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SIMULATING RUNOFF AND SEDIMENT YIELD ON SEMIARID WATERSHEDS

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Abstract

This paper describes a computer program called WESP (Watershed Erosion Simulation Program), a physically-based, distributed parameter, event-oriented, one-dimensional, numerical model for simulating surface runoff and sediment yield on small semiarid watersheds. The program includes components for computing rainfall excess rates, broad sheet flow (interrill flow), concentrated flow (rill and stream channel flow), erosion, sediment transport, and deposition. Rainfall excess is computed using the Green & Ampt equation with the ponding time calculation for an unsteady rainfall. The broad sheet and concentrated flow components are based on the kinematic wave equations. The sediment yield component is based on nonequilibrium dynamic sediment transport equations for simultaneous rates of entrainment and deposition. The watershed geometry is represented on WESP by a simplified scheme consisting of discrete broad sheet flow planes discharging into concentrated flow elements. The model was tested using sediment yield data from rainfall simulator plots and small semiarid watersheds in Tombstone, Arizona. The results indicated that the governing equations, the initial and upper boundary conditions, and the structural framework of the model describe satisfactorily the physical processes controlling surface runoff and sediment yield on small semiarid watersheds.

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Introduction

Physically-based mathematical models for sediment yield provide several advantages over existing sediment yield models. Most notably, the physically-based models provide an improved understanding of the fundamental sediment-producing processes, having the capability to access the spatial and temporal variations of sediment entrainment, transport and deposition processes and the potential to be applied to a broad range of watershed conditions.

The main purpose of this study was to accomplish the following two objectives: (1) develop a process-based mathematical model for simulating the spatial and temporal variations of sediment entrainment, transport and deposition processes on small semiarid watersheds and (2) calibrate and evaluate the model using information from rainfall simulator plots and small watersheds on semiarid environments.

Mathematical model

WESP includes components for computing rainfall excess rates, broad sheet flow (interrill flow), concentrated flow (rill and stream channel flow), and erosion, sediment transport, and deposition on interrill, rill, and stream channel systems. Figure 1 shows the information flow in program WESP. A brief description of each component is given below.

Rainfall excess

The first major component needed in constructing an event-based sediment yield model is rainfall excess or direct surface runoff. Rainfall excess is computed by subtracting the hydrologic abstractions or losses from input rainfall. The losses to be abstracted are 1) interception losses, 2) evapotranspiration losses, 3) depression storage, and 4) infiltration losses. Evapotranspiration losses are usually negligible during storm rainfall. The approach used on WESP ignores the first three losses mentioned above and only infiltration losses are used to compute rainfall excess. Rainfall excess is represented as the positive difference between instantaneous rates of rainfall and infiltration, or zero if the infiltration capacity rate is greater than the rainfall rate.

There are numerous infiltration models which have either been derived from soil physics consideration such as the Richards equation, or have been conceptually derived such as the Philip (Philip, 1969) and the Green and Ampt (Green and Ampt, 1911) equations.

The difficulties with the application of these models to watersheds arise from the spatial variability of soil properties, the initial conditions and the temporal and spatial variability of rainfall. Rainfall excess is computed in WESP using the Green & Ampt equation because of its simplicity and its satisfactory performance for a great variety of hydrologic problems. The equation was extended to soils of nonuniform initial moisture content with the ponding time calculation for an unsteady rainfall (Chu, 1978).

Broad sheet flow and concentrated flow

While a wide range of surface runoff model types exist, two fundamentally different modeling approaches can be identified: 1) empirical (black-box), and 2) physically-based (hydrodynamic) approaches.

The hydrodynamic approach is founded on the requirement to describe the runoff system in terms of fundamental laws of science (for example, the conservation of mass, energy, and momentum). This rigorous approach provides the potential to describe the relevant controlling mechanisms of the runoff system, the nature of their interaction, and their spatial and temporal variability. Application of physically based runoff models require that appropriate initial and boundary conditions be specified and further requires a geometrical representation of the runoff generating system. The empirical (black box) approach attempts to describe the runoff system in terms of empirical, or statistical, relationships which may range in complexity from a simple equation involving a single parameter to more complex suites of equations involving a much larger number of parameters. In contrast to physically based models, empirical (black box) models provide less insight into the internal mechanisms of the system and they are not designed to aid explanation.

It has been shown that the simplified hydrodynamic approach based on the kinematic wave theory (Lighthill and Whitham, 1955) is applicable to many broad sheet flow (Woolhiser and Liggett, 1967) and channel flow (Henderson, 1963; Brakensiek, 1967; Weinmann and Laurenson, 1979) situations. The broad sheet flow and concentrated flow components of WESP are based on the kinematic wave equations.

Erosion and sediment yield

Many erosion and sediment yield models have been developed to date. They can be loosely divided into two types: 1) empirical models based on the Universal Soil Loss Equation (USLE) or its parameters (Wischmeier and Smith, 1978), and 2) physically-based models that attempt to describe the relevant features of the sediment-generating system through simplified mathematical equations. In spite of the complexity of the sediment generation, transport and deposition processes, physically-based erosion models may be the most viable way to estimate time-dependent and spatially varying erosion responses to various land use and management activities. The erosion and sediment yield component of WESP is based on nonequilibrium sediment transport equations for simultaneous rates of entrainment and deposition. The WESP modeling approach describes the distributed erosion and sediment transport processes using a spatial resolution depicted as broad sheet flow systems (interrill flow systems) and concentrated flow systems (rill and channel flow systems).

Sediment transport on interrill flow systems

The one-dimensional continuity equation for a single particle size on an interrill flow system with uniform slope (Foster, 1982) is:

$$\frac{\delta(ch)}{\delta t} + \frac{\delta(cq)}{\delta x} = e_I - d_I \qquad (1)$$

where c is the local mean sediment concentration (ML^{-3}); h is the local depth of flow (L); q is the local discharge per unit width (L^2T^{-1}); e_I is the rate of sediment entrainment by raindrop impact ($ML^{-2}T^{-1}$); d_I is the rate of sediment deposition ($ML^{-2}T^{-1}$); t is the time (T); and x is the distance in the direction of flow (L). Dispersion terms have been neglected in equation (1).

Entrainment rates on interrill flow systems

Sediment entrainment rate by raindrop impact, e_I, is a function of the rate of detachment by raindrop impact and the rate of transport of sediment by shallow flow (Foster, 1982). In the WESP modeling approach, a simple functional form of entrainment by raindrop impact is assumed incorporating rainfall intensity as a measure of the rainfall erosivity (Foster, 1982) and rainfall excess rate as a measure of sediment transport by shallow flow (Lane and Shirley, 1985).

For a single particle size:

$$e_I = K_I i^2 (r_e/i) = K_I (i)(r_e) \qquad (2)$$

where K_i is a coefficient to measure soil detachability by raindrop impact ($ML^{-4}T$); i is the rainfall intensity (LT^{-1}); and r_e is the rainfall excess rate (ML^{-1}). Notice that when $r_e = 0$ (pre- or post-rainfall excess phase), or when $i = 0$ (post-rainfall phase) there is no entrainment by raindrop impact, and when $r_e = i$, (impermeable surface), entrainment rate by raindrop impact is not limited by transport of shallow flow.

Deposition rates on interrill flow systems

The mass rate of sediment deposition (downward flux) is proportional to the local mean sediment concentration (Mehta, 1983). For a single particle size:

$$d_i = \epsilon_i V_s c \tag{3}$$

where ϵ_i is a coefficient depending on the soil and fluid properties (dimensionless); V_s is the particle fall velocity (LT^{-1}); and c is the local mean sediment concentration (ML^{-3}).

Sediment transport in rill and channel flow systems

The one-dimensional continuity equation for a single particle size on a single rill or channel flow system can be written as (Bennett, 1974):

$$\frac{\delta (CA)}{\delta t} + \frac{\delta (CQ)}{\delta x} = e_r - d_c + q_s \tag{4}$$

where C is the local mean sediment concentration (ML^{3}); A is the local flow cross section area (L^2); Q is the local discharge(L^3T^{-1}); e_r is the source term for bed-material load ($ML^{-1}T^{-1}$); d_c is the rate of sediment deposition ($ML^{-1}T^{-1}$); q_s is the source term from lateral inflow ($ML^{-1}T^{-1}$); t is the time (T); and x is the distance in the direction of flow (L). Dispersion terms have been neglected in equation (4).

Entrainment rates on rill and channel flow systems

A general equation, initially developed for bed-load transport capacity, has been used on WESP to model entrainment by concentrated flow (Foster, 1982).

For a single particle size:

$$e_r = \begin{cases} K_r(\tau_0 - \tau_c)^b & \text{for } \tau_0 \geq \tau_c \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

in which,

$$\tau_o = \gamma f V^2/8g \qquad (6)$$

$$\tau_c = \phi(\gamma_s - \gamma) d_s \qquad (7)$$

where K_r is a coefficient for sediment entrainment by concentrated flow ($M^{1-b}L^{b-1}T^{2b-1}$); τ_o is the average shear stress ($ML^{-1}T^{-2}$); τ_c is the average critical shear stress ($ML^{-1}T^{-2}$); b is an exponent in the range 1.0 to 2.0; γ is the specific weight of water ($ML^{-2}T^{-2}$); f is the Darcy-Weisbach coefficient (dimensionless), V is the local flow velocity (LT^{-1}); g is the acceleration of gravity (LT^{-2}); ϕ is a coefficient depending on the sediment and fluid properties (dimensionless); γ_s is the specific weight of sediment ($ML^{-2}T^{-2}$); and d_s is the particle diameter size.

Deposition rates on rill and channel flow systems

The rate of sediment deposition (downward sediment flux) is proportional to the local mean sediment concentration and to particle fall velocity (Mehta, 1983).

The deposition rate for a single particle size is modeled on WESP as:

$$d_c = \epsilon_c w V_s C \qquad (8)$$

where ϵ_c is a coefficient depending on the soil and fluid properties (dimensionless); w is the flow top width (L); and the other variables were as defined earlier.

Watershed geometry

Several alternate geometric representations (Wooding, 1965; Brakensiek, 1967; Kibler and Woolhiser, 1970; Li et al., 1975; Alonso and DeCoursey, 1983) have been hypothesized and incorporate varying degrees of geometric abstraction. In general, one geometric representation that has been accepted by several researchers is that a watershed may be represented by a simplified network of broad sheet flow systems (planes) and concentrated flow systems (rill and stream channel elements) (Kibler and Woolhiser, 1970). This representation is used in WESP.

Model testing

To test the model, two sets of data were used: 1) data from rainfall simulator plots, and 2) data from two small experimental watersheds. The rainfall simulator plots and the two small watersheds are located on the U.S. Department of Agriculture, Agriculture Research Service Walnut Gulch Experimental Watershed near Tombstone, in southeastern Arizona.

Parameter estimation

The model parameters were estimated in three stages. In the first stage, small rainfall simulator plots (1x1 m) were used to estimate the soil erodibility parameter for raindrop impact (K_i in equation 2). In the second stage, large rainfall simulator plots (3x11 m) with rill flow systems were used to estimate the rill erodibility parameter (K_r in equation (5) for rill flow systems). In the third stage, sediment yield data from two small experimental watersheds were used to estimate the channel erodibility parameter (K_r in equation (5) for channel flow). Exponent b (equation 5) was assumed 1.0 for rill flow systems and 1.5 for channel flow systems. The sediment settling parameter, ϵ, was assumed 0.5 for interrill flow systems (Davis, 1978) and 1.0 for rill and channel flow systems (Einstein, 1968). The parameter for critical shear stress, ϕ, was assumed to be 0.047 for all simulation runs.

Given estimates of K_i (from small plots) and K_r (from large plots), the concentrated flow parameter K_r was optimized to fit the sediment concentration graph for each event. A starting estimate for K_r for channel flow was assumed to be always the same as K_r for rill flow systems. Simulated runoff rates and sediment concentration versus observed are shown for one plot event (Figure 2) and for one watershed event (Figure 3).

Conclusions

The following conclusions were drawn based on the model development and testing results: 1) The governing equations, the initial and upper boundary conditions, and the structural framework of the model describe satisfactorily the physical processes controlling surface runoff and sediment yield on small semiarid watersheds; 2) the source (entrainment) and sink (settlement) terms for the equations describing conservation of sediment mass on broad sheet flow systems (interrill flow systems) and concentrated flow systems (rill and stream channel flow systems) are mathematically consistent and incorporate appropriate initial and boundary conditions;3) further model testing is required for a broader range of soil and vegetative cover conditions in order to obtain a larger range of parameter values; and 4) future development of an "intelligent" interface for input file building, parameter identification, and model output interpretation is recommended for practical model applications.

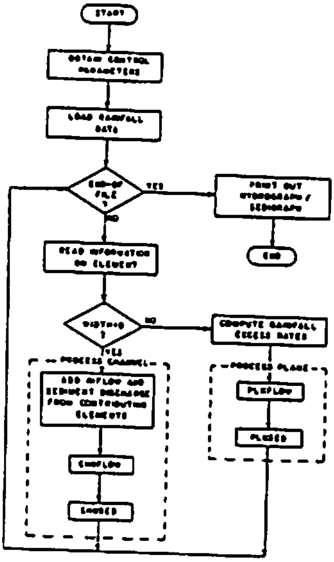


Figure 1 - Information flow in program WESP.

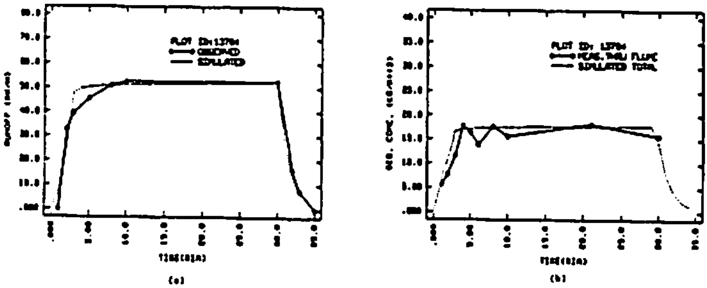
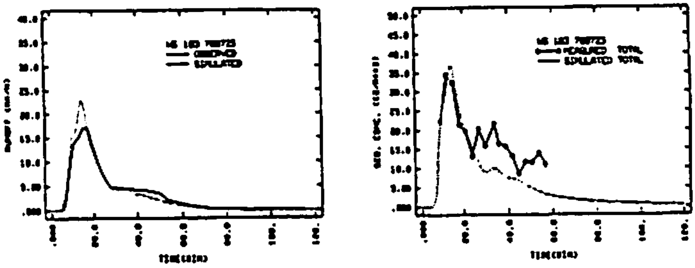


Figure 2 - Very wet run on bare plot: (a) hydrograph and (b) sedigraph.



(a)

(b)

Figure 3 - Storm event of 07/25/78 on watershed 63.103: (a) hydrograph and (b) sedigraph.

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