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A simplified hillslope erosion model with vegetation elements for practical applications

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Abstract

Soil and water conservation practices are increasingly being considered for curbing non-point source pollution from agricultural land. Several studies have demonstrated that stream power is a simple and good predictor of soil detachment and transport and can be used to predict the effect of soil and water conservation practices on soil loss. Our objective was, therefore, to develop a simple water erosion simulation model that is physically based on stream power, handles vegetation in terms of contact cover, and considers the settling velocity characteristics of the eroding sediment. The model assumes that rill flow can occur on hillslope segments with net erosion, but on segments with net deposition sheet flow is assumed. Input parameters include the depositability of the soil, rill shape, rill density, net precipitation, and an empirical power function describing the decrease of sediment concentration with vegetative cover increase. The model was evaluated by comparison of predicted and observed relationships between sediment concentration, slope, and vegetative residue cover in two experimental studies using simulated rainfall: one that involved erosion plots with various uniform slopes and levels of vegetative cover, and another that involved the observation of soil movement on mechanically shaped concave, uniform, and convex slopes with negligible vegetation. Without calibration, the model appeared to represent soil erosion relationships observed in these studies and is simple enough to be included in grid-based variable source hydrology models.

Keywords: Erosion model; Stream power; Vegetative cover; Complex topography

1. Introduction

Erosion prediction is the most widely used and most effective tool for soil conservation planning and design in the United States (Laflen et al., 1991a; Flanagan and Laflen, 1997). Water erosion is often predicted by using the factor-based Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), or its derivative RUSLE (Renard et al., 1994). However, because the USLE is effectively a data summary that explains soil loss variations statistically, it is not suitable for extrapolation beyond the limits of the data set (Ciesiolka et al., 1995; Foster, 1991). The need for improved soil erosion estimation is underscored by the expanding use of erosion prediction technology in GIS type watershed models in such

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areas as the development and implementation of public policy regarding land management (Foster, 1991; Napier and Johnson, 1998), the evaluation of chemicals transported in surface runoff (Laflen et al., 1991b; Fleming and Cox, 1998), and the identification of sources of sediment that are responsible for a decline in water quality in streams and rivers (Nagle et al., 1999).

As a result, the trend in erosion prediction during this decade has been toward models that focus on physical processes. These models have a greater potential for extrapolation beyond the databases used for development or validation (Rose, 1993), and to simulate sediment movement accurately with fewer calibrated parameters (Bingner, 1990). A major response to this need has been the United States Department of Agriculture (USDA) Water Erosion Prediction Project (WEPP) (Ascough et al., 1997). In WEPP, soil detachment and transport in rills are estimated based on the concept of estimated average shear stress of the water acting on the soil. Prosser et al. (1995) carried out an experimental study which supports ‘the concept of a threshold shear stress below which erosion is effectively prevented’.

Other process-based approaches to modeling water erosion have used the concept of stream power. Stream power was introduced by Bagnold (1977) as the rate of work of overland flow against the shear stress at the soil/water interface. Although a portion of stream power is dissipated primarily as heat, a fraction is effective in erosion. Potentially useful relationships have been found between sediment transport in rills and stream power (McIsaac et al., 1992; Rose, 1993; Nearing et al., 1997). For soils at uniform slope and without vegetative cover, Elliot and Laflen (1993), McIsaac et al. (1992) and Nearing et al. (1997) reported that stream power was a better predictor of sediment detachment and transport from rills than was shear stress. In addition, simulation of the erosion process by stream power can be improved if a distinction is made between the entrainment of cohesive soil and that of the deposited layer (Hairsine and Rose, 1992a; Proffitt et al., 1993). Finally, a process description that incorporates the settling velocity of sediment in flowing water (Marshall et al., 1996) allows consideration of erosion of cohesive sediment possessing a distribution of size classes.

The earlier process based erosion models are parameter intensive and too complex for implementation in watershed models that are used, for example, to design effective conservation plans and for regulatory purposes in land management or evaluation of non-point source loads. For these purposes, the physically based models need to be simplified so that only easily obtainable data is needed. The objective is, therefore, to develop a simple physically based watershed model that can be used to predict erosion and deposition in realistic landscapes that have hill sides with variable slopes and plant cover. The simplified model is based on the concept of stream power and will incorporate the settling velocity characteristics of the soil, as well as the concept of threshold shear stress. It closely follows, therefore, the work of Hairsine and Rose (1992b) as developed by Rose (1993) and that of Prosser et al. (1995). The simplified approach is consistent with grid-based hydrology models. Model output consists of net erosion and net deposition for the different grid sections. It also predicts where rill and sheet flow predominate. In this paper, the model is discussed and its capabilities are demonstrated by qualitative comparison of model prediction with the results of two studies, one involving variable levels of soil residue cover (McIsaac et al., 1990), and another that involves concave, uniform, and complex slopes (Young and Mutchler, 1969).

2. Methods

2.1. Model outline

The model accepts, as input, a series of hillslope segments and handles each segment individually. It estimates the concentration of sediment in overland flow according to the theory developed by Hairsine and Rose (1992a,b) and Rose (1993), which is broadened here to accommodate vegetative cover.

Fundamental to the theory of Hairsine and Rose (1992a) is the concept of stream power, which is the rate of work of overland flow causing the shear stress at the soil/water interface. Stream power (Ω, W/m^2) is given by (Bagnold, 1977) as:

$$\Omega = \rho g S R_{\mathrm{h}} V, \tag{1}$$

where ρ (kg/m^3) is the density of water, g (m/s^2) the acceleration due to gravity, S (m/m) the slope of the land surface, R_h (m) the hydraulic radius of flow (equal to flow depth of no rills), and V (m/s) is the velocity of flow averaged over the rill cross-section.

2.2. Sheet flow

A portion of the stream power is effective in increasing the concentration of sediment in overland flow by the processes of entrainment and re-entrainment. The upper concentration limit, C_t (kg/m^3), has been called the 'transport limit' by Foster (1982). Neglecting the threshold stream power for erosion commencement, Hairsine and Rose (1992a) show that for sheet flow over a plane bare soil surface:

$$C_t = \frac{F\Omega}{\phi g D}\left(\frac{\sigma}{\sigma-\rho}\right) = \frac{F\rho SV}{\phi}\left(\frac{\sigma}{\sigma-\rho}\right), \tag{2}$$

where F is the efficiency, i.e. the fraction of stream power effective in erosion, σ (kg/m^3) is the density of wet sediment, and ϕ (m/s) is the depositability of sediment. Depositability is defined as the average settling velocity (Rose, 1993) given by:

$$\phi = \sum_{i=1}^{I}\frac{v_i}{I}, \tag{3}$$

where v_i (m/s) is the settling velocity of sediment, divided into I equal mass classes.

The model estimates the velocity in Eq. (2) using Manning's equation. As a result, C_t has a further dependency on slope, and is related to the volume of overland flow (which is estimated according to the steady state excess of precipitation with respect to infiltration, an input parameter). After combining Manning's equation with the continuity equation, the model solves for flow depth, D. Then, it uses Manning's equation directly to calculate velocity as a function of slope, S, flow depth, D, and Manning's roughness coefficient, n.

2.3. Rill flow

In many cases, overland flow occurs within rills rather than by sheet flow. By considering the rates of erosion and deposition within rills, a more comprehensive representation of net soil erosion may be obtained (Hairsine and Rose, 1992b). If one assumes rectangular rills of width, W_r (m), within which water flows at depth, D (m), then the transport limit, C_t, is given by Hairsine and Rose (1992b) as:

$$C_t = \frac{F\Omega}{\phi g D}\left(\frac{\sigma}{\sigma-\rho}\right)\left(\frac{W_r}{W_r+2D}\right). \tag{4}$$

The term $W_r/(W_r+2D)$ is added, although the shear stress acts uniformly around the wetted perimeter (W_r+2D), because re-entrainment is assumed to occur from the deposited sediment residing only on the floor of the rill (width, W_r). Additionally, in the case of rill flow, the hydraulic radius is $R_h = W_rD/(W_r+2D)$ (see Eq. (1)). Thus, the expression for the transport limit, C_t, with respect to rectangular rills is:

$$C_t = \frac{F\rho SV}{\phi}\left(\frac{\sigma}{\sigma-\rho}\right)\left(\frac{W_r}{W_r+2D}\right)^2. \tag{5}$$

As with sheet flow, the velocity of flow within rills is estimated using Manning's equation. With rill flow, additional variables are the rill density, N (the number of rills per meter across the slope), and the width-to-depth ratio, f_r (m/m). With rill flow, the volume of flow per rill is important, and because the flow per rill is proportional to $1/N$, changes in the rill density, N, can cause significant changes in flow velocity and, thus, in the transport limit, C_t. The rill width-to-depth ratio, f_r, which is assumed constant even as rills increase in size, is instrumental because it affects the hydraulic radius.

2.4. Vegetation

Vegetative cover generally reduces the sediment concentration in overland flow. Vegetation which is close to the soil surface, termed contact cover, is particularly effective in reducing sediment concentration (Prosser et al., 1995). Specifically, contact cover reduces the rate of soil entrainment and re-entrainment, which results in a lower transport limit.

One way that the contact cover reduces the rate of re-entrainment is by shielding a portion of the deposited layer from overland flow. Thus, the expression by Hairsine and Rose (1992a) for the rate of re-entrainment of sediment of any general size class, i (r_{ri}), is modified by a factor, $(1-C_g)$, in order to accommodate for contact cover to give:

$$r_{ri} = \frac{HF\Omega}{gD}\left(\frac{\sigma}{\sigma-\rho}\right)\frac{M_{di}}{M_{dt}}(1-C_g), \tag{6}$$

where M_{di} is the mass fraction of size class i in the deposited layer, M_{dt} is M_{di} summed over all class sizes, and H represents the coverage due to the deposited layer. $H = 1$ is when the deposit layer is at maximum depth (Heilig et al., 2001). The new term $(1 - C_g)$ indicates the fraction of the soil surface not covered by vegetation, where C_g is the fractional contact cover ($0 \leq C_g \leq 1$, $C_g = 0$ when the soil is bare). Using Eq. (6), re-derivation of the expression for C_t gives:

$$C_t = \frac{F\Omega}{\phi g D}\left(\frac{\sigma}{\sigma - \rho}\right)(1 - C_g). \tag{7}$$

The stream power, Ω, in Eq. (7) is directly affected by the contact cover because the vegetation absorbs a portion of the shear stress normally borne by the soil. Stream power can be derived by adapting Eq. (1) with respect to the degree of contact cover, C_g. If $\tau_s = \rho g S D$ (N/m^2) describes the total surface shear stress, then τ_s can be split into two portions (as suggested by Prosser et al., 1995): τ_{ss}, the shear stress on the soil, and τ_{sc}, the shear stress on the contact cover. The fraction of the total shear stress exerted on the bare soil, τ_{ss}/τ_s, is plausibly some function of the uncovered portion of the soil surface, $(1 - C_g)$. Because the contact cover, C_g, not only shields the portion of bare soil but also reduces velocity and shear stress in the boundary layer, such a function is probably not linear. The following relationship is assumed in the model:

$$\frac{\tau_{ss}}{\tau_s} = (1 - C_g)^p, \tag{8}$$

where p is to be determined by calibrating the model with measured data. Then, the shear stress on the bare soil, τ_{ss}, is:

$$\tau_{ss} = \rho g S D (1 - C_g)^p, \tag{9}$$

and, consequently, the stream power, Ω, effective in erosion in the vegetative cover, is given by:

$$\Omega = \tau_{ss} V = \rho g S D V (1 - C_g)^p, \tag{10}$$

Eq. (10) is substituted into Eq. (7) to obtain the sediment concentration at the transport limit for sheet flow:

$$C_t = \frac{F\rho S V}{\phi}\left(\frac{\sigma}{\sigma - \rho}\right)(1 - C_g)^{p+1}. \tag{11}$$

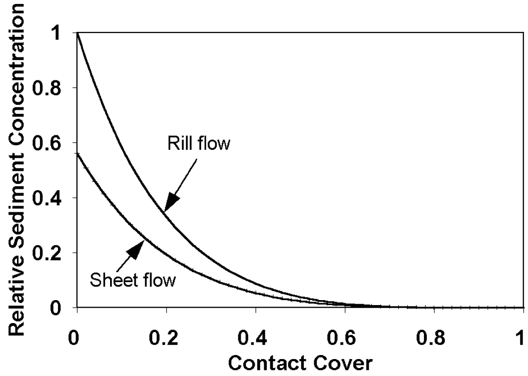

Fig. 1. Sediment concentration at the transport limit versus degree of contact cover for rill and sheet flow.

The transport limit where rill flow occurs can be derived in a similar way, following the form of Hairsine and Rose (1992b). The result is:

$$C_t = \frac{F\rho S V}{\phi}\left(\frac{\sigma}{\sigma - \rho}\right)(1 - C_g)^{p+1}\left(\frac{W_r}{W_r + 2D}\right)^2. \tag{12}$$

Fig. 1 shows the transport limits for sheet and rill flow, i.e. Eqs. (11) and (12), respectively, as functions of the degree of contact cover, C_g. It is clear that both transport limits decline in power form as C_g increases, approaching zero as C_g approaches unity. The transport limit for rill flow, of course, is significantly higher than that for sheet flow, particularly where vegetation is sparse, especially as C_g will normally be smaller once the rills have formed.

Vegetative cover also affects the stream power of overland flow indirectly, by reducing the average velocity of flow. Because velocity is estimated by Manning's formula, such an effect is modeled by correlating Manning's n with the degree of contact cover, C_g. This relationship will, obviously strongly depend on the nature of the vegetative cover. With a hedgerow, Rose et al. (1997) found that n was 0.1 or lower. To illustrate the model, a simple semi-empirical, but conservative estimate of the contact cover on n is obtained by linear interpolation with $n = 0.03$ when $C_g = 0$ (bare soil) and $n = 0.08$ when $C_g = 1$ (full contact cover) so that:

$$n = 0.05C_g + 0.03. \tag{13}$$

The decrease in flow velocity, V, is coupled with an

Table 1
Input values for erosion simulation model

Parameter	Description	Value, McIsaac et al. (1990)	Value, Young and Mutchler (1969)
R	Steady-state net precipitation (precipitation minus infiltration) (mm/h)	64	63.5
f_r	Ratio of rill width to depth	10, 3	10
N	Rill density (rills/m)	1, 7	1
β	Value of β, deposition	1.0	1.0
β	Value of β, erosion	0.8	0.8
ϕ	Depositability (m/s)	0.1	0.1
F	Fraction of stream power effective in erosion	0.1	0.1
C_{min}	Minimum sediment concentration due to vegetation (kg/m^3)	1	1
p	Value of exponent in Eq. (8)	3	3

increase in flow depth, D, so it is not immediately clear that an increase in contact cover causes a decrease in stream power, Ω. It becomes more obvious when stream power is expressed in terms of the flow rate, Q, which remains constant:

$$\Omega = \rho g S V\left(\frac{W_r D}{W_r + 2d}\right) = \rho g S Q\left(\frac{W_r}{W_r + 2D}\right). \tag{14}$$

From Eq. (14) it is clear that the stream power, Ω, will decrease as the flow depth, D, increases due to increased surface roughness.

Use of Manning's formula implies that the flow is turbulent. Obviously, if it were not, some other interpolation, e.g. of the Darcy–Weisbach friction, can be used. For instance, there is good evidence (Prosser et al., 1995) that with dense cover consisting often of dense grass, the Reynolds number might be large enough to suggest turbulent flow, but the dense cover leads to a quasi laminar flow as far as erosion is concerned. On the other hand, when the vegetation is sparse and the residue cover is the main factor, it is most likely safer to assume turbulent flow as over a bare soil.

2.5. Actual concentration

The transport limit, C_t, indicated by Eqs. (11) and (12), is the maximum concentration assumed to occur. Rose (1993) presents a method for relating the actual concentration, C (kg/m^3), to the transport limit, C_t, using a simplified erodibility parameter, β ($0 \leq \beta \leq 1$), given by:

$$\bar{C} = \bar{C}_t^{\beta}, \tag{15}$$

where $\bar{C}$ is the mean sediment concentration measured during an erosion event, and $\bar{C}_t$ is the mean calculated value of the sediment concentration at the transport limit for the same event. The parameter, β, is affected by the cohesive strength of the soil (Misra and Rose, 1995). In the model, β is ascribed two values: a higher value in the transport limiting case, where the sediment concentration approaches the transport limit, and a lower value in the detachment limiting case, where the concentration is significantly below the transport limit.

The value ascribed to the parameter, β, is linked to whether the model predicts net erosion or deposition to occur in the slope segment. Where deposition is predicted to occur, the model selects $\beta = 1$, the theoretically based maximum value. The reason for taking $\beta = 1$ is that with steady-state deposition, the soil will be fully covered by a newly deposited layer of sediment with low cohesive strength, resulting in a transport limited sediment concentration for which, by definition, $\beta = 1$ (Eq. (13)). Where erosion is predicted to occur, the model uses a lower value of β because there is no net deposition of sediment, so that the cohesive strength and the nature of the original soil will control the sediment concentration which will be entrainment-limited.

Whether or not the model predicts rills is also related to whether it predicts erosion or deposition. Where deposition is predicted, sheet flow is assumed, because steady state deposition should fill in irregularities in the soil surface, including irregularities due to rills. Rilling is common where erosion occurs, so erosion with rill flow can be modeled.

At each hillslope segment, the model iterates in order to predict whether erosion or deposition will occur. First, it assumes net erosion and computes the sediment concentration using the lower value of β. Then, it checks its assumption by comparing the sediment flux on the hillslope segment with the sediment flux leaving it. If there is a net loss of sediment, then the assumption of erosion is valid and the model moves on to the next segment. But, if there is a net gain of sediment, then the assumption of erosion is wrong. In this case, the model recalculates the sediment concentration using the higher value of β (i.e. $\beta = 1$) and, again, compares sediment flux on and off the segment.

2.6. Model implementation

The model is written as a Pascal program. The program requires two types of input parameters. The general input parameters (Table 1) include the steady state net precipitation, the hillslope width, the ratio of rill width to rill depth, the rill density where rills occur, low and high values of β, the soil depositability, the fraction of effective stream power, the minimum sediment concentration due to vegetation, and the value of the exponent, p, in Eq. (8). The hillslope segment parameters include the segment length, slope, and fraction of contact vegetation covering the soil surface, C_g. By specifying any sequence of segments of user-defined length, slope, and C_g, the user is able to delineate a variety of complex hillslope profiles. The program output for each hillslope segment includes sediment concentration, net rate of deposition or erosion, depth of overland flow, volume flow rate, velocity of flow, Manning's n, rill width, and the value used for β. The model also produces a graphical output of net erosion and deposition on each segment of the hillslope.

3. Model evaluation and testing

The model's performance was evaluated in two ways. First, we compared model output with data acquired at the Northwestern Illinois Agricultural Research and Demonstration Center in 1984 and 1985 on experimental erosion plots of generally uniform slope (McIsaac et al., 1990). In these experiments, simulated rainfall was applied at a uniform intensity of approximately 64 mm/h to a Tama silt loam soil. Runoff rates were measured volumetrically every 3 min, and 0.5 l runoff samples were collected and gravimetrically analyzed for sediment concentration (McIsaac et al., 1990). The plots were 3 m wide and 11 m long and had varying degrees of residue cover which were quantified by photographic methods. McIsaac et al. (1990) gives a more detailed description of the study. Raw data describing steady state concentration measurements was available from the University of Illinois, and the model was applied to various subsets of the data. Observations from plots having slopes between 5 and 11% with a full range of vegetative cover were investigated. Experiments which included the addition of clear water flow to the top of plots were excluded from our analysis. Data on the number of rills per meter, N, were derived from photographic slides taken at the time of sediment concentration measurement.

The second way that the model was evaluated was to qualitatively compare its predictions for complex slopes with the results of a study in which soil loss and runoff were measured from mechanically shaped concave, uniform, and convex slopes (Young and Mutchler, 1969). Precautions were taken when shaping the slopes to keep the soil surface homogenous. In the study, simulated rainfall at an intensity of 63.5 mm/h was applied to 12 plots 4.1 m wide by 23 m long, each having an average slope of 9%, although local steepness of concave and convex plots ranged from 5 to 15%. The study site was in southeastern South Dakota on a deep loess soil. The plots were plowed, cultivated, dragged, and left fallow for testing. Vegetative cover was negligible. For a complete description of this study see Young and Mutchler (1969).

3.1. Discussion of input parameters

The values of several input parameters selected for the model evaluation are approximations chosen to determine whether the model provides a reasonable representation of observed relationships. If the model appears to approximate observed relationships, then

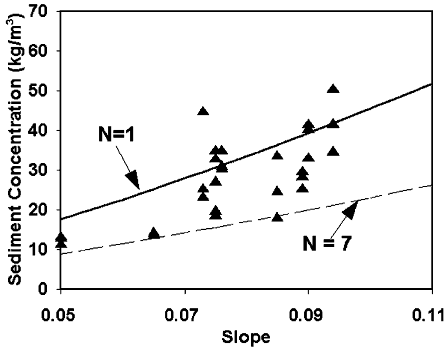

Fig. 2. Sediment concentration versus slope for nearly bare soil. Data points correspond to plots with residue cover less than 10% and canopy cover between 50 and 70%. Model predictions are shown for a rill density of $N = 1$ (solid line) and a rill density of $N = 7$ (dotted line). Data from McIsaac et al. (1990).

further data collection may be justified to more accurately estimate parameters used in the model. Further data would be required to obtain some of the parameters more accurately.

The parameter values used in the evaluation of the study by McIsaac et al. (1990), are listed in the third column of Table 1. The steady state net precipitation was set equal to the simulated rainfall intensity of 64 mm/h, probably a reasonable approximation since the soil was saturated, as indicated by the steady state runoff conditions when the observations were

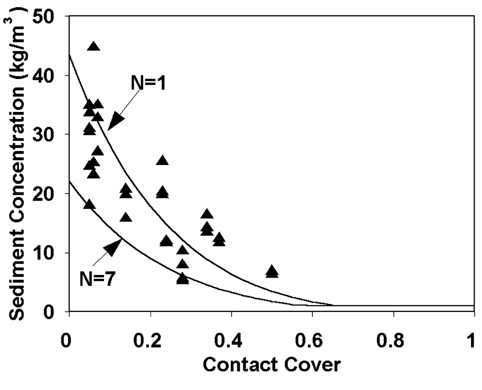

Fig. 3. Sediment concentration versus degree of contact cover. Data points correspond to slopes between 7 and 9%, having canopy cover between 50 and 70%, and tilled up and down the slope. Again, model predictions are shown for rill densities of $N = 1$ and $N = 7$. It is clear in both cases that the predicted sediment concentration approaches C_{min} as C_g approaches unity. Data from McIsaac et al. (1990).

recorded. Two sets of ratios of rill width to depth, f_r, and the rill density, N, were chosen in order to cover a range of rill patterns. The effect of N was simulated by reporting simulations from as high as $N = 7$ rills per meter—beyond which the sediment concentration would be similar to that of sheet flow (Fentie et al., 1997)—to as low as $N = 1$ rill per meter. This range of N values was found to be typical under similar conditions by Gilley et al. (1990). For the simulations presented $f_r = 10$ was adopted with $N = 1$, and $f_r = 3$ with $N = 7$, on the assumption that the less frequent rills would be somewhat wider and shallower, and the more frequent rills would be somewhat narrower and deeper. Rill profiles reconstructed from rill meter measurements supported these assumptions. Where net deposition is predicted, $\beta = 1$ was taken since sediment concentration should be at the transport limit. Where net erosion is predicted, $\beta = 0.8$ was chosen, indicating a significant reduction from the transport limit (Rose, 1993). The depositability, ϕ, is taken to be 0.1 m/s, a typical value for many cultivated soils and conditions (Rose, 1993; Ciesiolka et al., 1995; Marshall et al., 1996). The effective stream power fraction, F, was taken as 0.1, an appropriate value for turbulent flow (Rose, 1993). Based on the data of Hoey et al. (1987), the minimum concentration due to vegetation, C_{min}, was 1 kg/m^3. Finally, the value $p = 3$ was adopted (Eq. (8)) based on an analysis of a set of data describing soil loss with respect to varying levels of contact cover on a tilting flume subjected to simulated rainfall, as presented in Okwach et al. (1992) and Palis et al. (1990).

The values of input parameters chosen in the evaluation with respect to the study by Young and Mutchler (1969), which are listed in the fourth column of Table 1, are less critical because this evaluation was only used a qualitative spatial comparison. All values are the same as above except the steady state net precipitation, which was also taken to be equal to the rainfall intensity, in this case 63.5 mm/h, and the hillslope width of 4.1 m.

4. Results and discussion

4.1. McIsaac et al. (1990) study

In this first model evaluation, predicted and

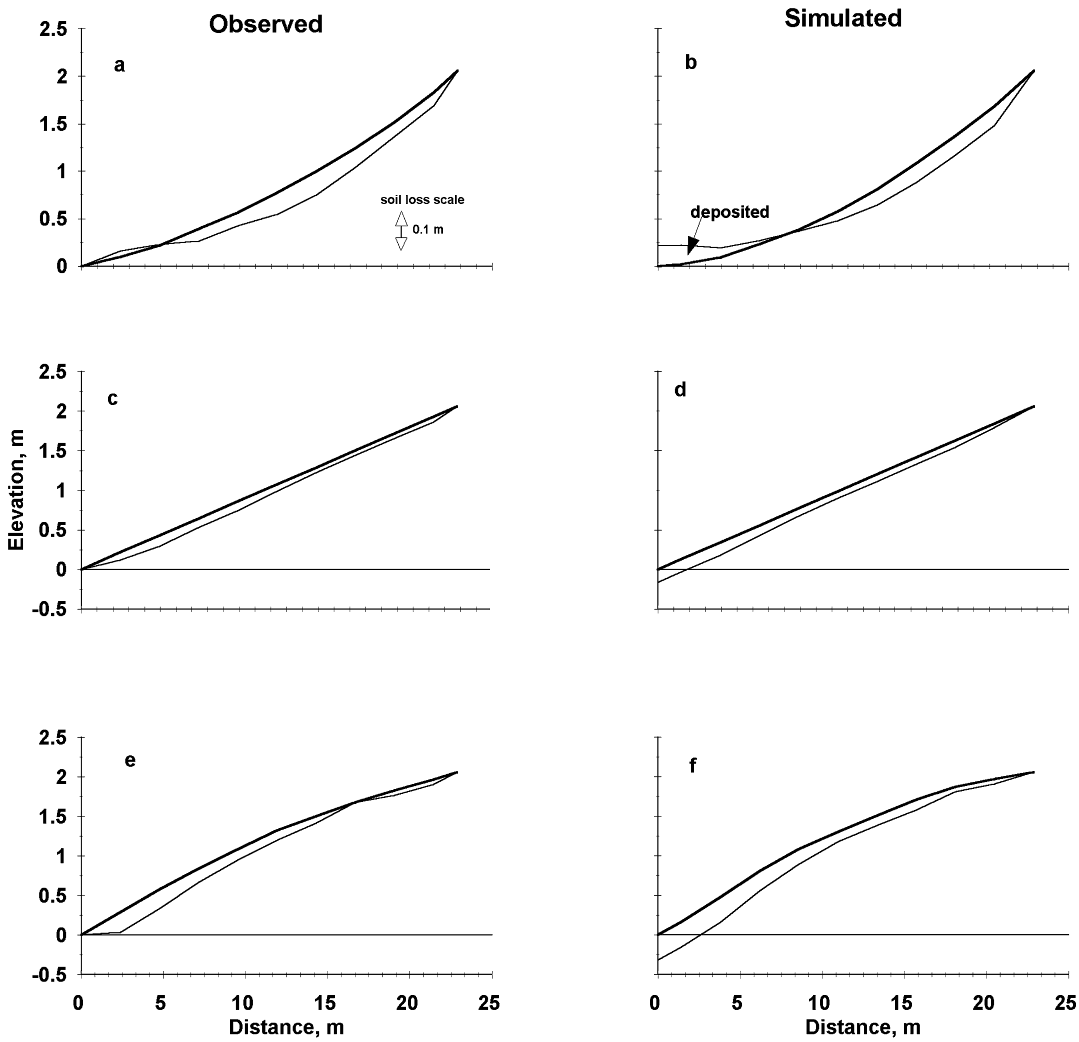

Fig. 4. Observed soil loss by Young and Mutchler (1969) and predicted (right) for a concave (a,b), uniform (c,d), and convex slope (e,f). The thick solid line is the original soil surface. The thin line is after erosion and deposition took place.

observed sediment concentrations are compared in three ways. The results are shown in Figs. 2 and 3.

Fig. 2 compares predicted and observed sediment concentrations as they change with slope, for nearly bare soil ($C_g < 0.10$) with consistent levels of canopy (aerial) cover which are not represented in the model. The results of the model are shown for the two extremes normally encountered in field plots ($N = 1$ and $N = 7$ rills per meter). For the McIsaac study, N values ranged from less than 1 up to 5 rills per meter. In both cases, the model assumes $C_g = 0.05$. The data points indicate reasonable predictions of sediment concentration magnitude, given the approximations involved in determining the input parameters. The modeled dependency on slope was also reasonable from both these data and from general experience of slope effects. The prediction curve corresponding to the larger rill density ($N = 7$ with $f_r = 3$, dotted line) frames the lower end of the data and indicates a comfortable agreement with the observed data. The prediction curve corresponding to the smaller rill density ($N = 1$ with $f_r = 10$, solid line) falls somewhat short of the higher end of the data, but N was less than 1 in some experiments (McIsaac, 1994). The model indicates considerable sensitivity to N, but less to f_r over the range investigated.

McIsaac et al. (1990) also measured sediment concentration at slopes from 0.05 to 0.1 under dense vegetation ($0.7 \leq C_g \leq 0.9$). The data on sediment concentration displayed no evidence of dependency on slope over the range investigated, average concentration being about 3 kg/m^3. With $C_g = 0.8$, the model predicted for all slopes that the sediment concentration would be equal to C_{min}. Rilling is unlikely under high vegetative cover. The model indication of no dependency of sediment concentration on slope under high residue cover was supported by the data of McIsaac et al. (1990).

Fig. 3 compares predicted and observed sediment concentrations as they change with degree of contact cover. The data points correspond to slopes between 7 and 9%. The model assumes a slope of 8%. Again, results are shown for $N = 1$ and $N = 7$. The agreement in trend with the data points indicate that the power relationship of Eq. (8) used in the model can describe the observations well. Comparison of magnitude of sediment concentration suggests that the predicted magnitudes of sediment concentrations are slightly low for intermediate levels of vegetation cover, but generally reasonable. It appears that the data in Fig. 3 call for a slightly lower value than 3 for the parameter p in Eq. (8).

The model appears to represent the relationships observed in this field study and absolute predictions of sediment yield would likely be improved with more accurate estimates or measures of input parameters. Variables such as the depositability, the rill width-to-depth ratio, the exponent p in Eq. (8), and C_{min} must be predictable with reasonable accuracy if the algorithm employed is to be useful. The database of depositability measurements for various soil types under various conditions is growing. Presumably, similar databases could be developed for other parameters.

4.2. Young and Mutchler (1969) study

The results of the second model evaluation are shown in Fig. 4. On the left is a pictorial representation of the observed elevation change from a 2-h rain on the three differently shaped hillslopes. The concave profile shows pronounced soil loss at the top of the slope, which tapers off towards the bottom; then, at the foot of the slope, deposition is observed. Both the uniform and convex profiles show increasing erosion from top to bottom; however, the uniform profile shows a steady rate of increase, while the convex profile shows a more pronounced rate of increase towards the bottom of the slope. The right side of Fig. 4 is a graphical output from the model of the steady state of erosion or deposition, corresponding to its predictions for the same three slopes. The same basic effects are predicted as are observed in Young and Mutchler (1969), including decreasing erosion then deposition on the concave slope, steadily increasing erosion on the uniform slope, and increasing erosion with a pronounced rate of increase towards the foot of the slope on the convex profile. The main difference between the observed and predicted results occur at the bottom of the slope. This is a direct consequence of the difference of boundary conditions: the plots of Young and Mutchler (1969) had fixed height plot outlets while in the simulation model the height could increase or decrease. Thus, at the bottom end, the Young and Mutchler plots showed no change in elevation while the simulation results indicated erosion or deposition.

5. Summary

An erosion model was developed based on the work of Hairsine and Rose (1992a,b), with the additional capability of simulating erosion on hillslopes covered with varying degrees of contact vegetative cover. The model was implemented as a Pascal computer program which accepts input from a file containing both general parameters and a sequence of hillslope segment parameters by which complex slopes can be delineated. The model was derived from the concept of stream power, quantifies the influence of vegetation in terms of contact cover, and incorporates the settling velocity characteristics of the soil.

The model was evaluated by comparing the relationships predicted by the model with those observed in two studies. The first study (McIsaac et al., 1990), involved erosion plots with uniform slopes between 5 and 11%, and levels of contact cover between 0 and 90%. In comparison to this study, the model predicted appropriate relationships between sediment concentration and slope, and sediment concentration and contact cover. It also predicted reasonable magnitudes of sediment concentration for a full range of slopes having sparse and dense cover, and for degrees of contact cover between 5 and 55% on slopes between 7 and 9%. The second study (Young and Mutchler, 1969) involved the measurement of soil loss from mechanically shaped concave, uniform, and convex slopes without vegetative residue cover. The model demonstrated good capability for qualitatively representing the pattern of erosion and deposition on such slopes without direct calibration. As is the case with many soil erosion models, the capability for accurate prediction is limited by the determination of the input parameters, as can be seen in the first evaluation of the model.

Presently, the prediction capabilities of the model are limited by its simple hydrology. This limitation can be overcome by including the algorithm in existing grid-based variable source area hydrology models for sloping soils such as developed by Zollweg et al. (1996) and Frankenberger et al. (1999).

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