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The US national project to develop improved erosion prediction technology to replace the USLE

L. J. LANE, D. L. SCHERTZ, E. E. ALBERTS, J. M. LAFLEN & V. L. LOPES

US Department of Agriculture, Agricultural Research Service, 2000 E. Allen Road, Tucson, Arizona 85719, USA

Abstract Recent advances in hydrology, soil science, erosion mechanics and computer technology have provided the technological basis for development of process-based erosion prediction technology. Concurrent trends in user requirements for erosion prediction have called for increased sophistication in the ability to predict soil erosion under a wide variety of land use and management practices. These applications include circumstances beyond the ability of current prediction technology as represented by the Universal Soil Loss Equation (USLE). Recently the US Department of Agriculture formulated a national project to develop an improved erosion prediction technology to replace the USLE. The USDA Water Erosion Prediction Project (WEPP) is designed to produce a prototype, computer-based erosion prediction technology by 1989 with a fully developed and implemented version in use by 1992. This paper describes the background and scope of the WEPP effort. General modelling concepts and relationships are introduced and specific formulations used in WEPP are described.

Le projet national des Etats Unis pour la mise au point d'une technologie améliorée de prévision de l'érosion en vue de remplacer l'USLE (Wischmeier)

Résumé Les projets récents en hydrologie, en science des sols, dans la connaissances du mécanisme de l'érosion et dans l'emploi des ordinateurs ont fourni la base technologique pour une méthodologie de prévision de l'érosion basée sur les processus. Les tendances convergentes dans les demandes des utilisateurs de prévision de l'érosion exigent une plus grande complexité dans la possibilité de prédéterminer l'érosion des sols pour une grande variété d'utilisation de ces sols et de pratiques agricoles. Ces applications comportent des cas de figures en dehors des possibilités de la technologie courante de prévision telle qu'elle est représentée par l'Equation Universelle de Pertes des Sols (USLE). Récemment le Département Américain de l'Agriculture a mis en forme un projet national ayant pour objet de mettre au point une technologie améliorée de prévision de l'érosion en vue de remplacer l'USLE (Wischmeier). Le USDA Water Erosion Prediction Project (WEPP) est conçu pour produire un prototype, technologie de prévision de l'érosion basée sur l'ordinateur, en 1989 avec une version terminée et bien au point, opérationnelle en 1992. La présente communication décrit les origines, la portée des efforts du WEPP. Les concepts généraux de mise en modèle et les relations utilisées sont présentées et les formulations spécifiques utilisées par le WEPP sont décrites.

BACKGROUND

For over 40 years, equations to estimate or predict soil erosion by water have been useful in dealing with soil erosion and sedimentation. The Universal Soil Loss Equation (USLE) is the most widely used of the erosion equations. It represents a simply understood and easily applied technology of enormous benefit to conservationists and land managers. The USLE has many strengths but it also has limitations.

At present, widely used technology for estimating water erosion is somewhat restrictive to continual improvement due to the lack of fundamental or process-based equations within the model structures. Fundamental erosion processes were described as early as the 1940s (i.e. Ellison, 1947 and others) and represented in form of useful equations by the 1960s (i.e. Meyer & Wischmeier, 1969). Recent advances in hydrology and erosion science have provided the means of developing improved erosion prediction technology based on infiltration theory, hydrodynamics of overland flow, and interrill and rill erosion processes. In 1985 the United States Department of Agriculture initiated a national project called the USDA Water Erosion Prediction Project (WEPP) to develop a new generation water erosion prediction technology (Foster, 1987).

SCOPE AND APPLICATIONS

Anticipated users of the new technology include all current users of the USLE, and anticipated uses range from conservation planning, to project planning, to resource inventory and assessment, and to special purpose erosion prediction and modelling.

The WEPP erosion prediction technology is to apply to "field-sized" areas ranging in size from a single hillslope up to perhaps a few hundred hectares in size. The size of the areas where WEPP can be appropriately applied depends upon the topography, soils and land use of the areas and their complexity as well as the required accuracy of the erosion predictions. The procedures are limited to areas where overland flow and surface runoff occur and should not be applied to areas where "partial area hydrology" and subsurface flow dominate.

The procedures are to compute sheet and rill erosion associated with overland flow and concentrated flow erosion (often called ephemeral gully erosion) in natural and constructed waterways. The procedures will deal with irrigation but will not consider the more classical gully erosion characterized by headcut advance and bank failure in the deeper more permanent channels.

The WEPP technology is being designed to apply to croplands, rangelands, and disturbed forest areas across the United States. About 30 cropland, 20 rangeland and 20 forest soils have been identified for rainfall simulator studies and special laboratory studies as part of the WEPP model development activities. These soils have a broad range of properties and will form the initial WEPP data base on the relationships between soil properties and field-measured soil erodibility. Similar studies are underway on a variety of land use and management practices affecting erosion.

The purpose of this paper is to briefly describe fundamental erosion mechanics used in development of process-based models to predict soil erosion by water and then to provide descriptions of the formulations used in the WEPP models. Emphasis is on the representative profile or hillslope version of the WEPP models.

BASIC CONCEPTS

The basis of most hillslope models for erosion is the concept that soil loss or sediment yield at the bottom of the slope is determined by the process of rainfall and runoff erosivity, and of sediment detachment, transport, and deposition in overland flow. Overland flow processes are in turn usually conceptualized as a mixture of broad sheet flow (called interrill flow) and concentrated flow (called rill flow). Most often, the two flow types are lumped and described as overland flow with computations based on a broad sheet flow assumption. As will be discussed later, the WEPP hillslope model is being formulated so as to explicitly account for flow concentration in rills.

Storm erosivity

The significance of raindrop impacts on soil detachment was well understood by the 1940s after the natural rainfall studies of Laws (1940) and the mechanical effects of raindrops studies by Ellison (1947). Horton (1945) described the fluvial aspects of erosion and described the slope length-runoff intensity effect in discussing the "belt of no erosion". More recently, raindrop detachment processes and runoff intensity influences were represented by the *R* factor in the Universal Soil Loss Equation (USLE), (see Wischmeier & Smith, 1978). Studies forming the basis of more mathematical treatments of storm erosivity include Meyer & Wischmeier (1969), Foster & Meyer (1972), Foster & Meyer (1975), Li (1977) and Foster *et al.* (1977).

Overland flow routing

Overland flow routing is a term used to analytically describe the movement of water over the land surface and implies the calculation of flow rates at positions along the hillslope. Horton (1945) described the process and kinematic routing was subsequently used to model it (see Henderson & Wooding, 1964; and Woolhiser & Liggett, 1967).

A basic issue in modelling overland flow is how faithfully the actual land surface is represented in the model used to represent it. All land surfaces are more or less irregular. Realistic modelling of unsteady, nonuniform, and three-dimensional flow processes on these natural surfaces remains beyond our ability. Two-dimensional flow models have been developed but remain impractical for most applications. Therefore, most modelling efforts have been based upon one-dimensional flow assumptions. In fact, most models assume broad, uniform sheet flow as the basis for development of the flow equations. The assumption of broad, uniform sheet flow results in model parameter distortions with the degree of parameter distortion dependent upon how irregular the overland flow surfaces really are (Lane & Woolhiser, 1977).

Overland flow is represented in two ways in the WEPP hillslope model. Broad, uniform sheet flow is assumed for the overland flow routing to develop the overland flow hydrograph. This hydrograph represents unsteady, nonuniform flow on an idealized surface. Once the unsteady flow calculations are made for the runoff peak rate and the duration of runoff, quasi-steady state flow is assumed at the peak rate and is partitioned into broad sheet flow for interrill erosion calculations and concentrated flow for rill erosion calculations. Flow partitioning is based on the proportion of the overland flow area occupied by rills. The proportion of the areas in rills is represented by a rill density statistic (equivalent to a mean number of rills per unit area). Representative rill cross sections are based on the erodible channel calculations from the CREAMS model (see Knisel, 1980) and width-discharge relationships derived from them (Lane & Foster, 1980). Depth of flow, velocity, and shear stress in the rills are calculated assuming rectangular channel cross sections. The erosion calculations are then made for a constant rate over a characteristic time to produce estimates of erosion for the entire runoff event.

Development of the runoff hydrograph

Kinematic wave equations for one dimensional overland flow result when the momentum equation is approximated by assuming the friction slope S_f is equal to the land slope S. The kinematic wave equations for runoff on a plane are

$$\partial h/\partial t + \partial q/\partial x = i - f \quad (1)$$

and with the Chézy form of the flow resistance equation

$$q = Kh^{3/2} \tag{2}$$

where

h = local depth of flow (m),
t = time (s),
q = discharge per unit width ($m^2\ s^{-1}$),
x = distance down the plane (m),
i = rainfall intensity ($m\ s^{-1}$),
f = infiltration rate ($m\ s^{-1}$), and
K = depth-discharge coefficient ($m^{½}\ s^{-1}$).

The solution to equations (1) and (2) provides $q(x,t)$ and $h(x,t)$ at all points on the plane and at all times during the runoff event. As will be shown, these variables are then used to compute the hydraulic variables for the subsequent erosion calculations.

Hydraulic relationships

The stage-discharge coefficients K in equations (2) can be written as

$$K = CS^{½} \tag{3}$$

or

$$K = (8gS/f)^{½} \tag{4}$$

where C is the Chézy resistance coefficient in $m^{½}\ s^{-1}$ and f is the Darcy-Weisbach friction factor (dimensionless). The equivalence between equations (3) and (4) means that f is related to C as $f = (8g/C^2)$ where g is the acceleration of gravity.

Total hydraulic resistance is represented by an additive relationship with friction factors as

$$f_{tot} = f_{soil} + f_{rr} + f_{cov} \tag{5}$$

where

f_{tot} = the total friction factor,
f_{soil} = the characteristic friction factor of the bare soil on a uniform surface,
f_{rr} = the friction factor due to the microtopographic irregularities (random roughness) of the overland flow surface, and
f_{cov} = the friction factor due to cover on the soil surface.

The reasoning behind equation (5) is that a rough surface or a surface with cover such as crop residue or gravel mulch offers additional resistance to flow over that offered by smooth, bare soil.

Shear stress in overland flow on a plane is calculated as

$$\tau = \gamma h S \tag{6}$$

where τ is shear stress (N m^{-2}), h is mean flow depth (m), S is the slope and γ is the specific weight of water (N m^{-3}).

Shear stress in concentrated flow is calculated as

$$\tau = \gamma RS \tag{7}$$

where R is hydraulic radius (m) defined as cross-sectional area perpendicular to the direction of flow divided by the wetted perimeter.

Interrill erosion processes

As raindrops strike exposed soil, intense hydraulic forces result in detachment of soil particles. These particles, now called sediment particles, are subsequently transported by two mechanisms. First is the mechanism of splash (see Ellison, 1947; Martinez, 1979). Second is the mechanism of transport by thin, sheet flow in the interrill areas. Some models include a term for detachment by flow in interrill areas but if this detachment in fact occurs, it is probably small in comparison with detachment by raindrop impact and by concentrated flow.

Therefore, interrill erosion is assumed in the WEPP model to be adequately represented by an equation of the form

$$E_i = C_i K_i i^2 \tag{8}$$

where:
E_i = interrill erosion rate (kg m^{-2} s^{-1}),
C_i = interrill cover parameter (dimensionless),
i = rainfall intensity (m s^{-1}), and
K_i = interrill soil erodibility parameter (kg-s m^{-4}).

In the WEPP model the interrill transport of detached sediment is accounted for in equation (8) by only using the rainfall intensity i during periods of rainfall excess. Rainfall occurring during periods in the storm when infiltration is greater than rainfall intensity does not contribute to interrill erosion.

Erosion in concentrated flow areas is modelled as a rate process proportional to the difference between the flow's ability to transport detached sediment, transport capacity, and the existing sediment load in the flow. This concept is used to model both detachment and deposition of sediment as follows. It $T_c > q_s$, then net detachment of sediment occurs and it is modelled as

$$E_r = D_c(1 - q_s/T_c) \tag{9}$$

where:
E_r = detachment rate (kg m^{-2} s^{-1}),
D_c = detachment capacity of the flow (kg m^{-2} s^{-1}),
T_c = transport capacity of the flow (kg m^{-1} s^{-1}), and
q_s = sediment load (kg m^{-1} s^{-1}).

Detachment capacity D_c is in turn computed as

$$D_c = C_r K_r (\tau - \tau_c) \qquad (10)$$

where:
C_r = rill cover parameter (dimensionless)
D_c = detachment capacity (kg m^{-2} s^{-1}),
K_r = rill soil erodibility parameter (s m^{-1}),
τ = average shear stress in the cross section (N m^{-2}), and
τ_c = critical shear stress required for detachment to occur (N m^{-2}).
If $T_c < q_s$ net deposition occurs and it is modelled as

$$D_f = D_r (T_c - q_s) \qquad (11)$$

where:
D_f = deposition rate (kg m^{-2} s^{-1}) and
D_r = deposition rate parameter (m^{-1}).
The deposition rate parameter is calculated as

$$D_r = (\beta V_f / q) \qquad (12)$$

where:
β = dimensionless parameter and
V_f = particle fall velocity (m s^{-1}).
Transport capacity at the bottom of the hillslope is estimated using the Yalin equation (Yalin, 1963; Foster *et al.*, 1981).

Computational time can be decreased significantly if the Yalin sediment transport equation is approximated as (Foster & Meyer, 1975)

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

where B is a coefficient. The coefficient B is obtained for each storm using the Yalin equation, its modification for multiple sediment particle size classes (Foster, 1982) and equations for particle size classes (from CREAMS, see Foster *et al.*., 1985). This is done by computing a value for T_c at the end of a uniform slope drawn through the beginning and end points of the given hillslope profile and equating T_c from the Yalin equation to T_c from equation (13).

Detachment of sediment particles is assumed to occur independent of sediment particle characteristics except as those characteristics affect T_c in equation (9). Deposition, as suggested by particle fall velocity in equation (12), depends very much on sediment characteristics. Equation (11) is non-linear so choice of a single value of D_r, dependent on single particle characteristics, introduces large errors. In the WEPP models, a value of D_r is computed by geometrically weighting D_r for the three smallest sediment particle classes.

DISCUSSION

We have shown how to use equations to describe erosion processes as part of erosion models and how specific equations are used in the WEPP hillslope model. Because of rather stringent user input requirements for simplicity of model input and limited computer time (Foster, 1987), several simplifications and approximations were made in formulating the WEPP hillslope model.

The continuity equation for sediment in overland flow is as follows:

$$\partial(ch)/\partial t + \partial(q_s)/\partial x = E_i + E_r \qquad (14)$$

where c is sediment concentration in kg m^{-3} and the other variables are as described earlier. To avoid the necessity of resorting to numerical procedures, we assume steady-state conditions so that equation (14) becomes

$$\mathrm{d}(q_s)/\mathrm{d}x = E_i + E_r \qquad (15)$$

which is an ordinary differential equation for sediment load as a function of distance.

The influence on estimated soil loss of approximating equation (14) by its steady-state approximation, equation (15), is unknown. However, it is the subject of current investigations using a more complete model (Lopes, 1987) and the results of these investigations will be reported as part of subsequent WEPP model documentation. The situation is much the same for the sediment transport capacity approximation described earlier (i.e. where T_c is approximately equal to $B\tau^{3/2}$). The precise influence of this approximation is under investigation using Yalin's equation along the hillslopes and the results will be reported later. Laboratory data, field data, and the CREAMS model (Knisel, 1980) are being used to test the accuracy and appropriateness of the sediment particle distribution approximation, by five particle size classes, used in the WEPP model.

A very large and extensive programme of field experiments is under way to estimate the model parameters (i.e. K in equation (2) and the friction factors in equation (5), K_i in equation (8), K_r and τ_c in equation (10), and D_r in equation (11)) on croplands (see Laflen *et al.*, 1987) and on rangelands (see Simanton *et al.*, 1987). These model parameters are in turn being related to soil properties (see Alberts *et al.*, 1987; West *et al.*, 1987).

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