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Finite Element Modeling of Erosion on Agricultural Lands

V.N. Sharda and Mark Nearing*

ABSTRACT

A finite element model simulating runoff and soil erosion from agricultural lands has been developed. The sequential solutions of the governing differential equations of Richards with a sink term, Saint-Venant in conjunction with kinematic wave approximation, and sediment continuity were used to simulate infiltration and soil water dynamics under cropped conditions; over land and channel flow; and soil erosion, respectively. The model has been refined to better simulate the inter-rill and rill erosion relationships. The comparison has shown that relations of Lattanzi et al. (1974) and Liebnow et al. (1990) for slope factor have tendency to over predict the inter-rill erosion when square of intensity alone is used without considering the runoff rate. The model of Kinnell (1993) based upon the product of runoff rate and rainfall intensity predicts better than those involving intensity alone under field conditions. The empirical relations evolved by Nearing (1997) using stream power concept predict rill erosion similar to the one given by Foster(1982) and higher than the one used in the WEPP model. It may be due to the fact that sediment load from rills is influenced more by the sediment transport limitations than the soil detachment. Assuming uniform particle size equivalent to median diameter over predicts the erosion rates with higher peak rates than the non-uniform particle size distribution. The analysis has also revealed that the shift of transport capacity from the excess to deficit type particle classes does not significantly alter the erosion rates and this concept need not be considered in the erosion simulation.

The phenomenon of equivalent rill width as used in the WEPP model for rill erosion simulation was found to be dependent upon ratio of friction factor of soil to that of total rill friction factor. No difference in erosion rates was observed with and without considering the rill widths till this ratio was about 0.7 for all the variable rainfall events. Beyond 0.7, the erosion rates were higher than without considering the rill widths for high intensity storms. The model was also updated to simulate erosion in impoundments and predicted and observed soil loss values were in reasonably good agreement when model was tested for Conservation Bench Terrace (CBT) system.

INTRODUCTION

The development of physics-based models has gained momentum in the recent past as they better describe the temporal and spatial watershed responses to erosion mitigation techniques. The finite element technique has been successfully applied to solve the partial differential equations of conservation of mass (continuity) and conservation of linear momentum governing the hydrologic and erosion processes. It has the added advantages of flexibility, generality, and consistency when compared to other numerical schemes. Sharda and Singh (1994) developed a finite element model simulating runoff and soil erosion from agricultural lands. The model reasonably simulated the runoff and soil erosion from major mechanical soil and water conservation measures.

The sequential solutions of the governing differential equations of Richards with a sink term, Saint-Venant in conjunction with kinematic wave approximation and sediment continuity were used to simulate infiltration and soil water dynamics under cropped conditions; overland and channel flow; and soil erosion, respectively. The sediment continuity equation was solved employing a fully implicit scheme for time integration and complete Yalin's equation was used to simulate sediment transport capacity. The inter-rill delivery and rill detachment were computed following Foster (1982).

However, the model assumed a representative particle size equivalent to median diameter and did not simulate erosion/deposition in impoundments. The model had a tendency to over predict the soil loss especially during high intensity storms. It was, therefore, necessary to refine and update the erosion simulation model following state-of-art in the inter-rill, rill, and transport capacity relationships. The focus of the present study was to evaluate the predominantly used empirical inter-rill and rill erosion relationships under field conditions for their efficiency and predictive power. The effect of shift of transport capacity from the excess to deficit type particle classes during erosion/deposition processes has also been studied. The model has been updated to simulate erosion for individual particle size fractions considering five particle size classes as suggested by Foster et al. (1985). It was also envisaged to upgrade the model to simulate deposition and transport in impoundments using modified overflow rate concept for variable flow conditions.

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Model Development

The Richards, Saint-Venant and sediment continuity equations simulating infiltration and soil water dynamics; overland and channel flow; and soil erosion, respectively may be described as:

One-dimensional Richards Equation

$$\frac{\partial}{\partial Z}K(h)\frac{\partial h}{\partial Z}-K(h)-S(Z,t)=C(h)\frac{\partial h}{\partial t} \quad (1)$$

One-dimensional Saint -Venant Equations

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}-q=0 \quad (2)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial Q^2 / A}{\partial x}=gA(S_0-S_f-gA\frac{\partial y}{\partial x} \quad (3)$$

Sediment Continuity Equation

$$\frac{\partial Q}{\partial x}+\rho_s\frac{\partial (C_s y)}{\partial t}=D_1+D_R=D_L \quad (4)$$

in which h is soil water pressure head, m; K (h) is hydraulic conductivity of the soil, m/s; C (h) is soil moisture capacity, $m^3/m^3/m$; S (Z,t) is rate of water uptake (sink term) by plant roots per unit volume of the soil under the prevailing moisture conditions, $m^3/m^3/s$; Z is space coordinate positive downwards, m; Q is discharge per unit width, $m^3/m/s$; q is net lateral inflow per unit length per unit width of flow plane, m/s; A is area of flow per unit width in the overland flow plane, m^2/m; S_o is bed slope of the flow plane, m/m; S_f is friction slope, m/m; x is distance in the direction of flow, m; y is depth of flow, m; g is acceleration due to gravity, m/s^2; Q_s is sediment mass discharge per unit width, kg/m/s; ρ_s is mass density of the sediment particles, kg/m^3; C_s is concentration of sediments in the flow, m^3/m^3; D_I is delivery rate of sediment from inter-rill areas, $kg/m^2/s$; D_R is rill erosion rate $kg/m^2/s$; D_L is lateral inflow rate of the sediment per unit length per unit width of flow regime, $kg/m^2/s$; and t is the time lapsed, seconds.

Application of Kinematic Wave Approximation (KWA) (Vieira, 1983) simplifies the momentum equation (3) to:

$$S_o = S_f \quad (5)$$

Describing the friction slope by the Manning law, the velocity of flow and discharge may be computed as:

$$Q = V\,A = 1/n\,R^{2/3}\,S_f^{\,1/2}\ A \quad (6)$$

in which V is the velocity of flow, m/s; R is hydraulic radius, m; and n is Manning's roughness coefficient ($m^{1/6}$). For dimensional homogeneity, the units of the constant 1 is $m^{1/2}/s$ in the S-I system.

Under unsteady conditions, substituting $Q_s = \rho_s\, C_s Q$ and $Q = V\,y$ and taking $Q_s/V = A_s$, equation (4) becomes:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}=D_L \quad (7)$$

where A_s is mass of sediment under movement for unit area, kg/m^2.

Simulation of Component Processes

The sink term in equation (1) defines the root water uptake by plants under prevailing moisture conditions in different layers of soil profile at any time during simulation. The potential evapotranspiration (PET) has been estimated using Penman's (1948) method as modified by Dooronbos and Pruitt (1975) from which plant transpiration has been computed using Richie's (1972) model. From this, the actual plant transpiration under prevailing moisture conditions, its distribution in different soil layers of root zone and the rooting depth on any day during plant growth have been computed by the methods suggested by Feddes et al. (1978), van Genuchten (1987) and Borg and Grimes (1986). To estimate rainfall excess rate, q, in equation (2), the interception losses, small in a cropped canopy, have been neglected, and Onstad's (1984) model relating depressional storage to random roughness and land slope has been used.

These equations are solved sequentially during each time step to compute infiltration rate, flow depth, velocity, discharge and finally the soil erosion or deposition for the desired duration of the flow process.

Finite Element Solution

The finite element solution of one-dimensional Richards equation with a sink term was developed using a Galerkin scheme (Pinder and Gray, 1977) with linear elements as suggested by Hayhoe (1978). For solving a system of ordinary differential equations with time as an independent variable, predictor-corrector method was employed with a fully implicit scheme for predictor and a Crank-Nicolson scheme for corrector. Similarly, Galerkin method was used for solving one-dimensional Saint-Venant equations with KWA and sediment continuity equation. The detailed description of the discretization and adaptation of finite element solution of the governing equations has been given in Sharda and Singh (1994). Algorithms for simulation and testing of selected inter-rill and rill erosion relationships, non-uniform sediments, concept of shift of transport capacity, phenomenon of rill width development and erosion in impoundment were developed and incorporated in the finite element model.

Field Evaluation

The developed model was tested under field conditions by collecting data from flat land configuration (control) and Conservation Bench Terrace (CBT) system. The CBT system comprised of 50x20 m size plots constructed at 2% slope with contributing and receiving (level bench) areas in the ratio of 3:1 (Fig. 1). In the level bench, 20 cm depth of impoundment was provided for paddy cultivation and the excess runoff was drained through rectangular weir having crest length equivalent to width of the plot. The efficacy of the CBT system was compared with traditional system of maize:wheat rotation in sloping borders of 50x20 m size also constructed at 2% slope. The details of the experimental procedure have been discussed in Sharda et al. (1994).

The soil and crop parameters evaluated to validate the finite element model under field conditions include inter-rill erodibility (3.4 e+006 $kg/s/m^4$), rill erodibility (0.0174 s/m), average specific gravity of particles (2.6), median diameter of particles (0.48 mm), average bulk density (1390 kg/m^3), maximum depth of maize crop (0.8 m), leaf area index (expressed by 4th degree polynomial), and days to crop maturity (90-100). The value of Manning's roughness coefficient was varied between 0.05 and 0.12 depending upon the crop growth stage. Table 1 gives the description of physical and water transport properties of the soil profile in the study area.

Five storm events representing variable rainfall distribution and different crop growth stages were selected during the period from 1990 to 1994 on July 15, 1990, July 28, 1991, Sept. 9, 1992, Sept. 11, 1993, and Aug. 15, 1994.

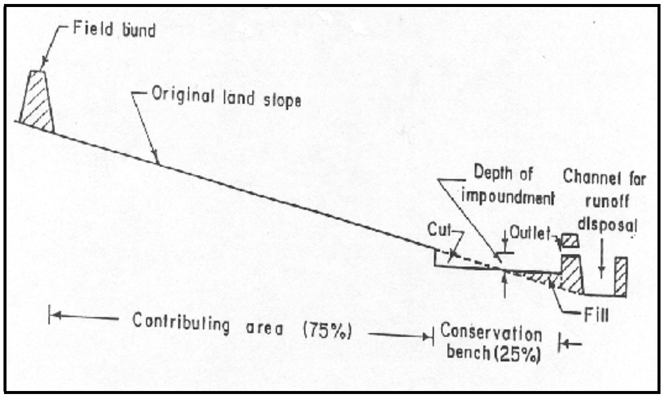

Figure 1: 3:1 Conservation bench terrace system.

RESULTS AND DISCUSSION

In the following sections, the results of the refinements in the erosion simulation model have been briefly discussed:

Simulation of Inter-Rill Erosion

Over the years, many refinements have been suggested to simulate the physical processes of soil detachment, transport and deposition. Elliot et al. (1989). analyzed a series of interrill erosion experiments to determine the inter-rill erodibility (K_i) of a number of cropland soils within WEPP model and related interrill sediment erosion (D_i) with rainfall intensity (I) and slope factor (S_F) as:

$$D_i = K_i \quad I^2 \quad S_F \qquad (8)$$

Where D_i is inter-rill erosion rate, kg/m^2/s; K_i is interrill erodibility, kg s^{-1} m^{-4}; I is the rainfall intensity, m s^{-1}; and S_F is the slope factor.

Guy et al. (1987) reported that 85% of the sediment delivered from inter rill areas was attributed to enhancement of transport capacity by raindrop impact and only 15% was attributed to non-disturbed runoff.

Lattanzi et al. (1974) developed the equation for inter-rill slope factor, S_F as:

$$S_F = 2.96 (\text{SIN } \phi)^{0.79} + 0.56 \qquad (9)$$

From the analysis of data of Lattanzi et al. (1974), Singer and Blackard (1982), Watson and Laflen (1986), Meyer and Harmon (1987), Liebnow et al. (1990) concluded that :

$$S_F=1.05 - 0.85 \exp (-4 \text{ SIN } \phi) \qquad (10)$$

where ϕ is the slope angle. Foster (1990) attributed the decreasing increase in S_F with slope gradient in equation 10 to a change from transport limiting conditions on lower slope gradients to detachment limiting conditions on high slope gradients. Kinnell(1993) modified the relation by including the runoff rate (volume of water discharged per unit area per unit time), Q_r (m^3/m^2/s) in the inter-rill delivery rate and replacing I^2 in equation (8) with the product I Q_r. Truman and Bradford (1995) also concluded that inter-rill erosion rate predicted by relations involving product of intensity and flow discharge are consistent with the principle of erosion mechanisms. Erodibility calculated using intensity alone increased with time and is a function of soil properties related to soil detachment and does not account for infiltration and runoff differences between soils. Chi-Hua Huang (1995) observed experimentally that due to inter dependency between the slope and runoff or rainfall intensity factors on sediment delivery, it is difficult to isolate their effects individually.

Table 1. Description of physical and water transport properties of the soil profile.

Depth (cm)	pH	O. C. (%)	Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	Bulk density	Sat. hyd. conduct. (cm/hr)	Max. W.H.C. Wt. basis (%)	Max. W.H.C. Vol. basis (%)
0-15	5.50	0.791	3.30	40.80	34.70	21.20	1.308	0.180	34.10	44.60
15-30	5.31	0.536	2.85	42.25	29.70	25.20	1.391	0.396	30.90	43.07
30-45	5.46	0.551	4.80	45.30	28.70	21.20	1.465	0.108	28.80	42.26
45-60	5.39	0.596	1.55	51.55	22.70	24.20	1.419	0.432	27.20	38.96
60-75	5.12	0.502	3.65	49.45	22.70	24.20	1.375	0.360	30.10	41.41
75-90	5.33	0.443	3.65	45.45	23.70	27.20	1.398	0.396	30.20	42.27
90-105	5.42	0.308	3.00	42.10	27.70	27.20	1.349	0.432	30.20	40.74
105-120	5.32	0.323	3.35	35.75	32.70	28.20	1.347	0.576	27.30	43.17

Bradford and Foster (1996) reported that most of the equations developed for slope steepness factor may not apply to a wide range of soils because the magnitude at which erosion processes of detachment and transport control sediment yield in inter rill areas may differ. To account for the infiltration effects on sediment transport, WEPP interrill erosion model was modified as (Flanagan and Nearing 1995):

$$D_i = K_i \quad I \quad q \quad S_F \qquad (11)$$

where q is rainfall excess rate.

From the critical review of the existing approaches, the empirical relation suggested by Elliot et al. (1989) employing the slope factor given by Lattanzi et al. (1974) and used in the model earlier was compared with the one using the term I^2 with slope factor defined by Liebnow et al. (1990) and that given by Kinnell (1993) using the term I Q_r in place of I^2 for simulating the inter rill delivery rates under field conditions. As may be seen from Fig. 2, the sediment rate predicted by using the relation suggested by Lattanzi has a tendency to over predict the erosion rate.

From the comparison, it has been inferred that for all types of storm distributions, the empirical relation of Lattanzi et al. (1974) for slope factor over predicts the erosion rate when the term I^2 is used particularly during the initial stages which is ascribed to the fact that it does not account for infiltration and runoff differences over time. It has been also observed that for high intensity storms, the differences among the three approaches are negligible (Fig.2) but for low intensity storms, the empirical relation of Lattanzi et al. (1974) for slope factor with the term I^2 results in steep rise of the sediment peak though the results of other two approaches remain well comparable (Fig.3). Hence, the relation suggested by Liebnow for slope factor with the term involving product of intensity and flow discharge (Kinnell, 1993) better simulates the interrill erosion rates under field condition when initial moisture levels and intensity distribution significantly affect the infiltration rate.

Rill Erosion Rate

Van lieu and Saxton (1984) modified the rill erosion equation by including the hydraulic Reynolds number. Foster et al.(1984) studied the rill hydraulics and developed velocity and shear stress relationships for rill erosion. Govers (1982) suggested that increase of erosion on the steeper slopes effects an associated increase of bed roughness thereby slowing the flow velocity. Huang et al. (1996) evaluated the detachment-transport coupling concept in the WEPP rill erosion equation and concluded that experimental data do not support this concept. Nearing et al.(1997) investigated the rill hydraulics and erosion as a function of slope and discharge rate. They found that Reynolds numbers are not good predictors of hydraulic friction factors in the rills. Unit flow discharge was found to be the best predictor of flow velocities in eroding rills. The best overall predictor for unit sediment load was found to be the stream power.

In the WEPP model (Flanagan and Nearing, 1995), rill erosion rate (D_r) is calculated (when sediment load is less than sediment transport capacity) as:

$$D_r = D_c \quad (1 - G/T_c) \qquad (12)$$

where D_r is rill erosion rate, kg/m^2/s, D_c is detachment capacity rate, kg m^{-2}s^{-1} G is sediment load, kg m^{-1} s^{-1} and T_c is sediment transport capacity in the rills, kg m^{-1} s^{-1} .

When hydraulic shear stress (τ_f) exceeds the critical shear stress (τ_c), Dc is given by:

$$D_c = K_r \quad (\tau_f - \tau_c) \qquad (13)$$

where K_r is a rill erodibility parameter, τ_f is flow shear stress acting on the soil particles (Pa) and τ_c is the rill detachment threshold parameter or critical shear stress of the soil (Pa). Net deposition is calculated when sediment load is greater than the sediment transport capacity.

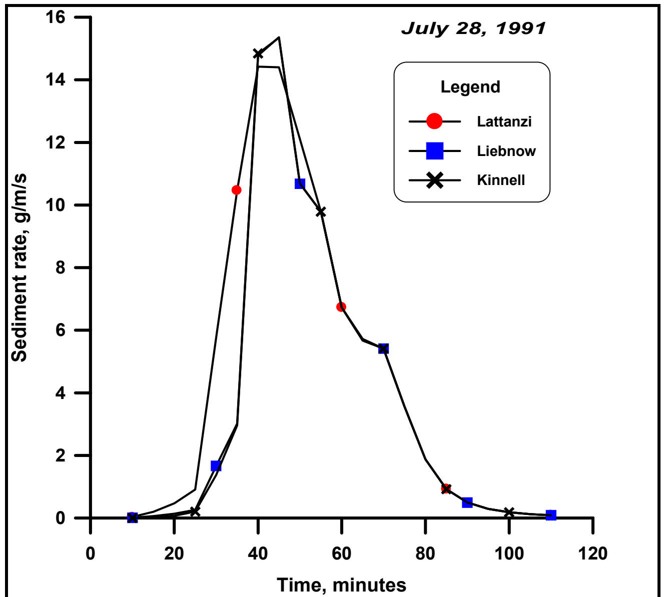

Fig. 2 Comparison of inter-rill erosion using different models

The model developed earlier was based upon rill erosion relations suggested by Foster (1982). It had a tendency to over predict erosion especially for high intensity storms, as it was not transport capacity limiting. The models of Foster (1982), Flanagan and Nearing (1995) as used in the WEPP model and Nearing et al. (1997) were evaluated for their efficiency in predicting rill erosion rate under field conditions. As may be seen from Fig. 4, the relations of Foster (1982) over predicted the erosion rate under field conditions as compared to other models. It was true for all types of storm events and rainfall distributions. It is attributed to the lack of any limiting phenomenon and assumption of potential erosion occurring during the processes of detachment and transport. The model developed by Nearing et al. (1997) when used as a source term for rill erosion rates has given comparable results to that of Foster (1982) but higher than that used in the WEPP model. It is due to the fact that the equation evolved by Nearing et. al. (1997) is more appropriate for use as a sediment transport equation rather than as a sediment source equation especially when sediment transport limitations strongly influence the sediment discharge. The deviation among the three models reduced for high intensity storms (eg. July 28, 1991 with total rainfall of 64.6 mm and average intensity of 35.2 mm hr^{-1}) (Fig.4) and is more pronounced for low intensity storms (eg. Sept. 11, 1993 with total rainfall of 26.2 mm and average intensity of 19.7 mm hr^{-1}) (Fig. 5).

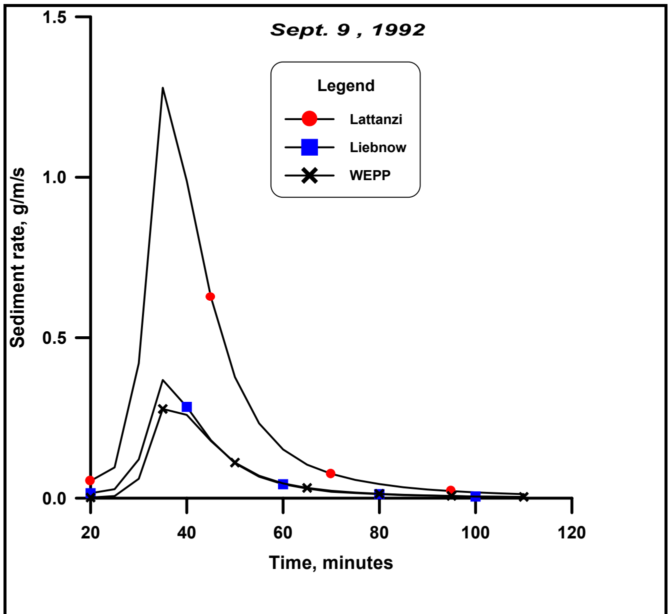

Fig. 3 Comparison of inter-rill erosion using different models

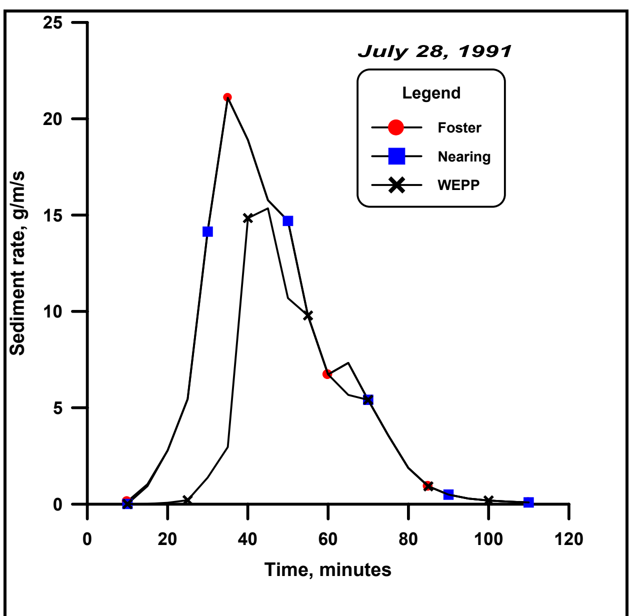

Fig. 4 Comparison of rill erosion using different models

Simulation for Non-Uniform Sediments

The model assumed uniform size of the sediments equivalent to median diameter of the particles. The model was refined to estimate erosion for each particle size fraction of the sediments. Sediment is composed of both primary particles of sand, silt and clay and aggregates, conglomerates of primary particles. Sizes range from less than 0.002 mm for clay to more than 1.0 mm for large aggregates.

Based upon the characteristics of a typical soil, the

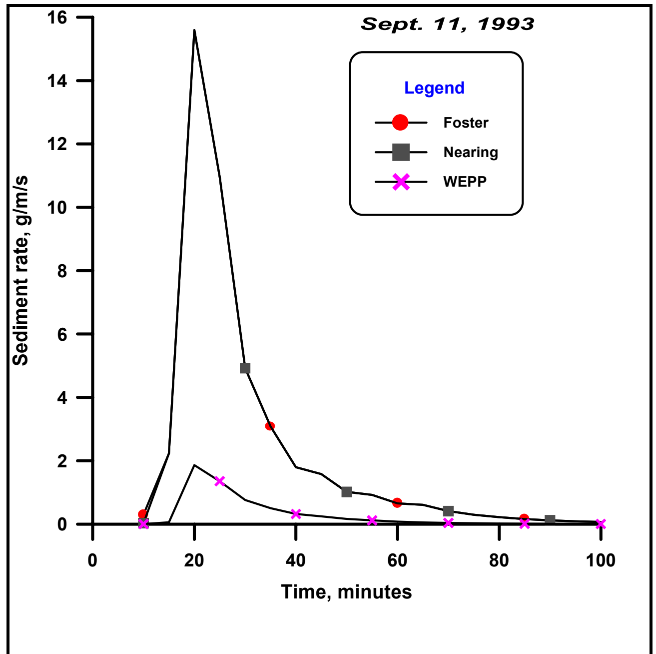

Fig. 5 Comparison of rill erosion using different models

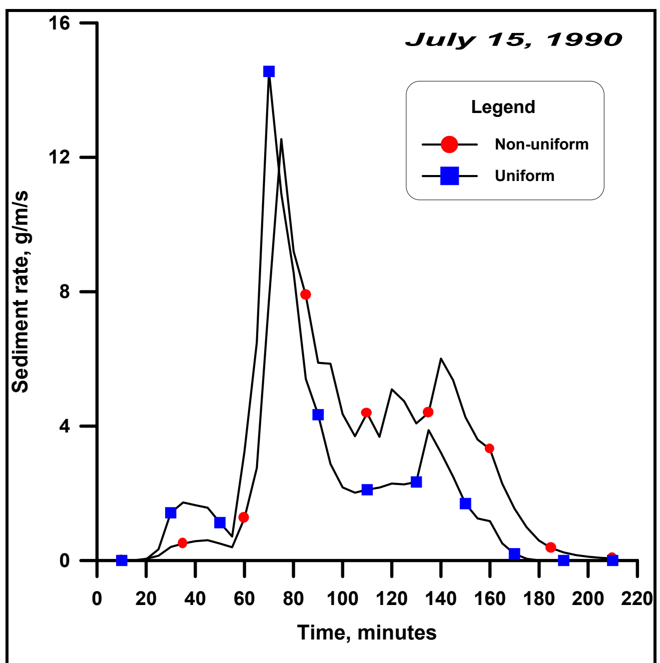

Fig. 6 Effect of uniform & non-uniform particle sizes on sediment yield

sediment mixture was divided into classes according to density and diameter. Firstly, roughness factor values for inter-rill sediment delivery were computed based upon soil loss ratios given by Wischmeier and Smith (1978). From it, the fraction of various particle types passing through inter-rill roughness depressions was calculated. The rill erosion rate for each particle size was also calculated similarly depending upon weightage of each type in the mixture. To compute the sediment transport capacity for non-uniform sediments, the Yalin equation was modified as per procedure outlined by Foster (1982).

Fig. 6 shows the effect of uniform (d_{50}) and non-uniform sizes on sediment load. As is evident, the assumption of uniform size equivalent to median diameter over predicts the erosion peak rate, which is invariably true for all types of storm events under consideration. Though the total sediment load remains unaffected for larger storms, for smaller events, the predicted sediment load is significantly higher when uniform size is assumed (Fig. 7). Hence, it is not desirable to assume a uniform size and all particle size fractions should be considered while predicting erosion or deposition in a given soil type.

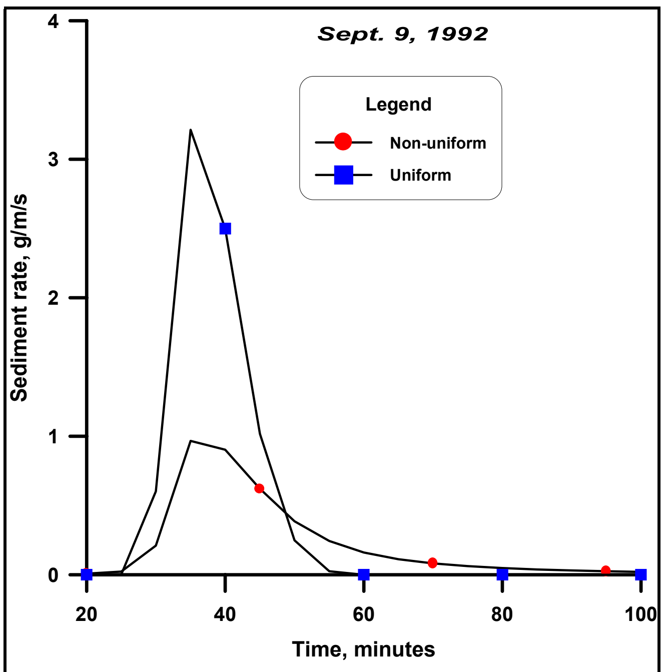

Fig. 7 Effect of uniform & non-uniform particle sizes on sediment yield

Shift of Transport Capacity

It is assumed that for large sediment loads, where sediment loads for each particle type are clearly in excess of the respective transport capacities for each particle type, or for small sediment loads, where sediment loads for each particle type are clearly less than the respective transport capacities for each particle type, the flow's total transport capacity is distributed among the available particle types based on particle size, density and flow characteristics and not on the makeup of sediment load.

The algorithm involving the concept of shift of transport capacity among the particle types as suggested by Foster (1982) following Davis (1978) was developed and incorporated in the model.

The analysis has revealed that assumption of shift of transport capacity is not desirable and unnecessarily adds to computer time. The sediment rates are not significantly different to the one without considering the shift of transport capacity for all the types of events (Fig. 8). However, for high intensity storms with multiple peaks, the peak sediment rate gets distorted, though the total sediment load remains unaffected (Fig. 9). For low intensity storm distribution, the difference in the sediment rates was practically negligible. Hence, it is not necessary to incorporate this concept in the model and the computation should be made based upon comparison of sediment load and transport capacity for each particle type.

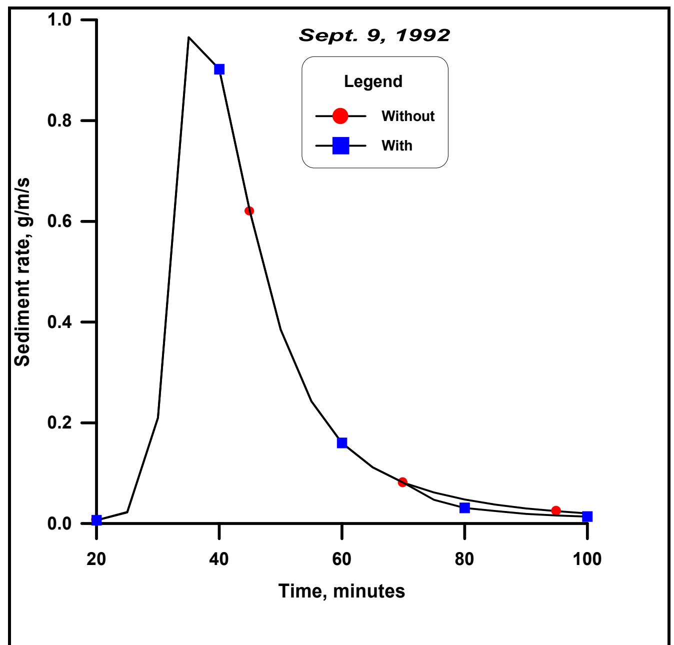

Fig. 8 Effect of shift of transport capacity on sediment yield

Rill Width Computation

In the WEPP model, the rill width is calculated assuming rectangular shape as suggested by Lane and Foster (1980):

$$w = c\ Q_o^{\ d} \qquad (14)$$

where w is the rill width in meters at the end of the slope and c and d are equilibrium parameters which are functions of soil and vegetation and Q_o is flow rate at the end of the slope in $m^3/\ s$. Gilley et al. (1990) recommended that universal values of c= 1.13 and d = 0.303 may be adopted. Knowing the flow depth, rill width and average slope, the shear stress acting on the soil is calculated as:

$$\tau_f = \Upsilon\ R\ S_0\ (f_s/f_t) \qquad (15)$$

where τ_f is Shear stress acting on the soil , Pa; R is hydraulic radius, m; Υ is the specific weight of water, $Kg/m^2/s^2$, S_0 is average slope gradient; f_s is friction factor for the soil; and f_t is total rill friction factor.

The ratio of f_s/f_t represents the partitioning of the shear stress between that acting on the soil and the total hydraulic shear stress which includes the shear stress acting on surface cover (Foster, 1982).

In the erosion simulation, the results were compared considering rill width formation in the overland flow plane as used in the WEPP with different ratios of f_s/f_t. The analysis has indicated that for smaller storm events, no significant difference in erosion rates was observed with and without considering the rill width development for all ratios of f_s/f_t (Fig. 10). However, for higher values of f_s/f_t, the erosion rates were found to increase especially in the recession limb for the larger events (Fig.11). It may, therefore, be concluded that rill width development phenomenon yields results similar to that without considering it, till f_s/f_t ratio is about 0.7. This ratio beyond 0.7 is very crucial for high intensity storms and need to be predicted more precisely under field conditions to better simulate the erosion rates.

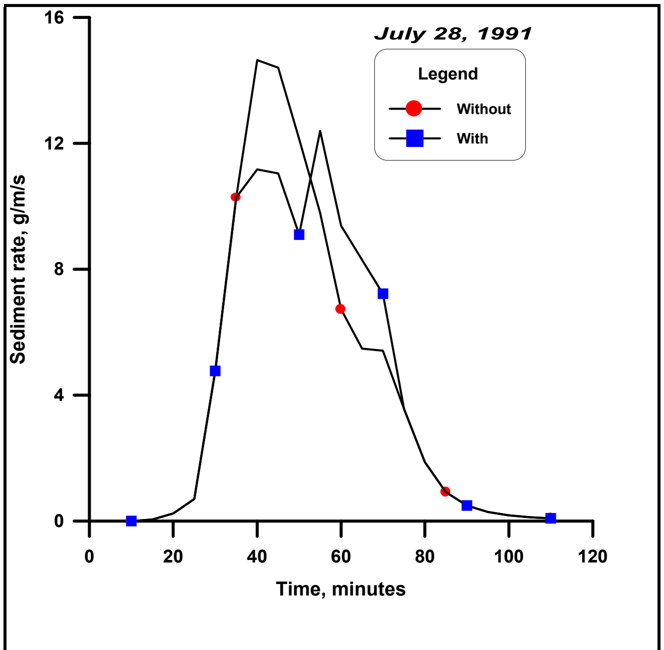

Fig. 9 Effect of shift of transport capacity on sediment yield

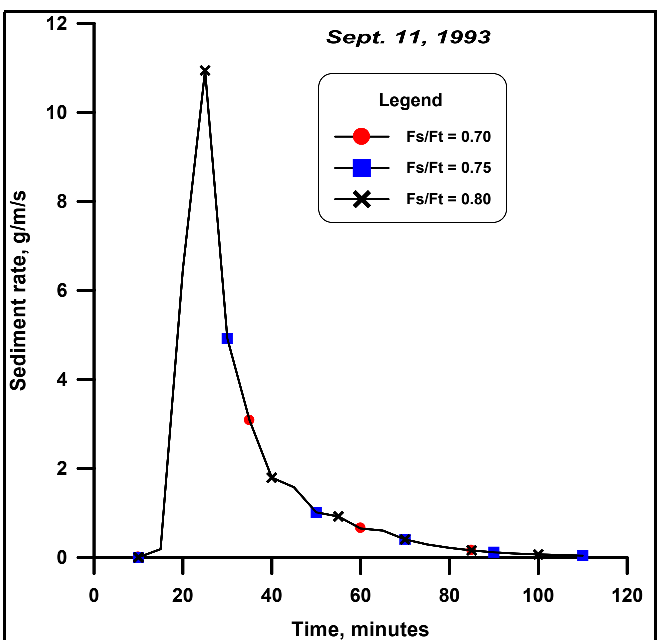

Fig. 10 Comparison of sediment yield using different friction factors for the rills

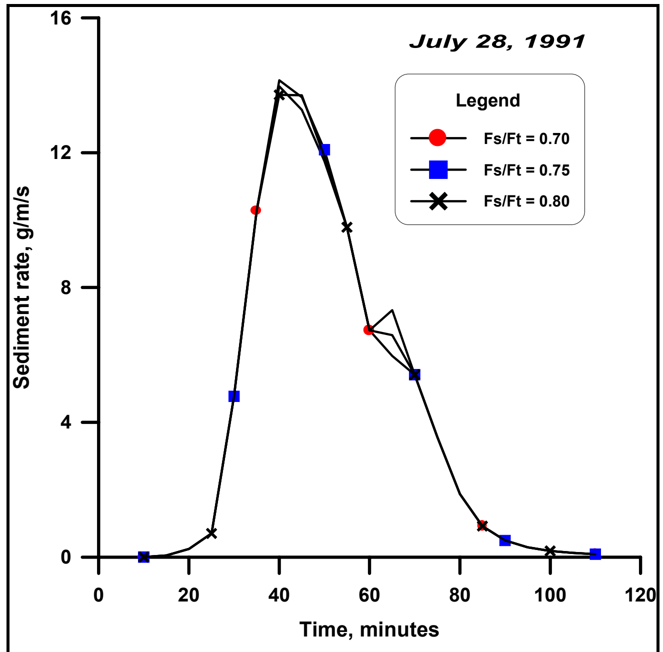

Fig. 11 Comparison of sediment yield using different friction factors for the rills

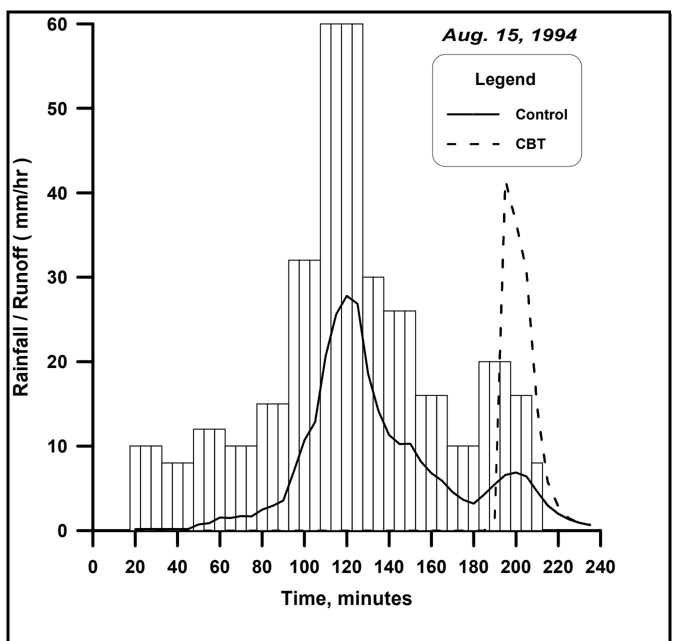

Fig. 12 Comparision of runoff from Control and CBT systems

Table 2 Comparision of simulated and observed runoff and soil loss for sloping borders and CBT system

Date	Rainfall (mm)	Sloping borders				CBT system			
		Runoff (mm)		Soil loss (kg)		Runoff (mm)		Soil loss (kg)	
		Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
July 15, 1990	94.1	40.3	35.1	605.0	642.0	41.0	32.0	42.0	28.0
July 28, 1991	64.6	21.9	24.6	426.0	473.6	20.9	17.5	28.0	18.0
Sept. 9, 1992	15.9	5.1	4.6	8.5	6.8	2.4	2.7	0.9	1.2
Sept.11, 1993	26.2	7.8	9.0	41.2	34.9	0.9	1.5	2.1	3.0
Aug. 15, 1994	78.3	21.0	24.0	60.9	70.8	10.2	11.3	6.8	5.9

Simulation of Erosion in Impoundments

Broadly, the models simulating sedimentation in impoundments can be classified into two types, viz; steady state flow (Peavy et al., 1985; Driscol et al., 1986) and variable flow rate models (Ward et al., 1979; Wilson et al., 1982; Warner and Schwab, 1992). The steady state or overflow rate models assume steady state inflow and out flow, rectangular reservoir, no re-suspension of sediments, completely mixed inflow and outflow and discrete particle settling. They do not normally hold good under field situations where inflow and outflow volumes as well flow rates change over time. The comparison of different models has indicated that modified overflow rate models were no more accurate than the DEPOSITS (Ward et al., 1979) model in predicting trapping efficiency. The Continuous STirred Reactors in Series (CSTRS), and Basin Analysis of Sediment laden INflow (BASIN) (Wilson and Barfield, 1985) models were found to correctly predict the shape of the effluent sediment graph as compared to DEPOSIT model which assumes no mixing of plugs (Lindley et. al., 1994).

Griffin et al.(1985) showed that two continuous stirred reactors in series were the optimum model to represent small ponds, however, the data also showed that one continuously stirred reactor was a reasonable representation. As suggested by Lindley et. al.(1994), CSTRS model with one reactor and two particle size subclasses was used to simulate erosion and deposition in impoundments during variable flow conditions and during no flow conditions quiescent settling theory was utilized. Fig. 12 shows the hydrographs realised for flat land configuration and CBT system. The CBT system was found to be quite effective in significantly reducing the runoff and soil loss (Table 2).The model was tested under CBT system for five different storm distributions. As evident from Table 2, the predicted and observed soil loss values compare reasonably well though the model has a tendency to under predict the sediment load particularly for bigger storms. As the storm size increases, the deviation between predicted and observed values was found to widen which may be attributed to the complexity of settling phenomenon in the impoundment under cropped conditions and underlying assumptions in the model development. Further refinement of the model is necessary to improve its predictive power.

CONCLUSIONS

The finite element model has been refined to simulate erosion from agricultural lands by incorporating the currently used techniques for computing inter-rill and rill erosion rates. The models for rill and inter-rill erosion have been compared under field conditions and reasons for discrepancies have been discussed. The model has been updated to simulate erosion for each particle type in a mixture of non-uniform sediment and results have been compared with the assumption of uniform size equivalent to median diameter. It is concluded that it is not proper to assume uniform size, which tends to predict higher peak sediment rates particularly for smaller storms.

The procedure considering shift of transport capacity from excess to deficit type was not found to be desirable as the sediment rates are not significantly affected when compared without considering this concept. For low intensity storms, no significant difference was noticed with and without considering the rill width development phenomenon as used in the WEPP model. For larger storms, the ratio of friction factor of soil to the total rill friction factor is very crucial and need to be precisely predicted under field conditions. The model reasonably simulated the erosion and deposition in impoundments though it slightly under predicts the erosion rates for larger events when tested for CBT system. It is ascribed to the complexity of settling phenomenon under cropped conditions and underlying assumptions in the model development.

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