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The Water Erosion Prediction Project: Erosion Processes

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The erosion process on hillslopes is conceptualized in the USDA Water Erosion Prediction Project (WEPP) as being divided into rill and interrill processes. Interrill erosion is described as a process of soil detachment by raindrop impact and sediment delivery to adjacent rill flow areas. Rill erosion is described as a rate process proportional to the flow's ability to detach sediment, sediment transport capacity, and the existing sediment load in the flow. Rill detachment occurs when hydraulic shear stress exceeds the critical shear stress of the soil and when sediment load in the rill is less than transport capacity. Net deposition occurs when sediment load is greater than transport capacity. Runoff peak rate, effective runoff duration, and effective rainfall intensity are the only hydrologic variables required for erosion calculations. This paper presents, with a certain detail, the basic concepts and governing equations used in WEPP to predict soil erosion on hillslopes. The physical nature of the parameters used in the erosion equations and their implications on erosion predictions are also briefly described.

Introduction

The first attempts to develop soil erosion prediction technology were initiated in the late nineteenth century (Hudson

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1971). The early single factor equations were developed based on local conditions. Multiple factor empirical equations were developed when more data became available and the basic understanding of the contributing factors improved (Ellison 1947; Musgrave 1947). Analyses of plot data from natural storms and from rainfall simulator studies culminated in the development of the equation most widely used today for upland erosion prediction - the Universal Soil Loss Equation (USLE) (Wischmeier & Smith 1960). Despite its widespread use and the breadth of experience which it incorporates, the equation is empirically based and does not include the processes of detachment and deposition in rill flow areas. The current perspective in soil erosion science is that process based mathematical models promise to be the most viable approach to improve understanding of the fundamental erosion processes and to enhance erosion assessment and control technology (Lane et al. 1988).

The objective of this paper is to present the basic concepts and governing equations used in the USDA Water Erosion Prediction Project (WEPP) models to predict soil erosion on hillslopes.

Basic Concepts

Soil erosion by water is the process of detachment and transport of soil particles by raindrop impact and runoff. Detachment is the removal of soil particles from the soil mass. Transport is the movement of sediment, detached soil particles, to a location away from the point of detachment. Impacting raindrops and surface runoff are the principal agents of soil particle detachment. Surface runoff is the principal agent of sediment transport. An impacting raindrop creates intense shear and pressure forces along the soil surface, which can detach large quantities of particles from the soil matrix. Detachment and transport of noncohesive sediment by runoff is controlled by slope length, slope steepness, particle size and weight distribution, electrochemical inter-particle forces, and gravitational and hydrodynamic forces.

To describe the extremely complex nature of the erosion process on hillslopes, the WEPP modeling approach conceptually divides the erosion process into interrill and rill erosion processes. The interrill erosion process is described in terms of detachment by raindrop impact and lateral transport of sediment by sheet flow into rill flow areas. The rill erosion process is described in terms of detachment and transport of sediment by concentrated flow in rill flow areas.

Overland Flow Hydraulics

Overland flow is represented in two ways in the WEPP hillslope model. First, unsteady state broad sheet flow on an idealized surface is assumed for the overland flow routing and hydrograph development. The overland flow routing procedure includes two options: an analytical solution to the kinematic wave equations, based on the method of characteristics, and a set of regression equations derived from the analytical solution for a broad range of slope gradients and slope lengths, surface roughnesses, soil textures, and rainfall distribution patterns. Because the analytical solution to the kinematic wave equations requires an upper boundary condition of zero flow depth, the concept of equivalent plane is used as a means to route water on a cascade of planes. Briefly, the equivalent plane concept assumes that a series of planes with different surface and slope characteristics can be represented by a single plane with equivalent surface and slope characteristics.

Once the runoff peak rate has been determined by using one of the methods mentioned above, the effective duration of runoff (defined as the time required to produce a total runoff volume for the rainfall event with a constant runoff at peak rate) is calculated. Steady state flow condition is then assumed at the runoff peak rate for rill (concentrated flow) erosion calculations. Erosion and deposition rates are calculated over a characteristic time to produce estimates of net erosion and net deposition for the entire runoff event.

Separate estimates of the Darcy-Weisbach friction factor are made for the rill and interrill areas. The total friction factor for rill areas (f_r) is calculated from:

$$f_r = f_s + f_c \tag{1}$$

where f_s = friction factor for smooth bare soil; and f_c = friction factor due to the cover by nonmovable material such as ground residue, stems, or stones.

The total friction factor for interrill areas (f_i) includes the same two components as does the total friction factor for rill areas plus an additional friction factor for surface roughness induced by tillage operations. A total equivalent friction factor is computed as an area weighted average of the rill and interrill values by the relationship:

$$f_t = (f_s + f_c)\, A_r + f_i\, (1 - A_r) \tag{2}$$

where f_t = total equivalent friction factor for overland flow areas; and A_r = fraction of total overland flow area occupied by rill areas. The total equivalent friction factor is used for overland flow routing.

Once the routing procedure is completed, overland flow is partitioned into interrill and rill flow. Rill width (b) is estimated by assuming a rectangular rill cross section and using the relationship:

$$b = b_r(Q)^{0.3} \tag{3}$$

where b_r = rill width coefficient computed as a function of fraction of silt in the tilled soil layer and average slope gradient ($T^{1/3}$); and Q = total discharge (L^3/T) which is computed as:

$$Q = q_p x r_s \tag{4}$$

where q_p = peak runoff rate per unit area (L/T); x = distance downslope (L); and r_s = rill spacing (distance between rills) (L).

Rill flow depth (y) is computed iteratively using the friction factor of the rill, the rill width, and the slope gradient:

$$y = \left(\frac{Q}{CS^{1/2}}\right)^{2/3} \frac{(b + 2y)^{1/3}}{b} \tag{5}$$

where, C = Chezy resistance coefficient ($L^{1/2}/T$) and is related to the Darcy-Weisbach roughness coefficient for rill flow as follows:

$$C = [8g/(f_r)]^{1/2} \tag{6}$$

where, g = acceleration of gravity (L/T^2); and S = slope gradient (dimensionless).

Rill cross-sectional area (A), wetted perimeter (P), and hydraulic radius (R) are then computed as A = by, P = b+2y, and R = A/P, respectively.

Sediment Transport Equation

Steady state sediment transport in one-dimensional flow in a single rill is described by the continuity equation (Foster 1982):

$$d(Q_s)/dx = d_r + d_i \tag{7}$$

where Q_s = local sediment load (M/T); x = distance downslope (L); d_r = net detachment or net deposition rate per unit length (M/L/T);

and d_i = lateral sediment inflow rate from the interrill area to the rill flow per unit length (M/L/T). In the WEPP hillslope model sediment load is converted to a unit rill width basis, or:

$$d(G)/dx = D_r + D_i \tag{8}$$

where $G = Q_s/b$ = sediment load per unit width (M/L/T); D_r = net detachment or net deposition rate per unit rill area ($M/L^2/T$); and D_i = lateral sediment inflow rate per unit rill area ($M/L^2/T$).

Rill Detachment and Deposition

Rill detachment is described in the WEPP hillslope model as a rate process proportional to the flow's ability to detach soil particles, sediment transport capacity, and existing sediment load in the flow. Rill detachment is calculated using an expression developed by Foster & Meyer (1972) for steady state flow:

$$D_r = D_c(1 - G/T_c) \qquad \text{for } T_c \geq G \tag{9}$$

where D_c = detachment capacity of flow ($M/L^2/T$); and T_c = sediment transport capacity of flow (M/L/T). Detachment capacity, D_c, and transport capacity, T_c, are defined by flow hydraulics, sediment properties, and soil conditions at a location. Equation (9) represents the concept that rill detachment is directly proportional to the difference between transport capacity and sediment load. Detachment capacity, D_c, is computed as:

$$D_c = \begin{cases} K_r(\tau - \tau_c) & \text{for } \tau > \tau_c \\ 0 & \text{for } \tau \leq \tau_c \end{cases} \tag{10}$$

where K_r = rill soil erodibility parameter (T/L); τ = average shear stress acting on the rill wetted perimeter (F/L^2); and τ_c = critical shear stress required for detachment to occur (F/L^2). Parameters K_r and τ_c are a function of soil properties and management conditions. For instance, tillage operations reduce τ_c and increase K_r leaving the soil more erodible than when undisturbed.

Equations (9) and (10) represent the concept that net detachment occurs in rill flow areas when the transport capacity (T_c) is greater than the sediment load (G) and the shear stress acting on the soil exceeds the critical shear stress. When the sediment load is greater than the transport capacity, equation (9) becomes negative, indicating net deposition, and it is rewritten (Foster & Meyer 1975) as:

$$D_r = (\beta V_f/q)(T_c - G) \qquad \text{for } T_c < G \tag{11}$$

where β = a dimensionless parameter reflecting the turbulence effect of raindrop impact and other disturbances on flow that hinder deposition; V_f = effective particle fall velocity (L/T); and $q = Q/b$ = flow rate per unit of rill width (L^3/T/L).

Equation (11) represents the concept that deposition rate is small when β is small (for instance, in the case of shallow flow highly disturbed by raindrop impact), or when V_f is small (in the case of fine particles such as clay-sized sediment) or when q is large (in the case where either flow velocity or flow depth is large).

The hydraulic shear acting on the soil is calculated using the Darcy-Weisbach uniform flow equation:

$$\tau = \gamma RS(f_s/f_r) \tag{12}$$

where R = hydraulic radius (L); γ = specific weight of water (F/L^3).

Sediment transport capacity is estimated using a simplified Yalin equation (Foster & Meyer 1975):

$$T_c = B(\tau)^{3/2} \tag{13}$$

where B = transport coefficient. A value for B is obtained for each storm by using the Yalin equation (Yalin 1963), its modification for multiple particle size classes (Foster 1982), and equations derived by Foster et al. (1985) for particle size classes. This is done by computing a value for sediment transport capacity at the bottom of a uniform slope drawn through the beginning and end points of the given hillslope profile , T_{ce}, using the Yalin equation, and equating T_{ce} to T_c from equation (13).

<u>Sediment Delivery Rate from Interrill Areas</u>

Lateral sediment inflow from interrill areas to rill flow areas is the result of detachment by raindrop impact and transport by broad sheet flow. From results of numerous studies on sediment delivery rate from interrill areas, the lateral sediment inflow to rill flow areas per unit rill area is assumed to be properly represented in the WEPP hillslope model by an equation of the form:

$$D_i = C_i K_i (I_e^2), \quad (14)$$

where, C_i = dimensionless interrill cover parameter; K_i = interrill soil erodibility parameter (MT/L^4); and I_e = effective rainfall rate ($L^3/T/L^2$), defined as the rainfall rate during periods of rainfall excess, and zero otherwise. Note that sediment delivery to rill flow areas from adjacent interrill areas is accounted for in equation (14) by only calculating D_i during periods of rainfall excess, i.e., when $I > f$, where I = rainfall rate ($L^3/T/L^2$); and f = soil's infiltration rate ($L^3/T/L^2$). The parameter C_i in equation (14) is a function of canopy height and the fraction of the soil surface covered by plant canopy and other materials in direct contact with the surface. The erodibility parameter K_i is defined for a base condition but its actual value depends on soil texture and other soil properties that are affected by climate, tillage operations, and other disturbances.

Summary

The erosion process is conceptualized in the USDA Water Erosion Prediction Project (WEPP) as being divided into rill and interrill components with erodibility parameters characterizing interrill and rill detachment processes. The mathematical equations which represent the fundamental processes of detachment and transport of sediment on interrill areas, and the detachment, transport and deposition in rill flow areas were presented. The physical nature of the parameters used in the erosion equations and their implications on erosion predictions were briefly described.

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