

MODSIM 95



November 27-30, 1995, The University of Newcastle

**International Congress on Modelling and Simulation
Proceedings
Volume 1: Agriculture, Catchment Hydrology and Industry**

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Modeling Erosion on Hillslopes: Concepts, Theory, and Data

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Experimental data from the Walnut Gulch Experimental Watershed are used with a simple hillslope sediment yield model to examine erosion processes at the hillslope scale, evaluate the influence of spatial variability of cover characteristics on these processes, and interpret the results with respect to hillslope stability. An application of the model on a representative hillslope profile on a small watershed strongly suggests the need for distributed, rather than lumped, vegetative canopy and surface ground cover information to avoid gross distortions in simulated erosion processes and the corresponding inferences of hillslope stability. Additional analysis of the model application results is used to illustrate how the lack of adequate technology enabling measurement of erosion processes simultaneously in time and space limits our ability to parameterize, evaluate, and thus validate process-based erosion models.

INTRODUCTION

Hillslope form and structure are directly related to vegetation composition and patterns, soil and soil surface characteristics, and the interactive processes affecting them. A key process affecting hillslope structure and stability is soil erosion by water, which causes detachment, transportation, and deposition of soil particles. Because erosion processes and their interactions vary with scale, the "scale" problem has become a central focus of erosion modeling of hillslopes. The interactions of soil erosion processes with soil, vegetation, surface cover, and topographic factors on hillslopes vary with time, space, and intensity scales to produce the hillslope features we see at any given time.

When soil particles are eroded, they are transported as sediment by flowing water. Sediment yield is the net result of sediment detachment by impacting raindrops and flowing water, sediment transportation by raindrop splash and flowing water, and sediment deposition. Flow rates and amounts change with time during a runoff event and with position along the hillslope in the direction of flow. Soil detachment, transportation, and deposition thus change with time and space. The sediment concentration in the flowing water must be known to determine sediment discharge rate. The product of sediment concentration (mass per unit volume of water) and flow rate (volume of

water per unit time) gives sediment discharge rate in mass per unit time. By integrating sediment discharge rates throughout the period of flow, sediment yield is obtained from the contributing area above the point of interest. These erosion processes are also dependent upon the intensity scale of the runoff event as thresholds (i.e. the detachment process) exist and are dependent upon the intensity scale of the driving forces.

The objectives of this presentation are to examine erosion processes at the hillslope scale, to focus on modeling the influence of spatial variability on the processes, and to interpret the results of an application of a particular hillslope model with respect to hillslope stability. An example application is used to describe how lack of adequate technology enabling measurement of erosion processes in time and space limits our ability to parameterize, evaluate, and thus validate process-based erosion models.

Erosion Processes and Modeling

Erosion processes appropriate at the hillslope scale were described as early as the 1940's (Ellison, 1947 and others) and represented in the form of equations by the 1960's (Meyer and Wischmeier, 1969). Closed-form solutions to steady-state forms of the sediment continuity equation resulted in

mathematical models of erosion by the early 1970's (Foster and Meyer, 1972).

During the 1970's, the impact of agricultural practices on off-site water quality became a major concern. The Chemicals, Runoff, and Erosion From Agricultural Management Systems (CREAMS) model (Knisel, 1980) was developed as a tool to evaluate the relative effects of agricultural practices on pollutants in surface runoff and in soil water below the root zone. Because sediment is a major pollutant and a carrier of contaminants, the CREAMS model included an erosion component. The main equation governing overland flow is the steady-state continuity equation for sediment transport (Foster et al., 1981).

The Water Erosion Prediction Project (WEPP) model (Lane and Nearing, 1989) is a daily time-step simulation model which uses the rill-interrill concept of soil erosion (Foster, 1982). The WEPP model simulates the processes that occur on a hillslope that determine the status of its soil, plant, residue and water. The status of these characteristics determines the response to a precipitation event. The WEPP profile version computes detachment and transport by raindrop impact, and detachment, transport and deposition by flowing water. It is applied to a hillslope where sheet and rill erosion can occur. The WEPP profile version also considers sediment deposition and is applicable from the top of a hillslope to a channel.

Many modeling approaches represent a hillslope as a single plane, a cascade of plane segments, or a combination of planar and convex or concave segments. Estimation of erosion parameters is generally based on spatially-averaged estimates of canopy cover and surface ground cover along the hillslope profile in the direction of flow. Present modeling methods rely upon point measurements to represent spatially varying hillslope processes. It may appear to make sense to average over the entire hillslope length because measurements of runoff and sediment discharge are usually limited to the end of an experimental plot representing a portion of the hillslope or to the lowest point at the bottom of the hillslope. However, a distributed sediment yield model will be used to illustrate that the practices of lumping hillslope properties and using data collected at a single point on the hillslope to calibrate and evaluate distributed models can introduce distortions. Model parameters derived in this manner may represent nothing more than fitted coefficients distorted beyond any physical significance and calculations from the beginning of the hillslope to the point of measurement remain unvalidated.

A Simple Model for Example Applications

A simple sediment-yield model for hillslopes was used to simulate erosion and sediment yield as a function of position (x) on the hillslope and to study the influence of spatial variability in hillslope properties (primarily vegetative canopy cover and surface ground cover) on sediment yield and mean sediment concentration. While the simple model is less powerful than more complex models, the single-event model used has an analytic solution, simplified input, and relatively few parameters.

Overland flow on a plane is approximated by the kinematic wave equations:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r \quad (1)$$

and

$$q = Kh^m \quad (2)$$

where h is the average, local flow depth (m), t is time (s), q is discharge per unit width (m²/s), x is distance in the direction of flow (m), r is rainfall excess rate (m/s), the depth-discharge coefficient K = CS^{1/2}, C is the Chezy hydraulic resistance coefficient for turbulent flow (m^{1/2}/s) and S is the dimensionless slope of the land surface. Note that the exponent m in Eq. 2 is 1.5 when the Chezy formula is used. A simplifying assumption required for an analytic solution is that rainfall excess rate is constant and uniform:

$$r(t) = \begin{cases} r & 0 \leq t \leq D \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where r(t) is rainfall excess rate, t is time, and D is the duration of rainfall excess in the same units as in Eq. 1.

The sediment continuity equation for overland flow is:

$$\frac{\partial(ch)}{\partial t} + \frac{\partial(cq)}{\partial x} = e_i + e_r \quad (4)$$

where c is total sediment concentration (kg/m³), e_i is interrill erosion rate per unit area (kg/s/m²), and e_r is net rill erosion or deposition rate per unit area (kg/s/m²).

A simplifying assumption for the interrill erosion rate is:

$$e_i = K_i r \quad (5)$$

where K_i is the interrill coefficient (kg/m^3). Simplifying assumptions for the rill erosion/deposition equation component are:

$$e_r = K_r (T_c - cq) = K_r \left[\frac{B}{K} q - cq \right] \quad (6)$$

where K_r is the rill coefficient ($1/\text{m}$), T_c is the transport capacity (kg/s/m) and is assumed equal to $(B/K)q$, and B is a transport-capacity coefficient ($\text{kg/s/m}^{2.5}$). Equations 1-4 (note that Eqs. 5 and 6 have been substituted in the right hand side of equation 4) are known as the coupled kinematic-wave and erosion equations for overland flow. As stated earlier, Eqs. 5 and 6 were suggested by Foster and Meyer (1972).

A significant development was the derivation of an analytic solution of the coupled kinematic-wave and erosion equations for overland flow during the rising hydrograph (Hjelmfelt et al., 1975). Following this, analytic solutions for the entire runoff hydrograph were derived by Shirley and Lane (1978) and described in detail by Lane et al. (1988). An explicit solution to coupled kinematic-wave and erosion equations on an infiltrating plane was derived by Singh and Prasad (1982). Related modeling efforts for erosion and deposition processes on a plane were described by Rose et al. (1983a) and applied to data from a small watershed in Arizona (Rose et al., 1983b).

Following development of a solution in time and space for the coupled kinematic-wave and erosion equations, the next step was to use the solution to derive a sediment yield model for a plane. The solution to the sediment continuity equation for the case of constant rainfall excess was integrated through time (Shirley and Lane, 1978) to produce a sediment-yield equation for a runoff event as:

$$Q_s(x) = Q C_b \\ = Q \left\{ \frac{B}{K} + (K_i - B/K) \left[1 - \exp(-K_r x) \right] \right\} / K_r x \quad (7)$$

where Q_s is total sediment yield for the entire amount of runoff per unit width of the plane (kg/m), Q is the total storm runoff volume per unit width (m^3/m), C_b is mean sediment concentration over the entire hydrograph (kg/m^3), x is distance in

the direction of flow (m), and the other variables are described earlier.

This sediment-yield equation for a single plane was extended to irregular slopes (Lane et al., 1995) approximated by a cascade of planes. They considered a slope composed of n slope segments x_1, x_2, \dots, x_n where x_n equals the total slope length (m). Hillslope topography was better approximated as the number of segments increased. With this extension to irregular slopes, inputs for the entire hillslope model are runoff volume per unit area and a soil-erodibility parameter. Input data for each of the individual segments are slope length and steepness, percent vegetative canopy cover, and percent ground cover. From the input data, parameter estimation procedures derived from calibrating the model using rainfall simulator data were used to compute the depth-discharge coefficient, interrill erodibility, rill erodibility, and sediment-transport coefficient. The calibration was accomplished using rainfall-simulator data from 10.7m by 3.0 m plots in the western USA.

Application of the model

Runoff and sediment yield data from a small subwatershed, Kendall 2 (K2), on the Walnut Gulch Experimental Watershed (operated by the USDA-ARS Southwest Watershed Research Center in Tucson, AZ, USA, Fig. 1) were used to apply the sediment yield model to a small watershed. Climate at the Walnut Gulch Watershed is classified as semiarid or steppe, with about two thirds of the annual precipitation occurring during the summer months as thunderstorms. Most soils are well-drained, calcareous, gravelly to cobbly loams. The primary use of the subwatershed used for calibration is grazing (Renard et al., 1993).

The hillslope model was calibrated using rainfall simulator data collected near the 1.86 ha K2 watershed. A database of 18 events with measured runoff and sediment yield from the watershed (Tiscareno-Lopez, 1994) was used to evaluate the application of the model to the K2 watershed. Measured volumes of runoff from the small watershed, measured topography, canopy cover, and ground cover from a representative overland profile, and estimated soil erodibility from the previously cited rainfall simulator studies were used as input to the model for calculating sediment yield. Computed sediment-yield estimates for the 18 events were compared with the corresponding measured values and explained about 60% of the variance in the measured data. With an R^2 value of 60%, the hillslope model was described as qualitative in nature (Lane et al., 1995).

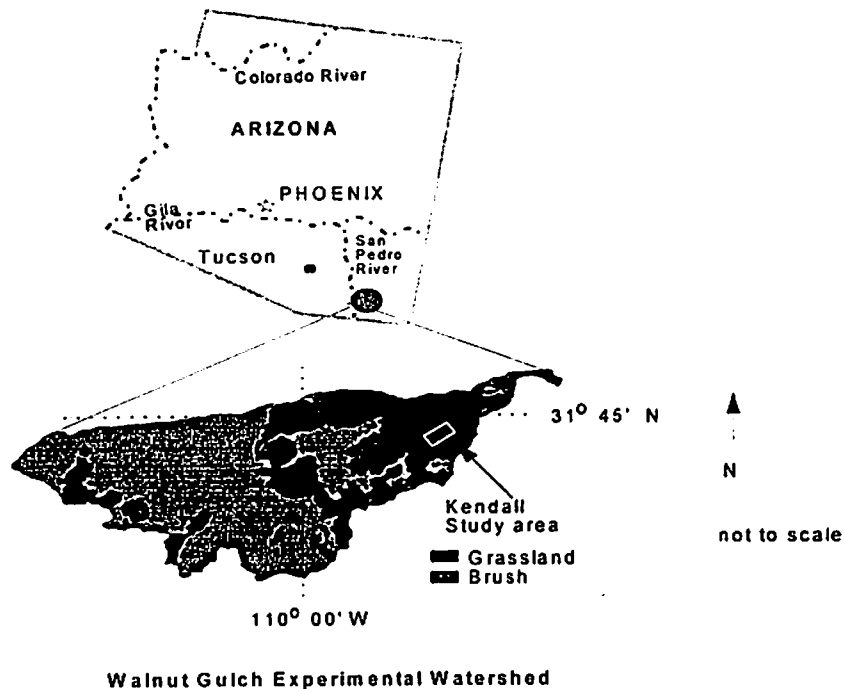


Figure 1. Location of watershed and study area.

To extend the analysis to the entire K2 watershed, 2 additional representative hillslope profiles were selected on the K2 watershed. Vegetation on these hillslopes are dominated by warm season short grasses with an average canopy cover of about 40%. Vegetative canopy cover and ground surface cover within each segment were estimated using line-point measurements (Bonham, 1989). Percentages of canopy cover, ground cover, and bare soil were calculated for each slope segment on the 3 profiles. Slope segment lengths and slope steepness were determined using an electronic transit. Measurements were made in July, and again in August of 1994. Subsequent discussions will focus on representative profile 1 as results were similar for all three profiles.

Hillslope topography, canopy cover, and ground cover for the July, 1994 data on representative profile 1 are shown in Figs. 2a and 2b, respectively. Simulated mean sediment concentration based on spatially uniform average canopy and ground cover and measured (spatially varying) canopy and ground cover for the representative profile 1 are shown in Fig. 2c (adapted from Lane et al., 1995). Simulated mean sediment concentration varies in the flow direction. As illustrated, using lumped or average values of canopy cover and ground cover significantly distorts the variation of mean sediment concentration along the hillslope profile (Fig. 2c).

The 122 m long profile 1 on K2 watershed was described by 26 segments (resulting in an

average segment length of 4.7 m). To evaluate the effects of spatial averaging in greater detail, the hillslope was described by 1 segment of 122 m length, 2 segments of 61 m, 3 segments of 41 m, 5 segments of 24m, 9 segments of 13.6 m, and all 26 segments with canopy cover and ground cover averaged over each segment. The simulation results for 26 segments (the original measured data) were assumed as the baseline values and were compared with the results for the simulated mean sediment concentration values obtained when cover values were averaged over 1, 2, 3, 5, and 9 segments. Simulated mean sediment concentrations at one meter intervals along the hillslope for the 1, 2, 3, 5, and 9 segment approximations were regressed against the corresponding values for 26 segments.

Coefficients of determination (R^2 values) vs. number of segments used to approximate the hillslope are shown in Fig. 3. Notice that about 9 segments are required to approximate the base line results. These model results imply that for the purpose of accurately representing the spatial variability of canopy cover and ground cover in the direction of flow, 9 segments of approximately 14 m each are required. This is a cover-based definition of modeling scale for this site and the particular hillslope model used. Averaging canopy and ground cover over larger distances results in increasing distortions in the simulated spatial variation in mean sediment concentration.

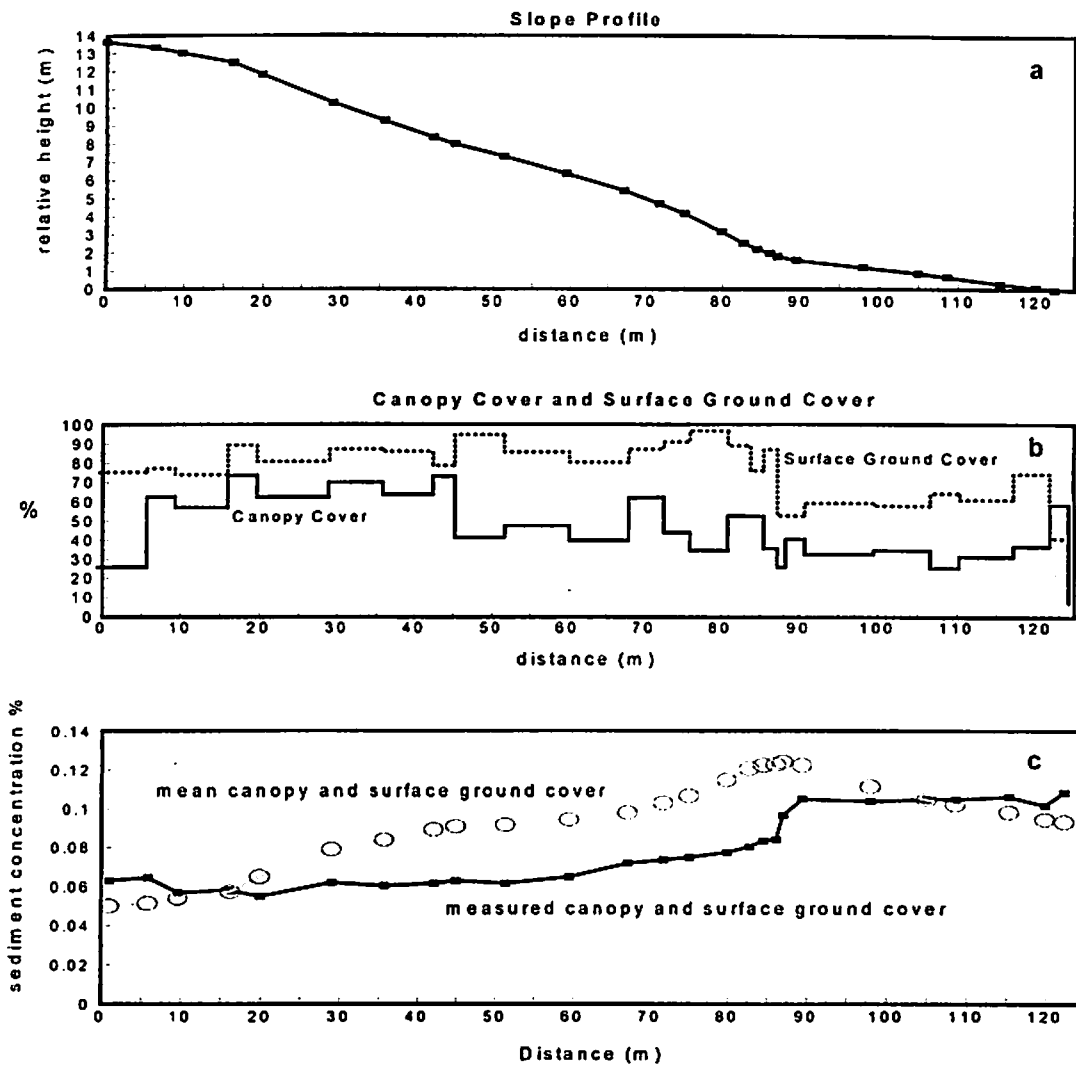


Figure 2. a) Representative hillslope profile, b) measured values of canopy and ground cover on the K2 watershed in July 1994, and c) simulated mean concentrations for both measured and average values of canopy and ground cover of the representative hillslope profile

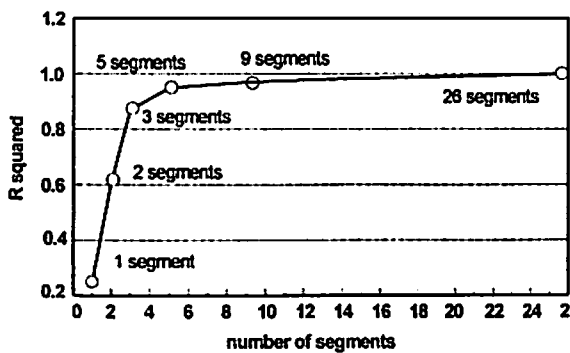


Figure 3. Relationship between the number of segments used to describe the hillslope and the ability to simulate sediment concentration.

The ramifications of these distortions are profound. If departures from a uniform mean

sediment concentration in the flow direction represent areas of disequilibrium where either net rill erosion (increasing concentration) or net deposition of sediment in rills (decreasing concentration) are occurring, then lumping the canopy and ground cover would lead to different conclusions concerning hillslope stability than if the canopy and ground cover were distributed. Conversely, if rainfall simulators which commonly sample 1 to 10 m of a hillslope were used to estimate model parameters, then the position on the hillslope where data were taken could result in significantly different parameter estimates.

These results and interpretations suggest the need to change current methodology for distributed erosion and sediment-yield modeling on hillslopes. First, the practice of lumping canopy and ground cover over the entire hillslope, when in fact they vary significantly as in the above

examples, brings into question the appropriateness of using overall averages for canopy and ground cover. Second, without advances in technology whereby erosion processes can be measured along the hillslope in the direction of flow, estimates of erosion processes along hillslope profiles remain unvalidated, and thus scientifically indefensible. New measurement techniques and technology are clearly needed.

DISCUSSION AND COMMENTS

A simple, qualitative, distributed model of hillslope erosion was used to examine the influence of spatial variability of vegetative canopy cover and surface ground cover on the resulting spatial variability of simulated sediment concentration. Although the model is simple, the example application suggests the need for distributed canopy and ground cover input information to avoid gross distortion in simulated erosion processes on hillslopes. The simulation results also clearly demonstrate the need for new technology to measure erosion process on hillslopes in time and space if parameter estimates from field data are to be free of gross distortions and distributed models are to be validated.

Emphasis herein has been on spatial variability of canopy cover and ground cover and their influence of variability in erosion processes. Runoff was assumed uniform over the area and results were representative of variations in cover only as they influence erosion processes. Similar analyses have been conducted to examine the effects of spatial variability of soil properties on hillslope runoff (e.g. Freeze, 1980) and the effects of spatially varying soil properties on hillslope erosion (e.g. Springer and Cundy, 1988). A more complete analysis of the influence of spatial variability in hillslope characteristics would include the influence of spatial variability in cover and soil properties as they influence runoff and erosion processes.

ACKNOWLEDGMENTS

This research was supported by the USDA-ARS, specifically the Southwest Watershed Research Center Erosion and Sedimentation research project. We gratefully acknowledge this support. We especially appreciate the invitation to the Congress and the generous support provided by the organizing committee for MODSIM'95.

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