to the VFSMOD screen.

,
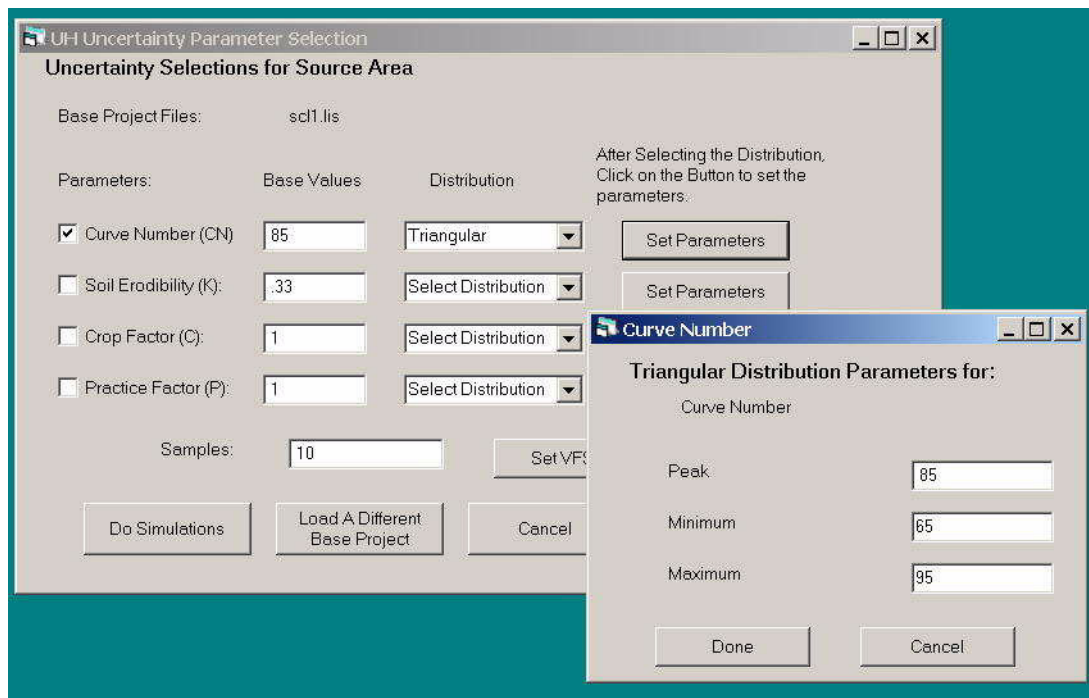
Similar to the UH uncertainty selection screen, only selected parameters are available for uncertainty analysis for VFSMOD. Currently, the parameters are the saturated vertical conductivity and initial water content for the Green Ampt infiltration submodel for the filter strip and the Dp (Particle Class diameter) and SS (Media Element Spacing) parameters. Selection of each parameter is done with the Check boxes and setting the distribution. Currently, the normal, log-normal, triangular, and uniform are available. After selecting the distribution, the Set Parameters button opens the window to enter the parameters defining the distribution. For the normal and log-normal distribution, the mean

and standard deviation are entered. The peak and maximum and minimum values specify the triangular distribution. The minimum and maximum values determine the range for sampling the uniform distribution.

On either of the screens, the number of simulations is also specified. These will typically range in the thousands, although the user can specify any number. On a Pentium III, 1 GHZ processor based desktop, each simulation takes from 10-15 seconds up to as much as 1 minute.
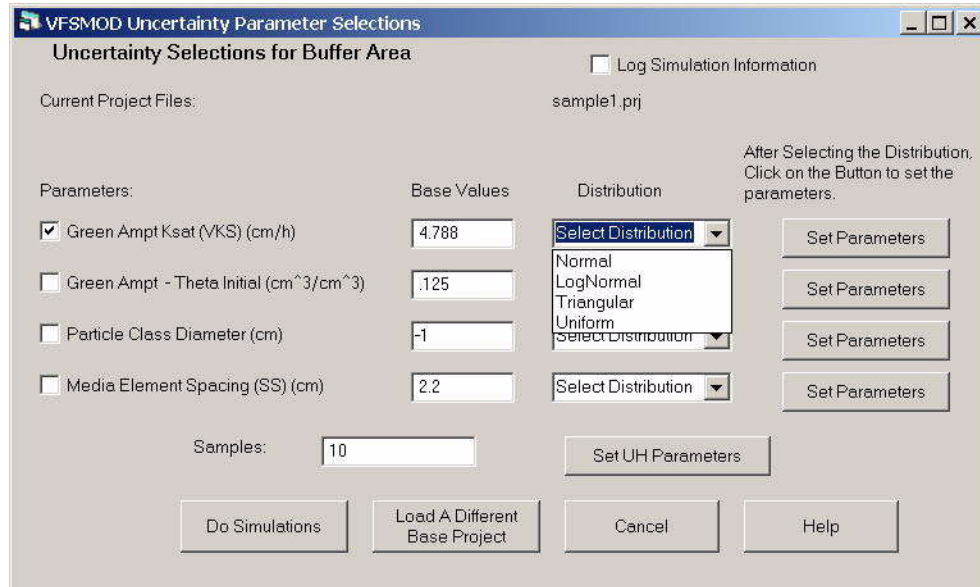
Once the simulations are complete, the user can do some analysis using VFSMOD. Selected storm outputs are saved in the output file. The format of this file is space-separated and is easily imported into another analysis package such as spreadsheet. The first thirteen lines contain header and general information on the parameter and the base project file. This information includes the parameters and their probability distributions and the base rainfall and filter strip length along with the base project filenames. Lines 3 – 10 include the information on each input parameter, 0-7 indicating the parameter, selection of the probability distribution for sampling the inputs – the options are-1 = no uncertainty, 0 = normal, 1 = lognormal, 2 = triangular, or 3 = uniform, and the parameters to define the probability distribution as shown below.

Distribution Number	Distribution	Parameters
-1	Not Sampled	
0	Normal	Mean, Standard Deviation
1	Lognormal	Log of Mean, and Log of the Standard Deviation
2	Triangular	Peak, Minimum and Maximum
3	Uniform	Minimum and Maximum

The tabular information presents the event level outputs and starts on the 14th line. Each line contains the results for one of the simulations. The columns are: retv – the return value for that simulation (0 indicates that simulation had no errors), CN – the curve number input, UHk – soil erodibility K input, UHc – crop factor input, UHp – practice factor input, isoks – the Green-Ampt saturated K input, aRoa - , isothetai – Green Ampt initial soil water content, and igrss – stem spacing input. Next the summary outputs for the storm are given. These include FldROmm and FldROm3 – the runoff from the source area (field) in mm and m3, VFSROmm and VFSROm3 – the runoff from the vegetative filter strip area in mm and m3, VFSinfm3 – the amount of infiltration in the vegetative filter strip in m3, FldSEDkg and FldSEDconc – the sediment from the source area (field) in kg and kg/L, VFSSEDkg and VFSSEDconc – the sediment lost from the vegetative filter strip in kg and kg/L, and SDR – the sediment delivery ratio (Mass Sediment from VFS/ Mass Sediment from Field) and RDR – the runoff delivery ratio (Runoff from VFS/Runoff from Field).

In addition, the Analysis option for the Uncertainty section includes some analysis options for the data. These options include plots of the frequency distribution, and cumulative probability distributions. These can be done for each sampled input parameter and for any of the output parameters.
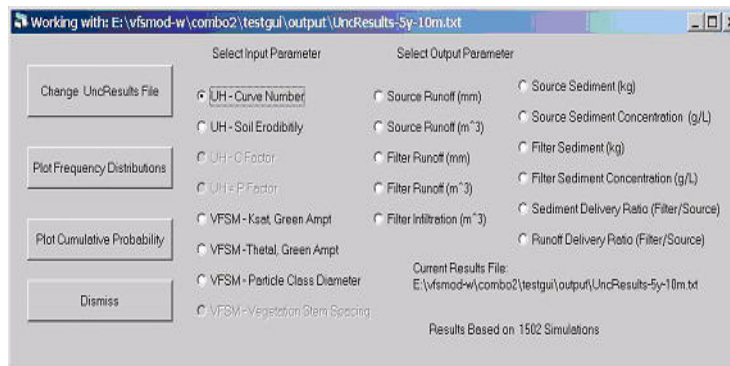
Examples of the frequency and cumulative probability distributions for sampling the curve number are shown below.
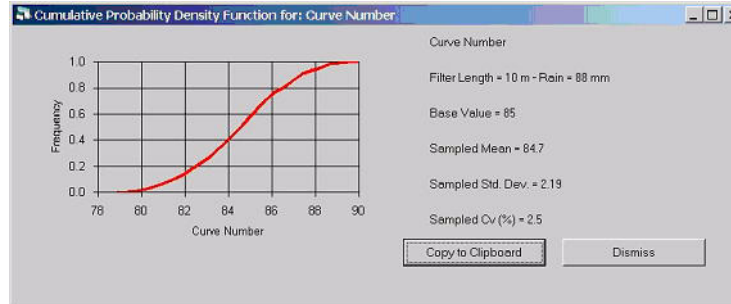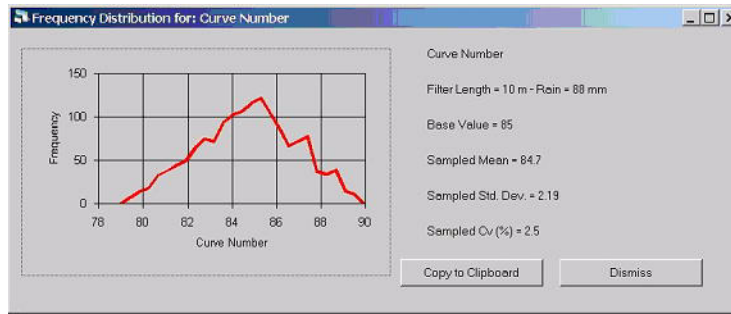
Examples of the graphs for the outputs are given for the sediment delivery ratio (SDR).
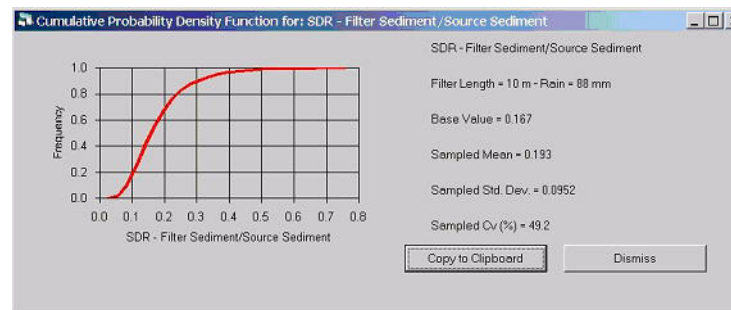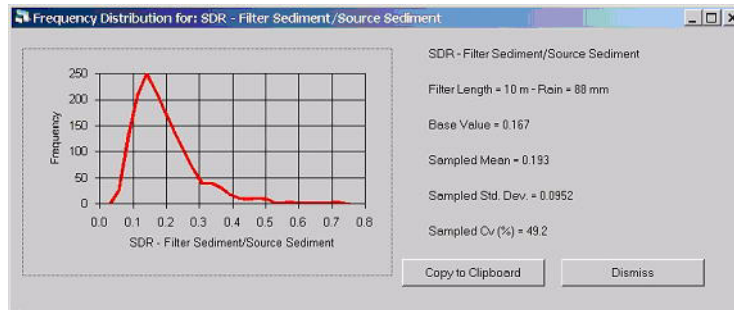
10. Design Screen

The design section of VFSMOD can be used to examine a range of storms and filter strip design parameters to assist in finding the optimum length for a given situation. A base UH and VFSMOD project is selected. The comparisons that can be included in the design are: i) a range of design storms for generating varying input runoff hydrographs and sediment loads; ii) arange of filter strip lengths; and iii) a range of filter vegetation density (grass media spacing).

During the design procedure, UH and VFSMOD are coupled automatically to explore the user selected range of factors included in the design. The programs execute as follows:

(1)   For each step (design factor combination), VFSMOD-W creates a *design.lis* combining inputs from the UH base project and a design storm.

(2)   Executes UH with the newly created *design.lis* and produces the VFSMOD files *design.iro, design.irn, design.isd* and *design.iso*.

(3)   Creates the remaining *design.igr* and *design.ikw* combining inputs from the VFSMOD base project and a design filter length/vegetation spacing value.

(4)   Creates a VFSMOD design.prj file using the files above and Executes the VFSM.

(5)   Loops back to (1) until all simulations are completed

Currently, there are no options for the Design Analysis section. The output file from the design analysis simulations can easily be imported into a spreadsheet for further analysis. The file format is comma-separated-variable (csv).

11. Troubleshooting vfsmod-w

As you encounter problems, you can e-mail us for help/assistance. In most cases, you should send us copies of the files giving problems along with a detailed description so we can recreate the problem. You can e-mail problems and any suggestions or questions via the web site: http:/www3.bae.ncsu.edu/vfsmod/. You can also e-mail your problems directly to carpena@ufl.eduor john_parsons@ncsu.edu.

Current Issues/Hints/Problems and Workarounds

(1)	Download the zip file containing the VFSMOD package, vfsmod-w-install.zip to your temp directory and unzip into a subdirectory. After setup is complete, you can delete the subdirectory. You can delete the zip file, but you may want to keep this in case you need to re-install the program.

(2)	During setup, you may receive a message that setup needs to update your system. If you receive this message, then allow setup to update your system. After setup updates your system, reboot and execute setup again.

(3)	In Windows 98, the MSDOS command window that vfsm.exe and UH.exe executes within is not automatically closed. You should close this manually.

(4)	On some systems, if you choose to install the package in drv:\Program Files, then the execution menu may not work correctly for UH and VFSMOD. We have seen this on Windows NT 4.0 systems. The default install directory is c:\vfsmod. To avoid this problem, we recommend you use this directory.

(5)	If you have a previous version of vfsmod on your computer, you should uninstall prior to installing this version.

(6)	With this version, on Windows NT, 2000, and XP, you will need Administrator privileges to install. A few system files are copied into the Windows System directories.

(7)	Since the vfsm and uh executables are written in Fortran and run at the Command window level, all filenames should not contain any spaces. Spaces in the filenames will cause unpredictable results. For example, my Project.prj will cause problems. Use something like my_Project.prj, this should work fine.

(8)

12. VFSMOD-W Change History

11/18/2000:

Added buttons in VFSMod Output Viewer for the remaining Output files: *.ohy, *.og1, *.og2

Made Nprop global and now the number of segments in the segment properties window updates when the user deletes and adds segments

2/5/2001:

The first level of the output filenames default to the same as the project name. The user can override this by changing the output filenames.

In the igr files, a check is made when the user changes the VL, buffer length. The new buffer length is checked against the segment properties. If these are unequal, a warning message box is displayed and the View/Edit Segment properties window is opened.

3/5/2003, vfsmod-w.exe – version 2.00.xx; UH.exe – version 1.06; vfsm.exe – version 1.06

- Major revisions for the entire system. Adding a number of buttons on pages to duplicate menu selections

- Added Sensitivity Analysis

- Added Uncertainty Analysis

- Added Design Analysis

5/20/2003, NEW FEATURES IN RELEASE V2.2.XX

- New, more intuitive, menu labels and lay-out

- Expanded and improved sensitivity and uncertainty analyses procedures. Individual filter areas or combines source-filter areas can be now analyzed individually. Multidimensional analysis is also available as well as print-out of graphical results. Ranges of user selected parameters are now automatically checked against physically admissible values.

- VFSMOD and UH have been further refined to improve integration with the GUI environment and graphical inputs.

- Improved handling of special cases (small runoff, impermeable surfaces, saturated soils, etc).

8/1/2005, RELEASE V3.0.XX

- A number of items were cleaned up in all of the code. Further testing of the sensitivity and uncertainty routines were done. A fairly extensive design procedure was added.

- Other changes can be found in the text logs in the install directories.

Part IV: VFSMOD: Appendices

1. APPENDIX 1: Description of the model subroutines

The source code is distributed with the model. This section is intended to be used with the source code, which contains more detailed documentation.

1.1 Program VFSMOD

The main program is the driver for the program subroutines as discussed in the previous section. This is done on the following steps:
(a) print banner, get I/O file names and open the files
(b) initialize matrices
(c) read inputs for sediment problem
(d) get inputs and parameters for hydrology problem
(e) get the Gauss quadrature parameters
(f) assemble the system matrix [A]
(g) perform LU decomposition over [A]
(h) Start the time loop to solve the problem for each time step

> h-1. select the rainfall intensity and BC (transform into depth (m)) at the first node of system (incoming hydrograph) for each time step.
>
> h-2. get effective rainfall and control execution of overland flow for an infiltrating surface by calling Green-Ampt model. The assumption is that when a certain node (NCHK) is flooded, i.e. X(NCHK)>0, all the surface will be flooded, and thus the maximum infiltration capacity for the rest of the event is selected as given by the Green-Ampt model. NCHK is selected by the user.
>
> h-3. form of r.h.s vector for that time step
>
> h-4. start Picard iteration
>> h-4.1. update $\{b\} = \{b^m\}$
>> h-4.2. feed the vector to the solver
>> h-4.3. check for convergence
>> h-4.4. update $X^m = X^{m+1}$
>> h-4.5. find flow component at iteration step
>> h-4.6. Picard iteration converges, proceed with time step, otherwise repeat
>
> h-6. update h and q for next time level
>
> h-7. do the following only 100 times, each time using the average flow of the last NWRITE values in between
>> h-7.1. call sediment transport subroutine if there is inflow (change units from $Q(m^2/s)$ to $QSED(cm^2/s)$)
>> h-7.1. write outputs to files
>
> h-8. repeat time loop for next time step until the end of the run

(i) write a summary of results at the end of the run
(j) close files and end program

1.2 FINPUT(LISFIL)

This subroutine writes the program banner, reads the name of the file set to be processed from the command line string, creates I/O file names accordingly, and opens I/O files.

1.3 INI(A,B,X,XM,X0,Q0,QM,SSE,NODEX)

The main program matrices are set to zero before the beginning of the simulation.

1.4 GRASSIN(ICOARSE,COARSE,LISFIL)

This subroutine reads in the main parameters of the sediment sub-model, calculates some of the additional parameters needed and echo this information into the output files. This is done in the following steps:

(a) read parameters from the *.igr and *.isd input files
(b) choose particle diameter (cm), fall velocity (cm/s) and particle density (g/cm^3) from the internal data base or if the particle class is not in the database, calculate values using Fair and Geyer method (1954) based on Stokes (note: all units in SI)
(c) if particle is fine(d_p<37 mm) don't run the wedge part (COARSE=0.D0)
(d) output some input values here and leave the rest for the INPUTS subroutine
(e) print heading for tables in output files

1.5 INPUTS(N,NBAND,NRAIN,RAIN,NBCROFF,BCROFF,TE,QMAX,VL, FWIDTH,PGPAR,VKS,NCHK,LISFIL)

This subroutine reads in the main parameters of the overland flow and infiltration sub-models, calculates some of the additional simulation parameters needed and echo this information into the output files. This is done in the following steps:

(a) read parameters from the *.ikw input file, assign nodes to the X values for each surface segment and calculate elemental Manning's a's
(b) calculate filter main slope, Sc and roughness for sediment calculations
(c) check if N is compatible with type of shape function selected and if not print message
(d) read rainfall distribution from *.irn
(e) read soil inputs from *.iso and calculate Green-Ampt parameters
(f) get downslope node for flood checking (SCHK)
(g) read runoff inflow at upper side of strip (BC) in (m^3/s) from *.iro
(h) find the bandwidth for the matrix, number of elements and number of nodes
(i) calculate convergence and wave form parameters (CR, C, FR, FK)
(j) calculate the PG Parameters from the Courant number values
(k) set the order of the integration rule
(l) output parameters

l-2. output hydrological and numerical parameters
l-1. output nodal information if selected (ielout=1)
l-2. output values for sediment transport (read previously in GRASSIN)
(m) issue a warning if any of the criteria (CR, FR, FK) is not met
(n) print heading for tables in output files

1.6 QUAD

Get the Gaussian Quadrature points for orders 1 through 5.

1.7 FORMA(A,NBAND,PGPAR)

This subroutine assembles the system matrix [A] as a banded matrix. This procedure involves the calculation of element matrices EK (subroutine ELEM) and their accumulation in the banded system matrix [A] (subroutine ASSM). Finally we end up by plugging in the BC for the problem (subroutine BCA).

1.8 ELEM(EK,PGPAR)

Form the element arrays EK:
(a) first initialize the element arrays
(b) begin integration point loop for the Gauss quadrature rule
        b-1. obtain shape function values
        b-2. get the value for each element of the array

1.9 SHAPE(XIS,PSI,DPSI,WF,PGPAR)

Calculate the values of the weighting and basis functions PSI, and their derivatives DPSI with respect to the master element coordinates at a specified value of XIS. A typical element $[x_1, x_{k+1}]$ consisting of k+1 nodes $x_1,..., x_{k+1}$ is always normalized into the master element $[-1,1]$ by the transformation over a typical element $[x_1, x_{k+1}]$, and there exist k+1 element shape functions PSI (each is a polynomial of degree k). The type of shape function used (linear, quadratic, modified quadratic and cubic) is selected according to NPOL

1.10 ASSM(A,EK,NBAND,NEL)

This subroutine adds the EK's to the global matrix [A]

1.11 BCA(A,NBAND)

Plug in first kind of BC (Dirichlet) in the system matrix [A]

1.12 FACTOR (A,N,NBAND)

Perform the lower and upper decomposition (LUD) over the system matrix [A] and store the lower and upper triangular matrices on the old [A] matrix

1.13 GASUB(TIME,DT,L,R,RAIN,NEND,TRAI)

This subroutine solves the infiltration problem for unsteady rainfall case using the Green-Ampt infiltration model. After ponding at the surface is detected the infiltration is allowed to reach its maximum potential for the rest of the run.   The assumption here is that the incoming field runoff moving at the surface will supply enough water to sustain the maximum infiltration for that time step. This means that the effective rainfall fed into the kinematic wave equation (*ie*) will be in most cases a negative value. The procedure is as follows:

(a) check if the end of runoff has been reached

(b) check for surface ponding at beginning (yes, NPOND=1; no, NPOND=0)

        b-1. without surface ponding at the beginning of the period (NPOND=0)

                b-1.1. with ponding at the end of the period (Cu >0)

                b-1.2. no ponding at the end of the period (Cu <0)

                b-1.3. Find values at the limit of this rainfall period regardless of time step

        b-2. with surface ponding at the beginning of the period (NPOND=1)

(c) return *ie* value to be used in that time step.

1.14 FORMB(B0,X0,Q0,N,BCRO,PGPAR)

In this subroutine the right hand side part of the matrix equation (vector b) is assembled in the following steps:

(a) find dx1 for integration rule

(b) initialize vector {b}

(c) begin vector formation element by element

        c-1. Initialize temporary vectors

        c-2. do integration point loop

        c-3. plug the element vector into the {b0} vector

(d) Plug in the boundary condition b(1)=BCRO

1.15 MODIFY(QM,B,BCRO,PGPAR)

In this subroutine the right hand side part of the equation (vector {b}) is assembled following the procedure discussed by Vieux et al (1990):
(a) find dx_1 for integration rule
(b) begin vector formation element by element
  b-1. do integration point loop
  b-2. plug the element vector into the {b} vector
(c) plug in the boundary condition b(1)=0

1.16 SOLVE(A,B,X,N,NBAND)

Solve the LUD transformed matrix [A] using a backward and forward substitution with:

  [A] {X} = {b}

since, [A]= [L].[U] then [L][U]{X} = [L]([U]{X})= [L]{Y}= {b}
solving, [L]{Y}=b (forward substitution)
  [U]{X}=y (backward substitution)

1.17 CONVER(N,X,XM,MFLAG)

This subroutine checks for convergence as:

$$\frac{max(X^{m+1} - X^m)}{max(X^{m+1})} \leq \varepsilon(10^{-8})$$

If there is convergence return MFLAG=1, otherwise MFLAG=0

1.18 UPDATE(N,X,X0)

Refresh values of the X vector, this is: $X^l = X^{l+1}$

1.19 FLOW(N,XT,QT)

Calculate the flow vector at each iteration or time step by using Manning's equation.

1.20 GRASSED(TIME,N,QIN,NODEX,ICOARSE, COARSE)

This subroutine is the driver for the sediment transport problem on grass filter strips. Notice that all units are CGS system (cm,g,s), including Manning's *n*, to follow the original method as described by the authors (Tollner et al., 1977; Barfield et. al, 1979; Hayes et. al, 1979, 1984; Wilson et al, 1981). For computational purposes the filter is divided into the following sections (notice the change in properties as sediment is deposited): A(t): top flat face of sediment wedge; B(t): downface of sediment wedge; C(t) & D(t): effective filter.

The calculation procedure is as follows:

(a) select flow and sediment load at filter entry. If strip was filled up in a previous step (NFUP=1), bypass sediment deposition calculations, add incoming and outgoing mass to totals and RETURN to main program.

(b) calculate the hydraulic properties at points (1), (2), (3) the filter to be used later on (subroutine OCF)

(c) solve Einstein's bed load transport equation to find the transport capacity (g_{s2}) at the end of B(t) (subroutine EINSTEIN)

(d) calculate shape of sediment wedge, sediment outflow, and trapping efficiency for the filter (subroutine STEP3)

(e) position points (1), (2), (3) at system nodes so that flow rates can be read at those points at next time step (subroutine POINTS)

(f) write outputs of sediment transport calculations.

1.21 OCF(NPLACE)

This subroutine solves the hydraulic properties for each of the filter's singular points by using Manning's equation and open channel flow theory. It utilizes the method proposed by Barfield et. al (1979) where the known values are S_s (spacing of the filter media elements, cm), S_c (filter main slope), *n* (Manning's for cylindrical media, s/cm$^{1/3}$), q_k (unit overland flow rate at the given point *k*, cm^2/s) and the unknowns are d_f (depth of flow at D(t), cm), V_m (depth averaged velocity at D(t), cm/s), R_s (hydraulic radius of the filter, cm). Notice that all units are in CGS system (cm,g,s), including Manning's *n*. The following steps are followed:

(a) flow depth and velocity set to zero for no flow at any given point

(b) otherwise, calculate R_s, V_m and d_f for the given point

(c) the resulting equation is solved by the Newton-Raphson iterative method

1.22 EINSTEIN(GS2,NTRCAP,COARSE)

This program solves Einstein's bed load transport equation to find the sediment transport capacity (g_{sd}) at the end of C(t) by following the method proposed by Barfield et. al (1979), where known values are d_p (particle size diameter, cm), S_c (filter main slope), R_s (hydraulic radius of the filter at D(t), cm), g, g_s (water and sediment weight density, g/cm$_3$), *g* (acceleration due to gravity, 980 cm/s$_2$), COARSE (% of particles from incoming sediment with diameter > 0.0037 cm, i.e. coarse fraction that will be routed through

wedge); and the unknown is g_{s2} (g_{sd}) (sediment transport capacity or sediment load entering downstream section, g/s/cm). Notice that all units in CGS system (cm,g,s). The following steps are implemented:

(a) check if the transport capacity is lower than concentration

  a-1. if lower deposition at the wedge occurs (first part of subroutine STEP3)

  a-2. if higher, there is enough energy to transport sediment through the wedge and no deposition occurs, all sediment is transported to the suspended sediment zone (zones C(t) and D(t)) (2nd part of subroutine STEP3)

1.23 STEP3(GS2,TIME,NTRCAP,COARSE)

This program solves STEP3 of the sediment transport problem after Barfield et al. (1979) and Hayes et al. (1984). The outputs from this part of the problem are: f (sediment fraction trapped in the deposition wedge); $X_1(t)$, $Y(t)$, $X_2(t)$ (sediment wedge geometry); *DEP* (depth of deposited sediment at lower section of the filter); T_r (sediment trapping efficiency). The procedure is as follows:

(a) if sediment transport capacity (g_{s2}) is greater than the fine sediment load fraction, g_{sim} (diameter>0.0037cm) all sediment goes through the wedge to the lower part of the filter (ntrcap=1).

(b) if transport capacity is lower than the fine sediment load fraction, then the FINE fraction goes through the wedge and the COARSE fraction is filtered at the wedge

(c) apply open channel flow theory and Einstein's bed load transport equation in B(t), find df, R_{ss}, S_e (Newton-Raphson method)

(d) find advancement of sediment front and outflow concentration

  d-1. if top of vegetation has not been reached, calculate the triangular wedge geometry.

  d-2. trapezoidal wedge geometry

(e) check if strip has been filled up. If so set flag NFUP=1, change sediment wedge geometry to a rectangle of hight H and length VL and bypass GRASSED in the future. Also, in this case avoid suspended sediment zone calculations.

(f) on the assumption that the trapped sediment is uniformly distributed on the bed of the filter's lower section area, calculate DEP, depth of sediment deposited for that Dt, and CDEP as a multiplier to reduce the actual sediment outflow, g_{so}(Wilson et al. 1981).

(g) write outputs

(h) update values for next time step

1.24 POINTS(N,XPOINTS,NODEX,VBT)

This program finds a_k (in uniform flow equation), X_1 (mid-point of downface of sediment wedge, cm), X_2 (bottom point of downface of sediment wedge, cm), X_3 (mid-point of effective filter length L(t), cm) and their associated *NODEX(i)* (nodes for the X_i points) to feed back to the overland flow submodel. The procedure is as follows:

(a) find points for each of the areas in filter

(b) if required reshape the surface topography and roughness of the filter. Notice that for entry a 0 slope value is not possible, thus a minimum SCENTRY=0.005 is chosen. The new values assigned are:
- Section A: slope=Sc, n=VN_2 (bare)
- Section B(t): slope=Set, n=VN$_2$, length VBT
- Sections C(t) & D(t): slope= unchanged, n= unchanged, length VLT

1.25 KWWRITE(N,L,M,QTEMP,X,BCRO,FWIDTH)

Write hydrology outputs to the *.oh*y file as a hydrograph, i.e. flow rate at the downstream end of the plane.

1.26 OUTMASS(VL,FWIDTH,TRAI,LISFIL)

This subroutine processes the output hydrograph and calculates the components of the water and sediment balance. The results are written to the summary file *.osm* and *.osp*.

2. APPENDIX 2: Model parameters and variables

2.1 Overland flow

A(I,J)	system matrix, square of dimensions nxn, ie. *[A]*
B(I)	right hand side vector of dimensions 1xn , ie *{b}*
BCRO	time-interpolated water depth at the first node of the system (m)
BCROFF(200,2)	boundary condition at the upstream node: time (s) vs. depth (m).
BCROFFQ	inflow hydrograph (m3/s) read from input file ROFFKW.IN
C	celerity of the wave (m/s)
DPSI(I)	derivative of the i-th shape (basis) function at XI
DR	duration of the simulation (s)
DT	increment of time (s)
DTC	Courant time step for the numerical solution
DX	space step (m)
DR	duration of the rain (s)
DX1	distance between nodes in element
EK(I,J)	entry in element stiffness matrix
EPS	convergence criteria (set to 10-8 in the program)
FK	kinematic flow number
FR	Froude number
FWIDTH	width of the strip (m)
HMAX	maximum flow depth at steady-state condition
MAXITER	maximum number of iterations alowed
MFLAG	convergence flag (0, no convergence; 1, convergence)
N	actual number of nodes in the domain
NBAND	bandwidth for the *[A]* matrix,
NDT	number of time steps
NELEM	actual number of elements in the domain
NL	order of the integration rule over each element
NMAX	maximum number of equations and variables that can be solved
NPOL	number of nodal points over each element (polynomial degree +1)
PGPAR(I)	Petrov-Galerkin parameters (i=1,4)
PSI(I)	i-th shape function at XI
QK(MAXEQN)	nodal a in Manning's uniform flow equation
QM(N)	flow vector at iteration m (cm2/s)
Q0(N)	flow vector at previous time step (cm2/s).
QMAX	maximum flow rate at steady-state condition (cm2/s)
R	rainfall excess at the node (lateral inflow) (m/s)
RNA(I)	Manning's roughness coefficient (s.m-1/3)
SOA(I)	slope of the element
SR	duration of the simulation (s)
SWIDTH	Source area width (m)
SLENGTH	Source area flow path length (m)
SX(I)	Distance from origin to the start of the i-th surface segment (m)

TE	Henderson's time to equilibrium (s)
THETAW	time-weight factor
VL	Filter length (m)
VN1	Mean filter Manning's roughness coefficient (s.m-1/3)
W(5,5)	Gauss quadrature weights
WF(I)	modified weighting functions
X(5,5)	solution vector, dimension 1xn, at time step l+1
XI(5,5)	Gauss quadrature point
XM(N)	solution vector {*xn*}, at iteration m, time step l+1
X0(N)	solution vector{*xn*}, at time step l

2.2 Infiltration

AGA	Green-Ampt's "A", saturated hydraulic conductivity, Ks (m/s)
BGA	Green-Ampt's "B" = Ks*Sav*M (m2/s)
CP	Chu's surface condition indicator for ponding at initial time
CU	Chu's surface condition indicator for no-ponding at initial time
DM	initial soil-water deficit (M)
F	cumulative infiltration (m)
FPI	cumulative infiltration when the end to ponding in reached (m)
L	rainfall period
LO	index to show if time step is in the same rainfall period (LO=L)
NCHK	Node number for flood checking
NPOND	flag for ponded (=1) non-ponded (=0) surface conditions
NEND	indicates that the end of runoff is reached
OI	initial soil-water content
OS	saturated soil-water content
PS	cumulative precipitation in m.
PSOLD	cumulative precipitation in m for last rainfall period.
PST	total cumulative precipitation in m.
RAIN(50,2)	time (s) and rainfall rate (m/s) over the VFS for each period.
RO	cumulative runoff rate at the node (without considering BCRO)
SCHK	relative distance from de upper filter edge where the check for ponding conditions is made (i.e. 1= end filter, 0.5= mid point, 0= beginning)
RPEAK	Maximum rainfall intensity for the storm
SAV	Green-Ampt's average suction at wet front(m)
SM	maximum surface storage (m)
STO	cumulative surface storage (m)
TP, TPP	Chu's (1978) tp and tp' coefficients
TI	time to infiltrate surface ponded water
TRAI	Total cumulative rainfal (m)
VKS	Saturated hydraulic conductivity (m/s)

2.3 Sediment transport

CDEP	Coefficient for reducing suspended sediment deposition in D(t)
CI	sediment inflow concentration (g/cm3)
COARSE	% of coarse particles (>37 microns) in incoming sediment.
ICOARSE	Flag, 0= all particles fine(<37 microns) don't run the wedge part.
DF	depth of flow at D(t) (cm)
DEP	depth of sediment deposited in suspended sediment zone D(t) (cm)
DFS	depth of flow at B(t) (cm)
DP	particle size, diameter (cm)
F	fraction trapped in the deposition wedge
FWID	width of the strip (cm)=FWIDTH/100
GAMMAW	water weight density (g/cm3)
GAMMASB	sediment weight density (g/cm3)
GSI	sediment load entering before field deposition, gsI: (g.s-1cm-1)
GSSI	sediment load entering the filter after field depos., gsi: (g.s-1cm-1)
GS2	sediment load entering downstream section, gsd: (g.s-1cm-1)
GSO	sediment load exiting the filter, gso: (g.s-1cm-1)
H	filter media height (cm)
NFUP	Flag, 0=strip is not filled-up, 1=strip is filled-up
NODEX(J)	node number for X1, X2, X3 points
PART(1)	sediment class diameter (cm)
PART(2)	sediment class fall velocity (cm/s)
PART(3)	sediment class weight density (g/cm3)
POR	porosity of deposited sediment
QSED(J)	overland flow rate for X1, X2, X3 points (cm2/s)
RS	hydraulic radius of the filter (cm)
RSS	hydraulic radius of the filter at B(t) (cm)
SE	equilibrium slope at B(t)
SS	spacing of the filter media elements (cm)
SC	filter main slope
VLCM	filter length in cm.
VM	depth averaged velocity at D(t)(cm/s)
VMS	depth averaged velocity at B(t) (cm/s)
VN	filter media Manning's, n= 0.012 for cylindrical media (s.cm-1/3)
VN2	Filter Manning's roughness coefficient for bare (sediment inundated) soil (s.cm-1/3)
XPOINTS(J)	Position for the 3 locations where de flow is read from the hydrology model (q1, q2, q3) at the 3 last faces of the filter (cm)
XT	X2=XPOINTS(2) (cm), width of sediment wedge from field edge
X1	width of sediment wedge in the field (cm)
YT	height of sediment deposition wedge at the initial triangular stage

3. APPENDIX 3: Soils and Vegetation data

3.1 Soils data (Green-Ampt parameters)

The model developers encorage the users to obtain the soil inputs for the model based on sail samples taken on site. If that is not possible or the model is applied to study the effect of soil type on the effectiveness of the VFS, the following table gives values for the Green-Ampt parameters as suggested by Rawls and Brakensiek (1983).

Soil Texture (USDA)	K_s (m/s) x10^{-6}	S_{av}(m)	$Porosity \approx \theta_s (m^3/m^3)$
Clay	0.167	0.0639-1.565 (0.3163)	0.427-0.523 (0.475)
Sandy-clay	0.333	0.0408-1.402 (0.2390)	0.370-0.490 (0.430)
Clay-Loam	0.556	0.0479-0.9110 (0.2088)	0.409-0.519 (0.464)
Silty-Clay	0.278	0.0613-1.394 (0.2922)	0.425-0.533 (0.479)
Silty-clay-loam	0.556	0.0567-1.315 (0.2730)	0.418-0.524 (0.471)
Sandy-clay-loam	0.833	0.0442-1.080 (0.2185)	0.332-0.464 (0.398)
Loam	3.67	0.0133-0.5938 (0.0889)	0.375-0.551 (0.463)
Silt-loam	1.89	0.0292-0.9539 (0.1668)	0.420-0.582 (0.501)
Sandy-loam	6.06	0.0267-0.4547 (0.1101)	0.351-0.555 (0.453)
Loamy-sand	16.6	0.0135-0.2794 (0.0613)	0.363-0.506 (0.437)
Sand	65.4	0.0097-0.2536 (0.0495)	0.374-0.500 (0.437)

Note: Values in parenthesis are mean values. For an alternative source of Green-Ampt soil parameters see also McCuen et al. (1981).

3.2 Manning's roughness coeficient, *n*

There are several publications dedicated to the stimation of this important parameter for overland flow routing (see Arcement et al., 1989). A summary of the most common values used in overland flow routing can be taken from Engman (1986), as:

Cover	Manning's n range (recommended)
Bare sand	0.01-0.013 (0.011)
Bare clay-loam (eroded)	0.012-0.033 (0.02)
Fallow - no residue)	0.006-0.16 (0.05)
Range (natural)	0.01-0.32 (0.13)
Range (clipped)	0.02-0.24 (0.10)
Grass (bluegrass sod)	0.39-0.63 (0.45)
Short grass prairie	0.10-0.20 (0.15)
Dense grass[a]	0.17-0.30 (0.24)
Bermuda grass	0.30-0.48 (0.41)

[a]Weeping lovegrass, bluegrass, buffalo grass, blue gramm grass, native grass mix (OK), alfalfa, lespedeza

3.3 Vegetation types for VFS's

The following data on vegetation is taken from Haan et al. (1994).

Vegetation (good stand)[a]	Density (stems/m^2)	Grass spacing S_s (cm)	Maximum height, H (cm)	Modified n n_m
VEGETATION TYPICALLY RECOMMENDED FOR VFS				
Yelow bluestem	2700	1.9	--	--
Tall fescue	3900	1.63	38	0.012
Blue gramma	3750	1.65	25	0.012
Ryegrass (perennial)	3900	1.63	18	0.012
Weeping lovegrass	3750	1.65	30	--
Bermudagrass	5400	1.35	25	0.016
Bahiagrass	--	--	20	0.012
Centipedegrass	5400	1.35	15	0.016

Vegetation (good stand)[a]	Density (stems/m^2)	Grass spacing S_s (cm)	Maximum height, H (cm)	Modified n n_m
Kentucky bluegrass	3750	1.65	20	0.012
Grass mixture[b]	2150	2.15	18	0.012
Buffalograss	4300	1.5	13	0.012
VEGETATION NOT RECOMMENDED FOR VFS[c]				
Alfalfa	1075	3.02	35	0.0084
Sericea lespedeza	650	3.92	40	0.0084
Common lespedeza	325	5.52	13	0.0084
Sudangrass	110	9.52	--	0.0084

a. To convert densities for good stand to other stands, multiply the given densities by 1/3, 2/3, 1, 4/3 and 5/3 for poor, fair, good, very good and excellent covers

b. Values vary depending on mixture. If a given grass type predominates, values for that species should be used.

c. Values of Ss above 2.5 cm can cause scour and are not recommended.

3.4 NRCS (SCS) Curve Numbers

Runoff curve numbers for urban areas[1] (From USDA-NRCS; 210-VI-TR-55, 2nd Edition, June 1986, Table 2-2a)

Cover Description		Curve Numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area[a]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)[b]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only)[c]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with l- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84

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1. Average runoff condition, $I_a = 0.2S$.

Cover Description		Curve Numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area[a]	A	B	C	D
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation)[d].		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c)					

a. The average percent Impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using area weighted averages for the CN's of the respective subareas. Or see figures 2-3 or 2-4 (TR55 document).

b. CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space covertype.

c. Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 (TR55 document) based on the impervious area percentage (CN 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.

d. Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 (TR55 document) based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Runoff curve numbers for cultivated agricultural lands.[1] (From USDA-NRCS; 210-VI-TR-55, 2nd Edition, June 1986, Table 2-2b)

Cover Description			Curve numbers for hydrologic soil group			
Cover Type	Treatment[a]	Hydrologic condition[b]	A	B	C	D
Fallow	Bare soil		77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C+CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	713	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C+CR	Poor	62	73	81	84
		Good	60	72	80	83
		Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

---

1. Average runoff condition, Ia=0.2S.

a. Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

b. Hydraulic condition is based on combination factors that affect Infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good >= 20%), and (e) degree of surface roughness. Poor: Factors impair infiltration and tend to increase runoff. Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Runoff curve numbers for other agricultural lands.[1] (Table 2-2c, From USDA-NRCS; 210-VI-TR-55, 2nd Edition, June 1986)

Cover Description		Curve numbers for hydrologic soil group			
Cover Type	Hydrologic Condition	A	B	C	D
Pasture, grassland, or range-continu- ous forage for grazing[a]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow-continuous grass, pro- tected from grazing and generally mowed for hay.		30	58	71	78
Brush-brush-weed-grass mixture with brush the major element.[b]	Poor	48	67	77	13
	Fair	35	56	70	77
	Good	[c]30	48	65	73
Woods-grass combination (orchard or tree farm).[d]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods.[e]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	d30	55	70	77
Farmsteads-buildings, lanes, drive- ways, and surrounding lots.		59	74	82	86

a. Poor,- <50%) ground cover or heavily grazed with no mulch. Fair: 50 to 75% ground cover and not heavily grazed. *Good:* 75% ground cover and lightly or only occasionally grazed.

b. Poor: <50% ground cover. Fair: 50 to 75% ground cover. *Good:* >75% ground cover.

c. Actual curve number is less than 30; use CN = 30 for runoff computations.

d. CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

e. Poor: Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning. Fair: Woods are grazed but not burned, and some forest litter covers the soil. *Good:* Woods are protected from grazing, and litter and brush adequately cover the soil.

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1. Average runoff condition, and Ia = 0.2S.

Runoff curve numbers for arid and semiarid rangelands[1] (Table 2-2d, From USDA-NRCS; 210-VI-TR-55, 2nd Edition, June 1986)

Cover Description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic Condition[a]	A[b]	B	C	D
Herbaceous-mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
aspen, mountain mahogany, bitter brush, maple, and other brush.	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper-pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub-major plants include saltbush, greasewood, creosote-bush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

a. Poor: <30% ground cover (litter, grass, and brush overstory); Fair: 30 to 70% ground cover; Good: >70% ground cover.
b. Curve numbers for group A have been developed only for desert shrub.

1. Average runoff condition, and Ia=0.2S. For range in humid regions, use Table 2-2c

3.5 MUSLE Crop factor C

Soil loss ratios (CFACT) to describe the effects of cropping management (From 1992 GLEAMS User Manual, Knisel et. al. 1992).

No	Cover, Crop Sequence, and manmagement[a]	Spring Residue[b]	Cover After Plant[c]	Soil loss ratio[d] for cropstage period and canopy cover[e]							
				F	SB	1	2	3:80	90	96	4L[f]
		LB	%	%							
	Corn after C, GS, G or COT In Meadowless Systems										
1	Rdl, sprg TP	4500	-	31	55	48	38	-	-	20	23
2		3400		36	60	52	41	-	24	20	30
3		2600	-	43	64	56	43	32	25	21	37
4		2000	-	51	68	60	45	33	26	22	47
5	Rdl, fall TP	HP	-	44	65	53	38	-	-	20	-
6		GP	-	49	70	57	41	-	24	20	-
7		FP	-	57	74	61	43	32	25	21	-
8		LP	-	65	78	65	45	32	26	22	-
9	RdR, sprg TP	HP	-	66	74	65	47	-	-	22	56[g]
10		GP	-	67	75	66	47	-	27	23	62
11		FP	-	68	76	67	48	35	27	-	69
12		LP	-	69	77	68	49	35	-	-	74
13	RdR, fall TP	HP	-	76	82	70	49	-	-	22	-
14		GP	-	77	83	71	50	-	27	23	-
15		FP	-	78	85	72	51	35	27	-	-
16		LP	-	79	86	73	52	35	-	-	-
17	Wheeltrack pl, RdL, TP[h]	4500	-	-	31	27	25	-	-	18	26
18		3400	-	-	36	32	30	-	22	18	30
19		2600	-	-	43	36	32	29	24	19	37
20		2000	-	-	51	43	36	31	24	20	47
21	Deep offset disk or plow	4500	10	-	45	38	34	-	-	20	23
22		3400	10	-	52	43	37	-	24	20	30
23		2600	5	-	57	48	40	32	25	21	37
24		2000	-	-	61	51	42	33	26	22	47
25	No-till plant in crop residue[i]	6000	95	-	2	2	2	-	-	2	14
26		6000	90	-	3	3	3	-	-	3	14
27		4500	80	-	5	5	5	-	-	5	15
28		3400	70	-	8	8	8	-	8	6	19
29		3400	60	-	12	12	12	12	9	8	23
30		3400	50	-	15	15	14	14	11	9	27
31		2600	40	-	21	20	18	17	13	11	30
32		2600	30	-	26	24	22	21	17	14	36

No	Cover, Crop Sequence, and manmagement[a]	Spring Resi-due[b]	Cover After Plant[c]	Soil loss ratio[d] for cropstage period and canopy cover[e]
				F	SB	1	2	3:80	90	96	4L[f]
		LB	%	%							
	Chisel, shallow disk, or fld cult, as only tillage										
33	On moderate Slopes	6000	70	-	8	8	7	-	-	7	17
34			60	-	10	9	8	-	-	8	17
35			50	-	13	11	10	-	-	9	18
36			40	-	15	13	11	-	-	10	19
37			30	-	18	15	13	-	-	12	20
38			20	-	23	20	18	-	-	16	21
39	On moderate slopes	4500	70	-	9	8	7	-	-	7	18
40			60	-	12	10	9	-	-	8	18
41			50	-	14	13	11	-	-	9	19
42			40	-	17	15	13	-	-	10	20
43			30	-	21	18	15	-	-	13	21
44			20	-	25	22	19	-	-	16	22
45	Do.	3400	60	-	13	11	10	-	10	8	20
46			50	-	16	13	12	-	12	9	24
47			40	-	19	17	16	-	14	11	25
48			30	-	23	21	19	-	17	14	26
49			20	-	29	25	23	-	21	16	27
50			10	-	36	32	29	-	24	20	30
51	Do.	2600	50	-	17	16	15	15	13	10	29
52			40	-	21	20	19	19	15	12	30
53			30	-	25	23	22	22	18	14	32
54			20	-	32	29	28	27	22	17	34
55			10	-	41	36	34	32	25	21	37
56	Do.	2000	40	-	23	21	20	20	15	12	37
57			30	-	27	25	24	23	19	15	39
58			20	-	35	32	30	28	22	18	42
59			10	-	46	42	38	33	26	22	47
60	On slopes>12%, lines 33-59 times factor of:	-	-	-	1.3	1.3	1.1	1.0	1.0	1.0	1.0
	Disk or harrow after spring chisel or field cultivation: lines 33-59 times:										
61	On moderate slopes	-	-	-	1.1	1.1	1.1	1.0	1.0	1.0	1.1
62	On slopes> 12%	-	-	-	1.4	1.4	1.2	1.0	1.0	1.0	1.0
	Ridge Plant[j]: lines 33-59 times factor of:										
63	Rows on contour[k]	-	-	-	0.7	0.7	0.7	0.7	0.7	0.7	0.7

No	Cover, Crop Sequence, and manmagement[a]	Spring Resi-due[b]	Cover After Plant[c]	Soil loss ratio[d] for cropstage period and canopy cover[e]							
				F	SB	1	2	3:80	90	96	4L[f]
		LB	%	%							
64	Rows U/D Slope<12%	-	-	-	0.7	0.7	1.0	1.0	1.0	1.0	1.0
65	Rows U/D Slope>12%	-	-	-	0.9	0.9	1.0	1.0	1.0	1.0	1.0
	Till Plant: limes 33-59 times factor of:										
66	Rows on contour	-	-	-	0.7	0.85	1.0	1.0	1.0	1.0	1.0
66	Rows U/D slope<7%	-	-	-	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Strip Till 0.25 of row spacing:										
68	Rows on contour	4500	60[l]	-	12	10	9	---	---	8	23
69		3400	50	-	16	14	12	---	11	19	27
70		2600	40	-	22	19	17	17	14	12	30
71		2000	30	-	27	23	21	20	16	13	36
72	Rows U/D Slope	4500	60	-	16	13	11	-	-	9	23
73		3400	50	-	20	17	14	-	12	11	27
74		2600	40	-	26	22	19	17	14	12	30
75		2000	30	-	31	26	21	20	16	13	36
	Vari-Till:										
76	Rows on Contour	3400	40	-	13	12	11	-	-	11	22
77		3400	30	-	16	15	14	14	13	12	26
78		2600	20	-	21	19	19	19	16	14	34
	Corn after WC of ryegrass or wheat stubble. WC reaches stemming stage										
79	No-till pl in killed WC	4000	-	-	7	7	7	-	7	6	m
80		3000	-	-	11	11	11	11	9	7	
81		2000	-	-	15	15	14	14	11	9	
82		1500	-	-	20	19	18	18	14	11	
	Strip till 0.25 space										
83	Rows U/D slope	4000	-	-	13	12	11	-	11	9	
84		3000	-	-	18	17	16	16	13	10	
85		2000	-	-	23	22	20	19	15	12	
86		1500	-	-	28	26	24	22	17	14	
87	Rows on contour	4000	-	-	10	10	10	-	10	8	
88		3000	-	-	15	15	15	15	12	9	
89		2000	-	-	20	20	19	19	15	12	
90		1500	-	-	25	24	23	22	17	14	
91	Tp, conv. seedbed	4000	-	36	60	52	41	-	24	20	
92		3000	-	43	64	56	43	31	25	21	
93		2000	-	51	68	50	45	33	26	22	
94		1500	-	61	73	64	47	35	27	23	

No	Cover, Crop Sequence, and manmagement[a]	Spring Resi-due[b] LB	Cover After Plant[c] %	F	SB	1	2	3:80	90	96	4L[f]
								%			
	WC succulent blades										
95	No-till pl in killed WC	3000	-	-	11	11	17	23	18	16	
96		2000	-	-	15	15	20	25	20	17	
97		1500	-	-	20	20	23	26	21	18	
98		1000	-	-	26	26	27	27	22	19	
99	Strip till 0.25 row sp	3000	-	-	18	18	21	25	20	17	
100		2000	-	-	21	21	25	27	21	18	
101		1500	-	-	28	28	28	28	22	19	
102		1000	-	-	33	33	31	29	23	20	
	CORN in Sodbased systems										
	No-till pl in killed sod:										
103	3-5 tons hay yld	-	-	-	1	1	1	-	1	1	1
104	1-2 tons hay yld	-	-	-	2	2	2	2	2	2	2
	Strip till, 3-5 ton hay										
105	50% cover, till strips	-	-	-	2	2	2	-	2	2	4
106	20% cover, till strips	-	-	-	3	3	3	-	3	3	5
	Strip till, 1-2 ton hay										
107	40% cover, till strips	-	-	-	4	4	4	4	4	4	4
108	20% cover, till strips	-	-	-	5	5	5	5	5	5	5
	Other tillage after sod:			n							
	CORN after Soybeans										
109	Sprg TP, conv till	HP	-	40	72	60	48	-	-	25	29
110		GP	-	47	78	65	51	-	30	25	37
111		FP	-	56	83	70	54	40	31	26	44
112	Fall TP, conv till	HP	-	47	75	60	48	-	-	25	-
113		GP	-	53	81	65	51	-	30	25	-
114		FP	-	62	86	70	54	40	31	26	-
115	Fall & Sprg chisel or cult	HP	30[o]	-	40	35	29	-	-	23	29
116		GP	25	-	45	39	33	-	27	23	37
117		GP	20	-	51	44	39	34	27	23	37
118		FP	15	-	58	51	44	36	28	23	44
119		LP	10	-	67	59	48	36	28	23	54
120	No-till pl in crop resid.	HP	40	-	25	20	19	-	14	11	26
121		GP	30	-	33	29	25	22	18	14	33
122		FP	20	-	44	38	32	27	23	18	40

No	Cover, Crop Sequence, and manmagement[a]	Spring Resi-due[b]	Cover After Plant[c]	Soil loss ratio[d] for cropstage period and canopy cover[e]							
				F	SB	1	2	3:80	90	96	4L[f]
		LB	%	%							
	BEANS after Corn										
123	Sprng Tp, Rdl, conv till	HP	-	33	60	52	38	-	20	17	p
124		GP	-	39	64	53	41	-	21	18	
125		FP	-	45	68	60	43	29	22	-	
126	Fall Tp, Rdl, conv till	HP	-	45	69	57	38	-	20	17	
127		GP	-	52	73	61	41	-	21	18	
128		FP	-	59	77	65	43	29	22	-	
	Chisel or fld cult:			q							
	Beans after Beans			r							
	GRAIN after C, G, GS, COT[s]										
129	In disked residues	4500	70	-	12	12	11	7	4	2	t
130		3400	60	-	16	14	12	7	4	2	
131			50	-	22	18	14	8	5	3	
132			40	-	27	21	16	9	5	3	
133			30	-	32	35	18	9	6	3	
134			20	-	38	30	21	10	6	3	
135	Do.	2600	40	-	29	24	19	9	6	3	
136			20	-	43	34	21	11	7	4	
137			10	-	52	39	27	12	7	4	
138	Do.	2000	30	-	38	30	21	11	7	4	
139			20	-	46	36	26	12	7	4	
140			10	-	56	43	30	13	8	5	
141	In disked stubble, Rdr	-	-	-	79	62	42	17	11	6	
142	Winter G after fall TP, RDL	HP	-	31	55	48	31	12	7	5	
143		GP	-	36	60	52	33	13	8	5	
144		FP	-	43	64	56	36	14	9	5	
145		LP	-	53	68	60	38	15	10	6	
	Grain after Summer Fallow										
146	With grain residues	200	10	-	70	55	43	18	13	11	u
147		500	30	-	43	34	23	13	10	8	
148		750	40	-	34	27	18	10	7	7	
149		1000	50	-	26	21	15	8	7	6	
150		1500	60	-	20	15	12	7	5	5	
151		2000	70	-	14	11	9	7	5	5	

No	Cover, Crop Sequence, and manmagement[a]	Spring Resi-due[b]	Cover After Plant[c]	Soil loss ratio[d] for cropstage period and canopy cover[e]							
				F	SB	1	2	3:80	90	96	4L[f]
		LB	%	%							
152	With row crop residues	300	5	-	82	65	44	19	14	12	
153		500	15	-	62	49	35	17	13	11	
154		750	23	-	50	40	29	14	11	9	
155		1000	30	-	40	31	24	13	10	8	
156		1500	45	-	31	24	18	10	8	7	
157		2000	55	-	23	19	14	8	7	5	
158		2500	65	-	17	14	12	7	5	4	
	POTATOES										
159	Rows with slope	-	-	43	64	56	36	26	19	16	
	Contoured rows, ridged when canopy cover is about										
160	10%	-	-	43	64	28	18	13	10	8	

a. Symbols: B, soybeans; C, corn; conv till, plow, disk and harrow for seedbed; cot, cotton; F, rough fallow; fld cult, field cultivator; G, small grain; GS, grain sorghum; M, grass and legume meadow, at least 1 full year; pl, plant; RdL, crop residues left on field; RdR, crop residues removed; SB, seedbed period; sprg, spring; TP, plowed with moldboard; WC, winter cover crop; ---, insignificant or an unlikely combination of variables.

b. Dry weight per acre after winter loss and reductions by grazing or partial removal; 4500 lbs represents 100 to 125 bu corn; 3400 lbs, 75 to 99 bu; 2600 lbs, 60 to 74 bu; and 2000 lbs, 40 to 59 bu; with normal 30-percent winter loss. For RdR or fall-plow practices, these four productivity levels are indicated by HP, GP, FP, and LP, respectively (high, good, fair, and low productivity). In lines 79 to 102, this column indicates dry weigth of the winter-cover crop.

c. Percentage of soil surface covered by plant residue mulch after crop seeding. The difference betweenn spring residue and that on the surface after crop seeding is reflected in the soil loss ratios as residues mixed with the topsoil.

d. The soil loss ratios, given as percentages, assume that the indicated crop sequence and practices are followed consistently. One-year deviations from normal practices do not have the effect of a permanent change. Linear interpolation between lines is recommended when justified by field conditions. See also footnote 7.

e. Cropstage periods are as defined on p. 18, Agriculture Handbook 537. The three columns for cropstage 3 are for 80, 90, and 96 to 100 percent canopy cover at maturity.

f. Column 4L is for all residues left on field. Corn stalks partially standing as left by some mechn\anical pickers. If stalks are shredded and spread by picker, select ratio from Table ?. When residues are reduced by grazing, take ratio from lower spring-residue line.

g. Period 4 values in lines 9-12 are for corn stubble (stover removed).

h. Inversion plowed, no secondary tillage. For this practice, residues must be left and incorporated.

i. Soil surface and chopped residues for matured preceding crop undisturbed except in narrow slots in which seeds are planted.

j. Top of old row ridge sliced off, throwing residues and some soil into furrow areas. Reridging assumed to occur near end of cropstage 1.

k. Where lower soil loss ratios are listed for rows on the contour, this reduction is in addition to the standard field contouring credit. The P value for contouring is used with these reduced loss ratios.

l. Field-average percent cover; probably about three-fourths of percent cover on undisturbed strips.

m. If again seeded to WC crop in corn stubble, evaluate winter period as a winter grain seeding (lines 132-148). Otherwise, see table E-9.

n. Select the appropriate line for the crop, tillage, and productivity level and multiply the listed soil loss ratios by sod residual factors from table E-10.

o. Spring residue may include carryover from prior corn crop.

p. See table E-9.

q. Use values from lines 33-62 with appropriate dates and lengths of cropstage periods for beans in the locality.

r. Values in lines 109-122 are best available estimates, but planting dates and lengths of cropstages may differ.

s. When meadow is seeded with the grain, its effect will be reflected through higher percentages of cover in cropstages 3 and 4.

t. Ratio depends on percent cover. See table E-9.

u. See item 12, table E-8.

3.6 Contour factor (P) values for MUSLE equation in UH

Contour factors (P Factor) (from Wischmeier and Smith, 1978).

Land Slope (%)	Contour Factor	Maximum Length	
		(ft)	(m)
1 - 2	0.6	400	122
3 - 5	0.5	300	91
6 - 8	0.5	200	61
9 - 12	0.6	120	36
13 - 16	0.7	80	24
17 - 20	0.8	60	18
21 - 25	0.9	50	15

3.7 References for Soils and Vegetation data

References for the above Tables are:

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