International Journal of Agricultural Science, Research and Technology ***Available online on: www.ijasrt.com***

Study On Flow Erosivity Indicators for Predicting Soil Detachment Rate at Low Slopes

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Abstract

Soil detachment is known as an important process in soil erosion and its quantification is necessary to establish a basic understanding of erosion. This study was carried out to find the best flow erosivity indicator(s) for predicting detachment rate at low slopes. For this purpose, 12 experiments including 6 flow discharges (75, 100, 125, 150, 175 and 200 ml/s) and 2 slope gradients (1.5 and 2%) were performed. Accordingly, different stream powers less than 0.175 W m^{-2} were simulated. Soil detachment rate was related to flow depth, flow velocity, unit flow discharge, shear stress, unit stream power and stream power as erosivity indicators. The results showed that the relationship was more significant at slope 2% (R^2>0.94) than slope 1.5% (R^2>0.84). Among different indicators, flow velocity and unit stream power exhibited unlinear relationships as exponential, while the others showed linear ones. Considering flow depth, unit flow discharge and unit stream power a range of critical values were obtained at different slopes. It was found that for shallow surface flows, measurement of flow depth is difficult while, unit flow discharge can be measured, accurately. Finally, the finding of this research reveals that stream power is the best indicator for predicting soil detachment rate. **[Sirjani and Mahmoodabadi. Study On Flow Erosivity Indicators for Predicting Soil Detachment Rate at Low Slopes. International Journal of Agricultural Science, Research and Technology, 2012; 2(2):55-61].**

Key words: Detachment rate, Flume, Hydraulic parameters, Sheet flow

Received: 28 July 2012, Reviewed: 15 October 2012, Revised: 20 October 2012, Accepted: 26 October 2012

1. Introduction

Soil erosion is recognized as a serious eco-environmental threat (Pan et al., 2006) and a land degradation problem (Erskine et al., 2002). Due to water erosion, soil productivity declines, moreover pollutants and sediment load increase in surface flows (Ghadiri and Rose, 1992). In recent years, there has been a worldwide trend in developing process-based erosion models (Nearing, 2004; Pieri et al., 2007). Process-based prediction models have received increasing attention for various theoretical and practical reasons. Models such as WEPP (Nearing et al., 1989), GUEST (Rose et al., 1983a,b,c) and EUROSEM (Morgan et al., 1998) as well as several others show great potential for application (Yan et al., 2008). In addition, these models have been proven to be a tool for improving our understanding of erosion processes and evaluating possible effects of land use changes on soil erosion (Deng et al., 2008).

Soil erosion has been defined as the phenomenon of detachment, transportation and deposition of soil particles by erosive agents. In other words, detachment, transport and deposition, are three basic processes of soil erosion (Defersha et al., 2011). Soil detachment is an important component of soil erosion, which its quantification is necessary to establish a basic understanding of soil erosion processes and to develop fundamental-based erosion models (Zhang et al., 2003). Detachment rate is defined as the dislodgment of soil particles from the soil mass at a particular location on the soil surface (Zhang et al., 2002). Rain-splash and running water are two of the most important detachment agents to remove soil particles from soil surface (Shih and Yang, 2009). In the absence of rainfall, detachment of soil particles by shallow overland flow is influenced by soil cohesion, soil aggregate properties, and hydraulic characteristics (Nearing et al., 1991). This process occurs when the stress or energy applied by the surface flow is great enough to pull the soil particles away from the bulk material (Zhang et al., 2003).

It is difficult to have an analytical solution for the prediction of soil erosion processes. However, accurate prediction of soil detachment rate is critical to the development of a fundamentally based erosion models (Zhang et al., 2002). Therefore, empirical approaches using physically based parameters should be used to estimate sheet erosion rate (Shih and Yang, 2009). In overland flow, the main hydraulic parameters controlling soil detachment are slope, flow velocity and flow depth. These variables can be combined in different ways to obtain composite predictor variables with a physical basis for sediment detachment such as hydraulic shear stress (Nearing et al., 1997), stream power (Hairsine and Rose, 1992a,b; Zhang et al., 2002), unit stream power (Moore and Burch, 1986; Yang, 1972; Shih and Yang, 2009) and effective stream power (Govers, 1992; Gimenez and Govers, 2002). Generally, in most process-based erosion models, sediment detachment is related to flow shear stress, stream power and unit stream power (Gimenez and Govers, 2002). Since, these erosive predictors are as function of basic hydraulic variables, they cannot be measured directly (Zhang et al., 2009). Therefore, through combinations of different slope gradients, flow rates, and flow depths, the relationship between soil detachment rate and these hydraulic parameters can be derived based on the data from hydraulic flume studies (Zhang et al. 2003).

Shear stress is defined as (Nearing et al., 1997):

$$\tau = \rho g D S \qquad (1)$$

where τ (Pa) is shear stress, ρ (kg m^{-3}) is water mass density, g (m s^{-2}) is the gravity constant, D (m) is the depth of flow and S (fraction) is the tangent value of bed slope degree.

Stream power is determined as (Zhang et al., 2002):

$$\Omega = \tau V = \rho g q S \qquad (2)$$

where Ω (W m^{-2}) is stream power, V (m s^{-1}) is flow velocity, and q (m^{-2} s) is volumetric flux per unit width, that is calculated as follows:

$$q = \frac{G}{W} \qquad (3)$$

where G (m^{-3} s) is volumetric discharge and W (m) is the width of plot or flume.

Unit stream power (U; m s^{-1}) is defined as (Yang, 1972):

$$U = VS \qquad (4)$$

Many studies have investigated soil erosion due to overland flow in different hydraulic conditions. However, few studies have assessed detachment rate at low slopes to obtain the best erosive indicator (Nearing et al., 1991; Zhang et al., 2002). The objective of this study was to determine the influence of different hydraulic parameters and their combinations on sheet erosion rate at low stream powers to find the best flow erosivity indicator(s) for predicting detachment rate.

2. Materials and methods

2.1. Soil sample

In this study, an agricultural soil was chosen and from the depth of 0 to 20 cm was sampled. At the time of sampling, the agriculture field had been under fallow for 2 yr. Soil sample was air-dried, crushed to pass through a 2 mm sieve and finally, some physical and chemical properties were measured (Table 1). Soil texture was determined by the hydrometer method (Page et al., 1992a). Soil pH and EC were measured in saturated paste and saturated paste extract, respectively (Page et al., 1992b). Soil organic carbon was determined as described by Walkley and Black (1934) and the percent of $CaCO_3$ equivalent was measured using the titration method (Pansu and Gautheyrou, 2006). Some physical and chemical properties of the soil are given in Table 1. The texture of soil is classified as clay loam. The soil has considerable amount of $CaCO_3$ equivalent and electrical conductivity (EC) is more than 4 dS m^{-1} while, the content organic carbon is low.

2.2. Experimental setup

Experiments were conducted using a tilting flume with the length and width of 2 and 0.5 m, respectively. For soil pre-wetting and also removing drainage water, a mesh floor was fixed as drainage system on the bottom of flume. After many pre-experiments to find the best flume dimensions for simulation sheet flow, avoid rilling and make low stream powers, the initial length and width of flume were reduced to 1 and 0.2 m, respectively (Figure 1).

Table 1. Some physical and chemical properties of the soil used in the study.

Soil Property	Unit	Amount
Clay	(%)	34.4
Silt	(%)	32.0
Sand	(%)	33.6
Organic carbon	(%)	0.2
$CaCO_3$	(%)	21
EC	(dS m^{-1})	4.19
pH	-	8.45

EC: Electrical Conductivity.

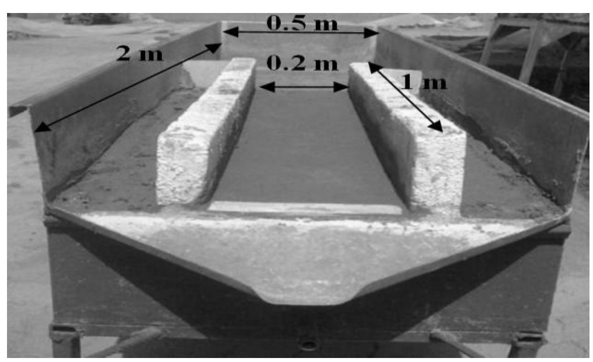

Figure 1. The applied flume for sheet flow experiment with initial (2 m×0.5 m) and test area (1 m×0.2 m) dimensions.

In all experiments, fresh soil sample was placed in the flume and to obtain a flat surface, a wooden board was pulled on the soil from top to the end of the flume. Afterward, the soil in flume was pre-wetted for 24 hours. Then, the drainage water was removed out of the flume and immediately the experiment was run. Before each experiment, flow discharge and bed slope was adjusted at desired values. In this study, 12 experiments including 6 flow discharges (75, 100, 125, 150, 175 and 200 ml/s) and 2 slope gradients (1.5 and 2%) were performed. These flow discharges and flume slopes were selected, since no concentrated flow was allowed to occur.

2.3. Measurement of hydraulic parameters and detachment rate

Based on of the selected flow discharges and flume slopes, different flow erosivities were generated to simulate sheet erosion. Each experiment was executed until a constant runoff rate (i.e. steady state condition) was reached. As a consequence, most events took at minimum 30 min, while sediment laden water exiting flume was sampled at different time intervals (1 and 5 min). The samples were oven-dried at 105 °C to obtain runoff discharge and detachment rate. During each experiment, flow velocity was measured using the dye method. Finally, using steady state hydraulic variables and their combinations, different erosivity indicators were made.

3. Results and discussion

3.1. Single-parameter indicators

Results showed that detachment rate varied between 3.9×10^{-5} and 2.5×10^{-3} kg m^{-2} s^{-1}. In this study, the best equation (linear or unlinear) describing the relationship between detachment rate and each hydraulic parameter was found. Figure 2 shows the relationship between detachment rate and sheet flow depth at two different slopes. As is shown, increasing flow depth, detachment rate increased linearly for both slopes. Nearing et al. (1991) observed that detachment rate is affected by flow depth as a logarithmic function however, the effect of slope was found to be more important than flow depth. Figure 2 shows that for a constant flow depth, detachment rate is higher for the slope of 2%, due to higher flow erosivity. Moreover, the relationship between detachment rate and flow depth was more significant at slope 2% (R^2=0.96) compared to slope 1.5% (R^2=0.86). However, the slope of trend-line for both flume slopes is nearly the same. Similarly, Zhang et al. (2002) concluded that the effect of flow depth on detachment rate is influenced by the slope gradient. Also, Fu et al. (2011) found that the main parameter influencing on sediment detachment and transport in overland flow are slope.

Flow velocity is another important hydraulic parameter considering in soil erosion modeling. This parameter depends on flow discharge, slope gradient (Zhang et al., 2002) and soil surface roughness (Zhang et al., 2009; Zhang et al., 2011). Detachment rate as a function of mean flow velocity at two different slopes is presented in Figure 3. The result showed that mean flow velocity changed from 0.16 to 0.26 ms^{-1}. Also, it was found that for both slopes, detachment rate increased with flow velocity, exponentially whereas, the relationship for flow depth was linear. This means that higher flow velocities resulted in much more detachment rates. In other words, detachment rate is more sensitive to velocity than flow depth. Similar to the case of flow depth (Figure 2), the relationship between detachment rate and mean flow velocity is more significant at slope 2% (R^2=0.94) compared with slope 1.5% (R^2=0.84). Zhang et al. (2002) found that the effect of slope gradient on detachment rate is more significant at steeper slopes.

3.2. Multi-parameter indicators

By multiplying flow depth and velocity, unit flow discharge can be obtained as a composite predictor. Figure 4 shows the relationship between detachment rate and unit flow discharge. The amount of q is varied between 2.9×10^{-4} to 8.9×10^{-4} m^2 s^{-1}. Increasing q detachment rate increases at both slopes, linearly. In addition, compared to slope 1.5%, detachment rate is higher at slope 2%. This means that due to increasing stream power as a result of flow discharge and slope gradient, detachment rate increased. The result also indicates that determination coefficient (R^2) was relatively more significant at slope 2%. Furthermore, the critical value of q is less for slope 2%, indicating that smaller flow discharges need to detach soil particles at this slope. Zhang et al. (2002) reported that detachment rate is more affected by flow discharge than slope gradient. Moreover, Zhang et al. (2003) found a linear relationship between flow discharge and detachment rate. Our result indicated that in general at low slopes, detachment rate is affected by both sheet flow discharge and slope gradient.

In most physical process-based erosion models, detachment rate has been expressed as a function of unit stream power (Moore and Burch, 1986; Yang, 1972), shear stress (Nearing et al., 1997) and stream power (Zhang et al., 2002). Based on definition, unit stream power is product of flow velocity (V) and slope gradient (S) and so the resultant V×S can be applied as a multi-parameter indicator for detachment rate. Figure 5 shows the relationship between detachment rate and unit stream power. This parameter ranged from 2.45×10^{-3} to 5.18×10^{-3} ms^{-1}. An unlinear relationship as exponential was found between detachment rate and unit stream power, so that increasing unit stream power detachment rate increased. This is because of this fact that unit stream power is function of velocity while, there was an unlinear relationship between velocity and detachment rate. It is apparent from the result that applying unit stream power, the influence of each slope on detachment rate can be separated. In addition, the relationship between detachment rate and mean flow velocity is more significant at slope 2% (R^2=0.94) compared with slope 1.5% (R^2=0.84).

Another combination of erosivity agents is defined as shear stress which is derived from D×S. The relationship between flow shear stress and detachment rate at 2 slopes is plotted in Figure 6. The result indicated that shear stress varied between 0.26 and 0.68 Pa. Also, detachment rate increased as a linear function of shear stress. Similar to the former indicators, determination coefficient (R^2) was more significant at slope 2% (R^2 = 0.96). Similarly, Zhu et al. (2001) found better relationship between detachment rate and shear stress for unlinear trend-line in comparison to linear one. Compared to unit stream power, shear stress found unable to distinguish the effect of two slopes on detachment rate. Our finding implies that critical shear stress is between 0.26 and 0.30 Pa.

Stream power is one of the best indicators of flow erosivity and is the resultant of multiplying flow depth, slope gradient and velocity is. The result showed that stream power ranged from 0.043 to 0.175 W m^{-2}. In this study, detachment rate increased as a linear function of stream power at both slopes (Figure 7). Yet, the relationship is more significant at slope 2% than slope 1.5%. In addition, the critical stream power at slopes of 1.5 and 2% was nearly the same (between 0.051 and 0.054 W m^{-2}). This implies that soil particles could be detached when stream power is more than 0.054 W m^{-2}. Proffitt and Rose (1991) and Proffitt et al. (1993) concluded that for stream powers less than 0.01 W m^{-2}, the greatest contribution to sediment concentration was attributed to rainfall detachment, whilst at higher stream powers, runoff entrainment was the dominant contributor to sediment concentration.

3.3. Comparison between indicators

Table 2 presents the summary results of relationship between detachment rate and hydraulic parameters. In general, all the indicators could predict detachment rate satisfactory, nevertheless, there are some differences in their capabilities. In addition, the relationship was found to be better at slope 2% than slope 1.5%. Among different indicators, flow velocity (V) and unit stream power (U) showed an unlinear relationship as exponential, whilst the others exhibited linear. This is a determinant issue, since process-based parameters such as soil erodibility and critical values can be determined more easily and accurate in linear state. In other words, a linear relationship refers to a constant slope for the fitted curve which is ascribed to soil erodibility, whereas determination of erodibility in unlinear scenario is disputable. Furthermore, in many studies (e.g. Nearing et al., 1989), a linear relationship has been fitted for obtaining the critical values of shear stress (τ_0) or stream power (Ω_0). Comparison of detachment rates at two applied slopes of 1.5 and 2% indicates that considering flow depth (D), unit flow discharge (q) and unit stream power (U) results in two different critical values. In other hand, these indicators seem not to be able to determine a unique critical value at different slopes.

According to Table 2, shear stress (τ) and stream power (Ω) are more satisfactory indicators in predicting detachment rate. Some other researchers (Zhang et al., 2002, 2003) believe that flow detachment rate is better correlated to stream power than either shear stress or unit stream power.

Moreover, shear stress is a hydraulic term associated with forces acting on soil surface, while stream power is an energy term (Zhang et al., 2002). Although, some researchers investigated detachment rate as a function of soil and hydraulic properties (Nearing et al. 1991; Parsons et al. 1994), some others focused on the dynamic and modeling of overland flow (Rose at al. 2006).

Table 2. The summery results of relationship between detachment rate and hydraulic parameters

Indicator	Determination coefficient (R^2)		Relationship type	
	Slope 1.5%	Slope 2%	Slope 1.5%	Slope 2%
Flow depth (D)	0.86	0.96	Linear	Linear
Flow velocity (V)	0.84	0.94	Exponential	Exponential
Unit flow discharge (q=DV)	0.87	0.96	Linear	Linear
Unit stream power (U=VS)	0.84	0.94	Exponential	Exponential
Shear stress (τ =ρgDS)	0.86	0.96	Linear	Linear
Stream power (Ω=ρgDSV)	0.87	0.96	Linear	Linear

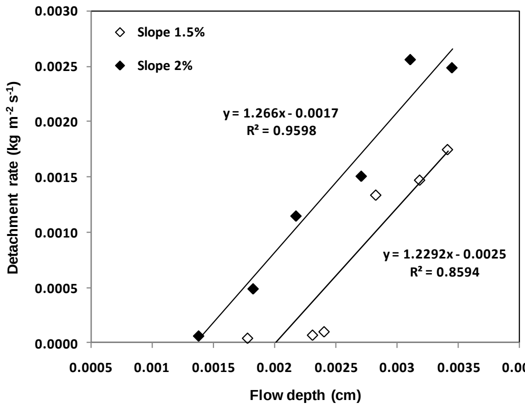

Figure 2. Relationship between detachment rate and flow depth (D) at two different slopes.

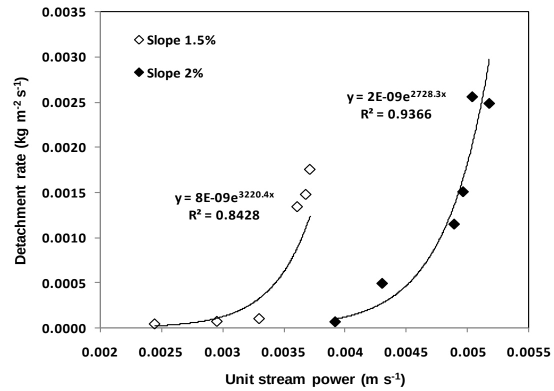

Figure 5. Detachment rate as a function of unit stream power (U=VS) at two different slopes.

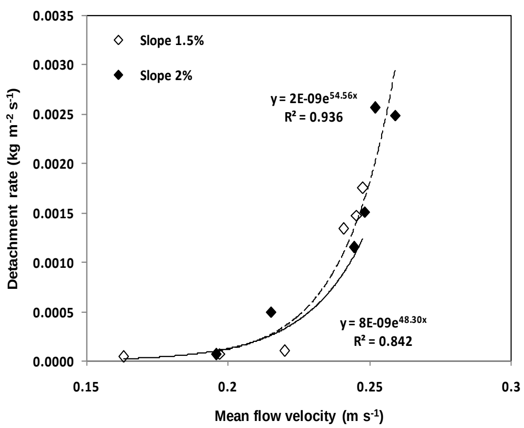

Figure 3. Detachment rate as a function of mean flow velocity (V) at two different slopes.

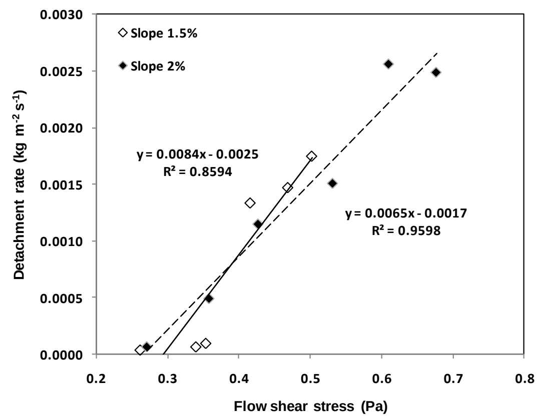

Figure 6. Relationship between detachment rate and flow shear stress (τ =ρgDS) at two different slopes.

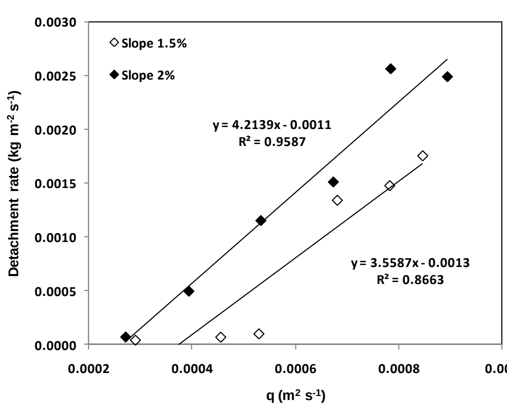

Figure 4. Relationship between detachment rate and unit flow discharge (q=DV) at two different slopes.

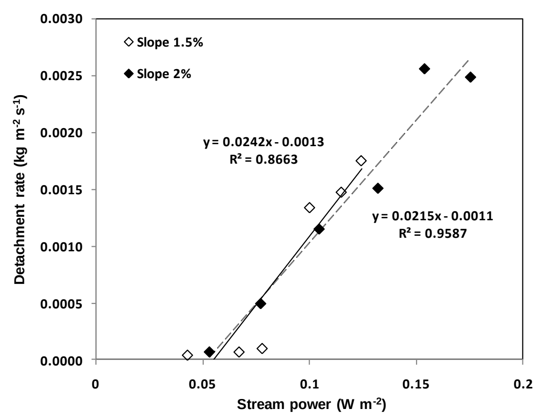

Figure 7. Relationship between detachment rate and stream power (Ω=ρgDSV) at two different slopes.

Based on definition, τ is obtained through D×S, while Ω is the result of q×S. In flume studies at low slopes, especially for those simulated low stream powers, shallow surface flow is generated. In this condition, measurement of flow depth is difficult and/or mistakable. In comparison, unit flow discharge (q) can be measured by volumetric method, accurately. This practical fact implies that stream power is a better indicator to predict soil detachment rate.

4. Conclusion and Recommendations

The relationship between detachment rate and different hydraulic parameters as erosive indicator showed that in general, the relationship is better fitted at slope 2% than slope 1.5%. Among different indicators, flow velocity and unit stream power exhibited an unlinear relationship as exponential, whereas determination of erodibility in unlinear scenario is disputable. It was concluded that considering flow depth, unit flow discharge and unit stream power results in two different critical values at different slopes. In fact, using these indicators at different slopes, a unique critical value is not achieved. In flume studies at low slopes, especially for those simulated low stream powers, shallow surface flow is generated. In this condition, measurement of flow depth is difficult and/or mistakable while, unit flow discharge can be measured, accurately. The finding of this research reveals that stream power is the best indicator for predicting soil detachment rate.

References

1. Defersha, M. B., Quraishi, S. and Melesse, A. (2011). The effect of slope steepness and antecedent moisture content on interrill erosion, runoff and sediment size distribution in the highlands of Ethiopia. Hydrol. Earth Syst. Sci., 15: 2367-2375.
2. Deng, Z. Q., Lima, J. L. D. and Jung, H. S. (2008). Sediment transport rate-based model for rainfall-induced soil erosion. Catena, 76: 54-62.
3. Erskine, W. D., Mahmoudzadeh, A. and Myers, C. (2002). Land use effects on sediment yields and soil loss rates in small basins of Triassic sandstone near Sydney, NSW, Australia. Catena, 49, 271-287.
4. Fu, S., Liu, B., Liu, H. and Xu, L. (2011). The effect of slope on interrill erosion at short slopes. Catena, 84, 29-34.
5. Ghadiri, H. and Rose, C. W. (1992). An Introduction to Nonpoint Source Pollution Modeling. In: Ghadiri, H. and Rose, C. W., (Eds.), Modeling Chemical Transport in Soils, Natural and Applied Contaminants. LEWIS Publication, pp. 1-14.
6. Gimenez, L. and Govers, G. (2002). Flow detachment by concentrated flow on smooth and irregular beds. Soil Sci. Soc. Am. J., 66:1475-1483.
7. Govers, G. (1992). Evaluation of transport capacity formulae for overland flow. In: Parsons, A. J. and Abrahams, A. D. (Eds.), Overland flow: hydraulics and erosion mechanics. UCL Press, London. pp. 243-273.
8. Hairsine, P. B. and Rose, C. W. (1992a). Modeling water erosion due to overland flow using physical principles. 1. Sheet flow. Water Resour. Res., 28:237-243.
9. Hairsine, P. B. and Rose, C. W. (1992b). Modeling water erosion due to overland flow using physical principles. 1. Rill flow. Water Resour. Res., 28:245-250.
10. Moore, I. D., and Burch, G. J. (1986). Sediment transport capacity of sheet and rill flow: Application to unit stream power theory. Water Resour. Res. 22:1350-1360.
11. Morgan, R. P., Quiton, J. N., Smith, R. E., Govers, G., Poesen, J. W., Auerswald, K., Chisci, G., Torri, D. and Stycaen, M. E. (1998). The European soil erosion model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. Earth Surf. Process. Landforms, 23(6): 527-544.
12. Nearing, M. A., Bradford, J. M. and Parker, S. C. (1991). Soil detachment by shallow flow at low slopes. Soil Sci. Soc. Am. J., 55: 339-344.
13. Nearing, M. A., Foster, G. R., Lane, L. J. and Finkner, S. C. (1989). A process-based soil erosion model for USDA-Water Erosion Prediction Project Technology. Trans. ASAE., 32(5): 1587-1593.
14. Nearing, M. A., Norton, L. D., Bulgakov, D. A. and Larionov, G. A. (1997). Hydraulics and erosion in eroding rills. Water Resour. Res., 33:865-876.
15. Nearing, M.A. (2004). Capabilities and limitations of erosion models and data. ISCO 2004. 13th International Soil Conservation Organization Conference. Brisbane, Australia.
16. Page, A. L., Miller, R. H. and Jeeney, D. R. (1992a). Methods of Soil Analysis, Part 1. Physical Properties. SSSA Pub., Madison. 1750 p.
17. Page, A. L., Miller, R. H. and Jeeney, D. R. (1992b). Methods of Soil Analysis, Part 2. Chemical and Mineralogical Properties. SSSA Pub., Madison. 1159 p.
18. Pan, C., Shangguan, Z. and Lei, T. (2006). Influences of grass and moss on runoff and sediment yield on sloped loess surfaces under simulated rainfall. Hydrol. Process., 20: 3815-3824.
19. Pansu, M. and Gautheyrou, J. (2006). Handbook of Soil Analysis, Mineralogical, Organic and Inorganic Methods. Springer. 993 p.

20. Parsons, A. J., Abrahams, A. D. and Wainwright, J. (1994). On determining resistance to interrill overland flow. Water Reso. Res., 30, 3515-3521.

21. Pieri, L., Bittelli, M., Wu, J. Q., Dun, S., Flanagan, D. C., Pisa, P. R., Ventura, F. and Salvatorelli, F. (2007). Using the Water Erosion Prediction Project (WEPP) model to simulate field-observed runoff and erosion in the Apennines mountain range, Italy. J. Hydro., 336: 84-97.

22. Proffitt, A. P. B. and Rose, C. W. (1991). Soil erosion processes: I. The relative importance of rainfall detachment and runoff entrainment. Aust. J. Soil Res., 29: 671-683.

23. Proffitt, A. P. B., Hairsine, P. B. and Rose, C. W. (1993). Modeling soil erosion by overland flow: Application over a range of hydraulic conditions. Trans. ASAE., 36 (6): 1743-1753.

24. Rose, C. W., Parlange, J. Y., Sander, G. C., Campbell, S. Y. and Barry, D. A. (1983). Kinematic flow approximation to runoff on a plane: An approximate analytic solution. J. Hydro., 62: 363-369.

25. Rose, C. W., Williams, J. R., Sander, G. C. and Barry, D. A. (1983a). A mathematical model of soil erosion and deposition processes: I. Theory for a plane land element. Soil Sci. Soc. Am. J., 47: 991-995.

26. Rose, C. W., Williams, J. R., Sander, G. C. and Barry, D. A. (1983b). A mathematical model of soil erosion and deposition processes: II. Application to data from an arid-zone catchment. Soil Sci. Soc. Am. J., 47: 996-1000.

27. Rose, C. W., Yu, B., Ghadiri, H., Asadi, H., Parlange, J. Y., Hogarth, W. L. and Hussein, J. (2006). Dynamic erosion of soil in steady sheet flow. J. Hydro. 333, 449-458.

28. Shih, H. M. and Yang, C. T. (2009). Estimating overland flow erosion capacity using unit stream power. Int. J. Sediment Res., 24: 46-62.

29. Walkley, A., Black, I. A. (1934). An examination of the degtjareff method for determining soil organic matter, and proposed modification of the chromic acid titration method. Soil Sci., 37: 29-38.

30. Yan, L. J., Yu, X. X., Lei, T. W., Zhang, Q. W. and Qu, L. Q. (2008). Effect of transport capacity and erodibility on rill erosion processes: A model study the Finite Element method. Geoderma, 146: 114-120.

31. Yang, C.T. (1972). Unit stream power and sediment transport. J. Hydraulics Div. Am. Soc. Civil Eng., 98:1805-1825.

32. Zhang, G. H., Liu, B. Y., Liu, G. B., He, X. W. and Nearing, M. A. (2003). Detachment of undisturbed soil by shallow flow. Soil Sci. Soc. Am. J., 67: 713-719.

33. Zhang, G. H., Liu, B. Y., Nearing, M. A., Huang, C. H. and Zhang, K. L. (2002). Soil detachment by shallow flow. Trans. ASAE., 45: 351-357.

34. Zhang, G. H., Liu, Y. M., Han, Y. F. and Zhang, X. C. (2009). Sediment transport and soil detachment on steep slopes: I. Transport capacity estimation. Soil Sci. Soc. Am. J., 73: 1291-1297.

35. Zhang, G. H., Wang, L. L., Tang, K. M., Luo, R. T. and Zhang, X. C. (2011). Effect of sediment size on transport capacity of overland flow on steep slopes. Hydro. Sci. J., 56(7): 1289-1299.