RAINFALL AND SLOPE CHARACTERISTICS AFFECTING SOIL EROSION ON HILLSLOPES

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ABSTRACT

A soil erosion model including interrill erosion and rill erosion was developed for hillslope. The rainfall and slope characteristics affecting soil erosion on hillslopes was analyzed by simulation. The results show that the slope length and gradient, rainfall intensity and process have varying influence on runoff and soil erosion. The unit discharge of runoff and erosion rate increases with increases in the rainfall intensity and the slope length. The same precipitation but with different rainfall processes may cause different runoff and erosion results. The effect of the slope gradient on runoff and soil erosion can be both positive and negative. There exists a critical slope gradient for runoff and soil erosion.

1. INTRDUCTION

Soil erosion on hillslopes is a complex process of the interaction between rainfall and soil. The rainfall and slope characteristics have important influence on soil erosion. In the Loess Plateau area of China, serious soil erosion over long periods leads to fragmentation of surface morphology. The lengths and slope gradients of hillslopes are appreciably different. Besides, the distribution of precipitation is highly nonuniform, and the rainfall intensity of rainstorms is also quite different. These extreme differences in topography and rainfall lead to different erosion characteristics. Therefore, the study of the basic characteristics of soil erosion on slopes is essential for the protection of soil in the Loess Plateau area.

The simulation model is an important tool to investigate the characteristics of soil erosion on hillslopes. However, most of the models have been applied to predict soil erosion from a watershed, and do not discuss the characteristics of erosion on a hillslope. This may partly be due to inadequate knowledge of physical processes leading to soil erosion and paucity of experimental and field data. Therefore, the objective of this study was to develop a soil erosion dynamic model based on physical processes and investigate the characteristics of soil erosion on hillslopes.

2. EROSION MODEL ON HILLSLOPE

The soil erosion on hillslopes can simply generalize into two basic dynamics processes, including the process of runoff generation caused by rainfall, and the process of sediment yield and transport on hillslopes by overland flow. Thus, the proposed model includes two component models: the rainfall-runoff sub-model, and the soil erosion sub-model.

2.1 Rainfall-Runoff Model

Overland flow is the result of interaction between rainfall and infiltration. The kinematic wave approximation has long been applied successfully to hillslopes (Woolhiser and Liggett 1967; Singh 1996). The governing equations of overland flow on the hillslopes can be written as:

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=p\cos\theta-i \qquad (1)$$

$$q=n^{-1}h^{5/3}S_0^{1/2} \qquad (2)$$

where x (m) is the distance down slope, h (m) is the water depth, q (m^2s^{-1}) is the unit width discharge, p is the actual rainfall intensity, i (ms^{-1}) is the soil infiltration, θ is the inclination angle of slope, n ($sm^{-1/3}$) is the Manning roughness coefficient, and S_0 is the slope gradient ($S_0=\sin\theta$).

A revised Green-Ampt infiltration model was employed to describe the process of rainfall infiltration (Mein and Larson, 1973). The infiltration rate can be expressed as following form:

$$\begin{aligned} i &= p, \qquad & t \le t_p \\ i &= K[1+(\theta_s-\theta_i)S/I, \qquad & t > t_p \end{aligned} \tag{3}$$

where *K* is the saturated hydraulic conductivity, θ_s is the saturated volumetric water content, θ_i is the initial volumetric water content, and *S* is the soil suction, *I* is the cumulative infiltration, t_p is the time to ponding, $t_p = I_p / p$. I_p is the cumulative infiltration when the infiltration rate equals the rainfall rate.

$$I_p = (\theta_s - \theta_i)S/(p/K-1) \tag{4}$$

$$K(t-t_p) = I - I_p - S(\theta_s-\theta_i)\ln\left[\frac{I+S(\theta_s-\theta_i)}{I_p+S(\theta_s-\theta_i)}\right] \tag{5}$$

2.2 Soil Erosion Model

In general, the soil erosion on hillslopes includes two parts of interrill erosion and rill erosion, which can be described by the following sediment continuity equation (Govers and Poesen 1988; Liu, et al. 2006):

$$\frac{\partial hC}{\partial t} + \frac{\partial qC}{\partial x} = D_r + D_i \tag{6}$$

where *C* is the sediment concentration, D_r is the rill erosion rate, and D_i is the interrill erosion rate.

Interrill erosion depends on soil and slope characteristics, rainfall intensity, and hydraulic factors of runoff. Based on the experiments, a formula for interrill erosion rate was derived by Liu et al. (2005):

$$\frac{D_i d}{R_c} = 1.8\times10^{-9}\left(\frac{h}{d}\right)^{1.5}(1.05-0.85e^{-4\sin\theta}) \tag{7}$$

where R_c (kgs^{-1}m^{-1}) is the saturated sediment-transport capacity of overland flow, which can be calculated according to Low (1989) , and *d* (m) is the diameter of soil particles.

The sediment transport in rill flow generally belongs to non-equilibrium transport. Assuming that the rill erosion rate is proportional to the difference between the maximum sediment transport capacity of rill flow T_c and the actual sediment transport rate q_s, one has:

$$D_r = \alpha(T_c - q_s) \tag{8}$$

The maximum sediment transport capacity of rill flow T_c can be calculated by Yalin's formula (Yalin, 1963).

The parameter α can be named as the restoration coefficient of sediment transport capacity. In general, α is not a constant and depends on the flow properties and sediment condition. Using a series of experiments in laboratory, we obtained the following relationship (Liu et al. 2007):

$$\frac{1/\alpha}{R} = 1.5\times10^4\left[\frac{\tau-\tau_c}{(\rho_s-\rho)gd}\right]^{0.15}\left(\frac{u}{\sqrt{gd}}\right)^{-1} S_0^{1.5} \tag{9}$$

where *R* is the hydraulic radius, τ is the flow shear stress, τ_c is the critical shear stress.

3. INFLUENCE OF RAINFALL

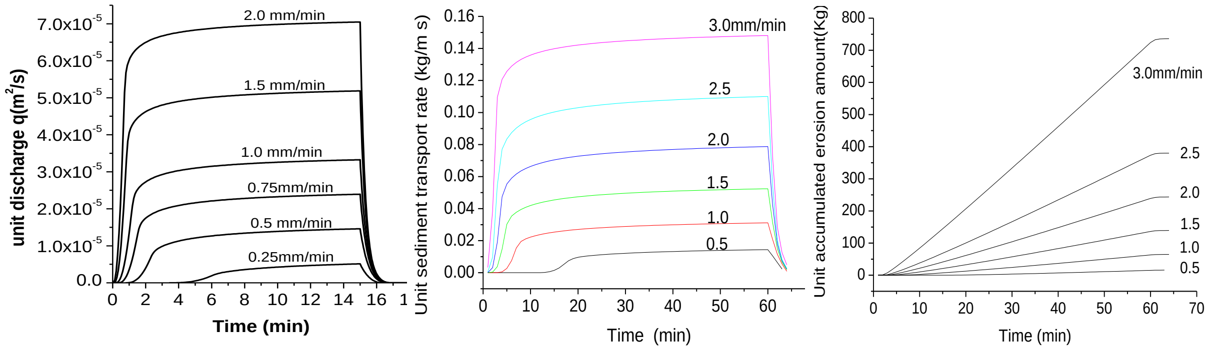
The influences of the length and slope gradient of hillslopes, rainfall intensity and distribution on the runoff and soil erosion processes were analyzed by applying the proposed soil erosion. The soil parameters used in calculation are shown in Table 1.

Table 1 Soil Parameters Used in Calculation

Parameter	Value	Parameter	Value	Parameter	Value
θ_s	57(m^3/m^3)	γ_0	1300 N/m^3	K	0.75 mm/h
θ_i	12(m^3/m^3)	d	0.05 mm	S	0.06 m

3.1 Rainfall Intensity

Runoff and soil erosion on the slope were simulated for six different rainfall intensities. The calculated values of unit discharge of runoff, unit erosion (sediment transport) rate and unit accumulated erosion amount as functions of time for various rainfall intensities are shown in Figure 1 (a), (b) and (c), respectively. The simulated results show that the unit discharge of runoff, the unit erosion rate and the unit cumulative erosion amount increased remarkably as the rainfall intensity increased. However, it is worth noting that they do not increase linearly with rainfall intensity. This is because of two reasons. First, the excess rainfall increases more for rainstorms with greater rainfall intensity; second, the eroding and transport capability of runoff does not increase linearly with runoff. The result is that large rainstorms easily cause greater runoff and erosion. Indeed, what is unique about erosion on the Loess Plateau is that the bulk of it always occurs during large rainstorms.



(a)Unit discharge of runoff **(b) Unit erosion rate** **(c) Unit accumulated erosion amount**

Figure 1 Soil Erosion for Different Rainfall Intensities

3.2 Rainfall Process

To analyze the influence of rainfall process, three kinds of rainstorms were chosen. The peak of Type A rainstorm is in the beginning of the duration, the peak of Type B is in the center of the duration, and the peak of Type C is toward the end, as shown in Figure 2. Especially, among them, rainstorm A and rainstorm C have the same rainfall amount.

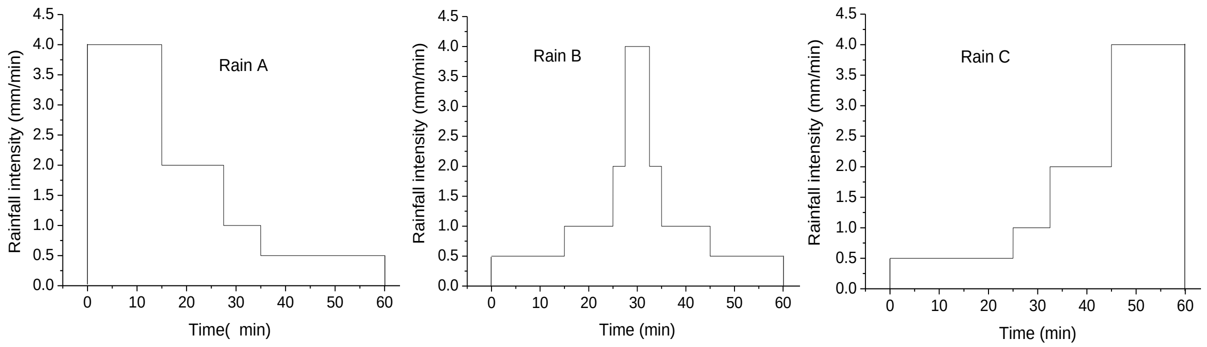
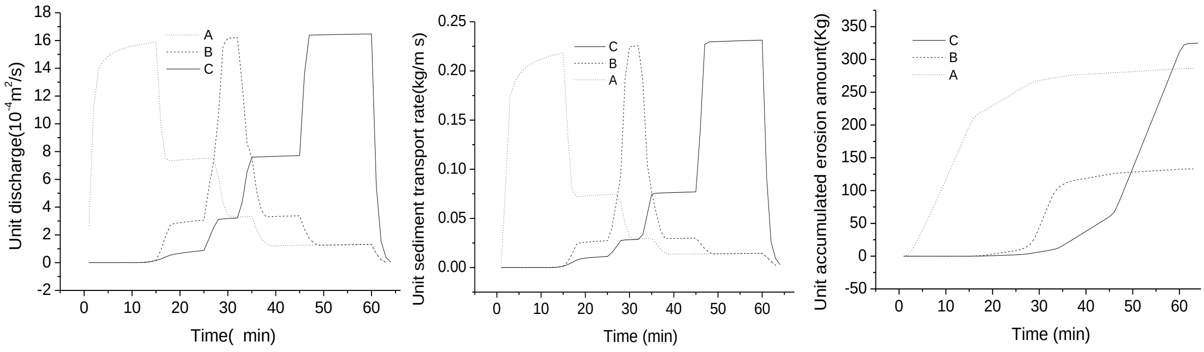


Figure 2 Three Kinds of Rainstorms

Keeping soil parameters unchanged (see Table 1), runoff and soil erosion processes on hillslope were simulated for these three kinds of rainstorms (Type A, Type B and Type C). Figure 3 illustrates the simulation results of unit discharge of runoff, unit sediment transport rate and unit accumulated erosion amount as functions of time. Visibly, different rainfall patterns led to different runoff processes and erosion results. Especially, for the two kinds of rainfall patterns (A and C) with the same rainfall amount, the peak of unit sediment transport rate for rainfall Type C is a little greater than that for rainfall Type A. Similarly, the unit accumulated erosion amount for rainfall C is a little greater than for rainfall A. This indicates that the same rainfall quantity but different rainfall process may generate a little different erosion values. The latter peak value of rainstorm may lead to more serious soil erosion. In fact, in the initial period of rainfall the infiltration rate is high and then it rapidly starts decreasing; as a result the infiltration rate becomes lower and steadier and the rainfall excess rate becomes higher with time for the same intensity of rain. This is the reason that the latter the rainfall peak the higher the eroding capability of runoff at the moment of the peak value.



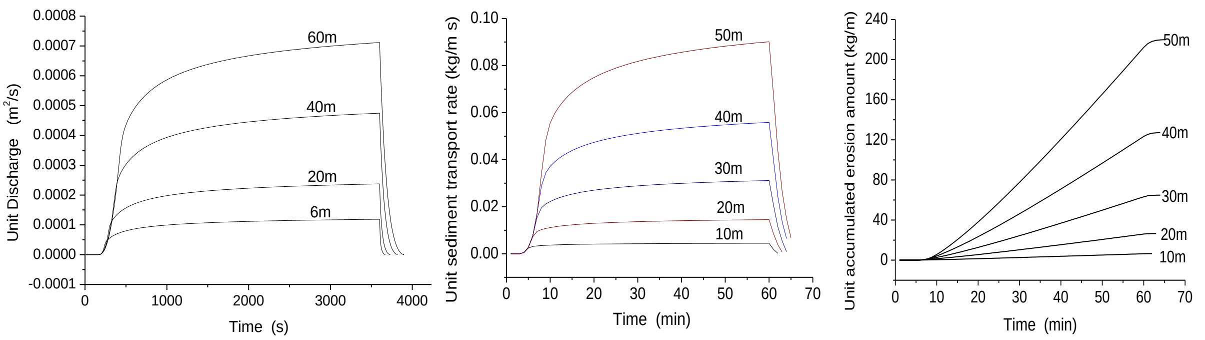
(a)Unit discharge of runoff **(b) Unit erosion rate** **(c) Unit accumulated erosion amount**

Figure 3 Runoff and Erosion Characteristics for Different Rainfall Processes

4. INFLUENCE OF SLOPE CHARACTERISTICS

4.1 Slope Length

Under the condition of uniform rainfall intensity (1mm/min), the processes of runoff and soil erosion were simulated for different slope lengths. Figure 4 shows the calculated unit discharge of runoff, unit sediment transport rate and unit accumulated erosion amount for various slope lengths. The calculated results show that the unit discharge of runoff, the unit erosion rate and unit accumulated erosion amount increased remarkably as the slope length increased. In the initial period of erosion, the unit discharge and erosion rate of runoff increased quickly, then gradually tended to steady value. Correspondingly, the accumulated erosion amount increased slowly in the initial period, then, gradually reached a linear increase. In fact, the sediment transport rate increased nonlinearly along the slope, i.e., it did not increase linearly with the slope length. This indicates that the influence of the slope length became gradually weaker when the slope length decreased to a certain extent. This result reveals that short slopes would be beneficial for decreasing soil erosion.



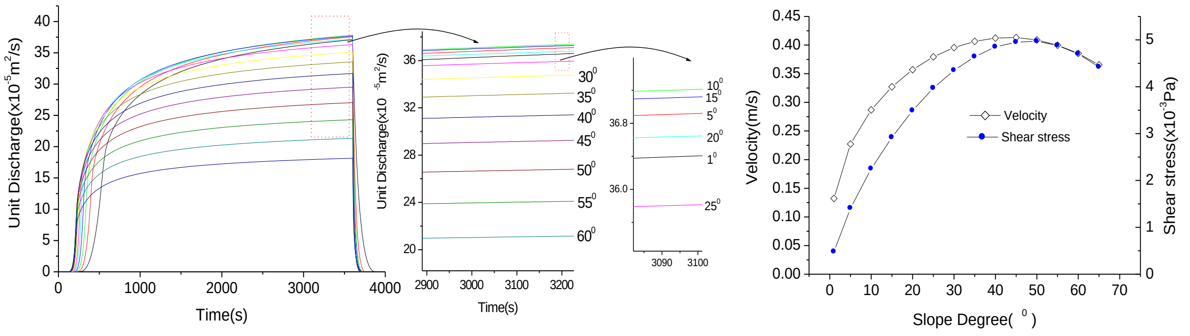
(a)Unit discharge of runoff **(b) Unit erosion rate** **(c) Unit accumulated erosion amount**

Figure 4 Runoff and Soil Erosion for Different Slope Lengths

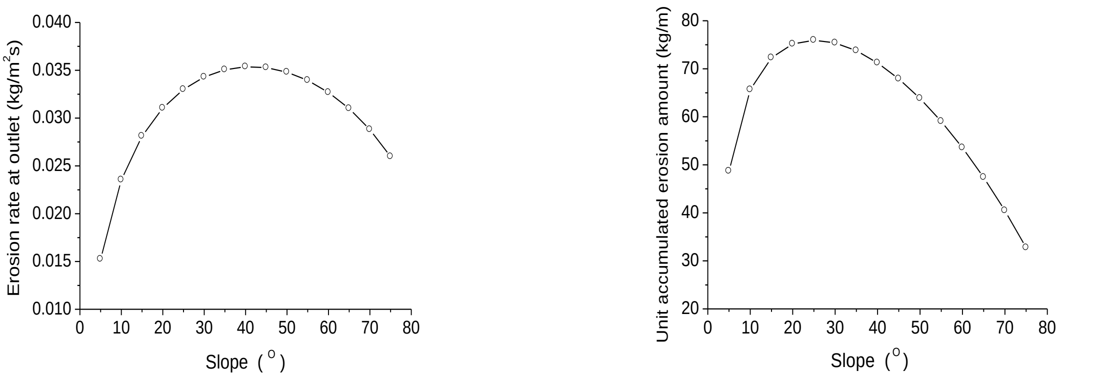
4.2 Slope Gradient

The influence of slope gradient on runoff generation on hillslopes was firstly analyzed. The simulated results were shown in Figure 5 (a) and (b). The processes of runoff discharge are different for different slope gradients. The flow velocity and shear stress at the outlet initially increased with the slope gradient, and then began to decrease when the slope gradient reached a critical value (as shown in Figure 5(b)). Although the corresponding critical slopes were not equal, both of them were found within the range of about 40^O~50^O.

For uniform rainfall intensity (1mm/min), soil erosion was calculated for fifteen slope gradients. The simulation results are illustrated in Figure 5 (c) and (d). The influence of the slope gradient on soil erosion was rather complex. For steady erosion, the calculation results show that the erosion rate at the outlet and accumulated erosion amount initially increased with the slope gradient, and then began to decrease when the slope gradient reached a critical value. However, the corresponding critical slopes for erosion rate at the outlet and accumulated erosion amount were not equal. The erosion rate reached a maximum value at about 45^0 of the slope gradient, and the maximum value of accumulated erosion amount occurred at about 25^0 of the slope gradient.



(a) Unit discharge of runoff **(b) Velocity and shear stress**



(a) Unit erosion rate at the outlet **(b) Unit accumulated erosion amount**

Figure 5 Influences of Slope Gradient on Runoff and Soil Erosion

The erosion rate mainly depends on velocity and shear stress of runoff, so it is easy to understand that erosion rate has a critical slope gradient at about 45^0. However, the variation of erosion rate along the slope is nonlinear and is also different for different slope gradients. Thus, the critical value of the accumulated erosion amount occurred at about 25^O. This is one of the reasons that most theoretical analysis results give greater critical slopes of about 40^o~50^o, and most experimental observations yield smaller critical slopes of about 20^o~30^o. Most theoretical results were obtained from an analysis of the eroding capability, i.e., erosion rate of overland flow, but most experimental results were obtained by analyzing the total erosion quantity, i.e., accumulated erosion amount.

The slope gradient is one of the most important factors affecting the surface flow erosion. The above analysis shows that it is more important to decide the critical slope of soil erosion from accumulated erosion amount. The results obtained here may be significant for programming the utilization of slope land in the Loess Plateau area of China.

5. CONCLUDING REMARKS

A soil erosion model including interrill erosion and rill erosion was developed for hillslopes. The rainfall and slope characteristics affecting runoff and soil erosion on hillslope was analyzed by simulation. The following conclusions are drawn from this study:

(1) The unit discharge of runoff, unit erosion rate and accumulated erosion amount increase remarkably as rainfall intensity increases. However, both unit erosion rate and accumulated erosion amount do not increase linearly with rainfall intensity.

(2) Different rainfall patterns led to different runoff processes and erosion results. The same rainfall amount but with different rainfall processes may cause different erosion amounts. Although the differences between them are small, there exists the trend that the later the rainfall peak value is, the higher the maximum values of the main hydraulic parameters are. Similarly, the later the rainfall peak value the higher the eroding capability which can lead to more serious soil erosion.

(3) The unit discharge of runoff, unit erosion rate and accumulated erosion amount increase remarkably as the slope length increases. The unit erosion rate increases nonlinearly along the slope and soil erosion becomes more serious with the increase of the slope length. This result reveals that short slopes would be beneficial for decreasing soil erosion.

(4) There exists a critical slope gradient for runoff generation and soil erosion. With increasing slope gradient, the unit runoff discharge, unit erosion rate at the outlet and accumulated erosion amount first increase to a peak value, then decrease again. However, the critical slopes are different for runoff discharge, erosion rate at the outlet and the total erosion amount. The critical slope gradient is about 45^o for unit discharge of runoff and erosion rate at the end of the slope, but about 25^o for the accumulated erosion amount.

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6. REFERENCES

Govers, G. and Poesen, J.W.A. (1988). Assessment of interrill and rill contribution to total soil loss from an upland field plot. *Geomorphology*, 1(4), pp 343-345.

Liu, Q.Q., Chen, L., Li, J.C., et al.(2007). A non-equilibrium sediment transport model for rill erosion. *Hydrol. Process.*, 21, pp1074-1084

Liu, Q.Q., Singh, V.P., Xiang, H. (2005). Plot erosion model using gray relational analysis method. *J. Hydrol. Eng.*,10(4), pp 288-294.

Liu, Q.Q., Xiang, H., Singh, V.P.(2006). A simulation model for unified interrill erosion and rill erosion on hillslopes. *Hydrol. Process.*, 20, pp469-486.

Low, H.S. (1989). Effect of sediment density on bed-load transport. *J. Hydraul. Eng.*, ASCE, 115, pp 124-138.

Mein, R.G. and Larson, C.L. (1973). Modeling infiltration during a steady rain. *Water Resour. Res.*, 9 (2), pp 384-394.

Singh V.P. (1996). Kinematic wave modeling in water resources: Surface Water Hydrology. John Wiley & Sons, New York.

Woolhiser D.A., Ligget J.A. (1967). Unsteady, one dimensional flow over a plane—The rising diagram. Water Resources Research 3 (3): 753-771.

Yalin, M.S. (1963). An expression for bed-load transportation. *J. Hydraul. Div.*, ASCE, 89, pp 221-248.